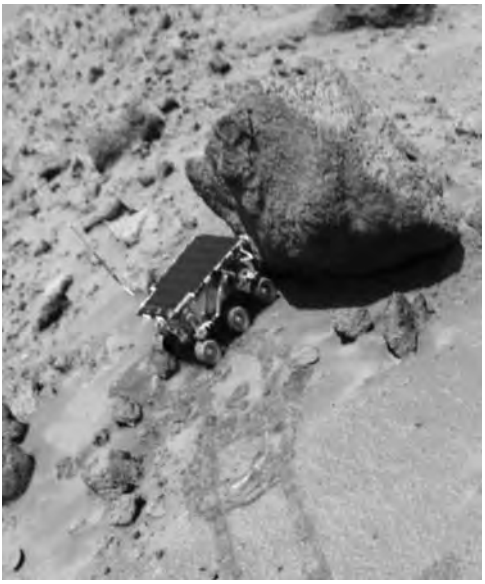

CHAPTER FOUR

SPACE SCIENCE

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Introduction

The National Aeronautics and Space Act of 1958 directed NASA to contribute to the growth of human knowledge of Earth and space and to preserve America's role as a leader in space science and technology. Specifically, in the Declaration of Policy and Purpose, the Act stated, "The Congress declares that the general welfare and security of the United States require that adequate provisions be made for aeronautical and space activities." It next said, "The aeronautical and space activities of the United States shall be conducted so as to contribute materially to one or more of the following objectives: (1) the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space; . . . (5) The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere; . . . (7) Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results thereof . . . ."[1] In the years since NASA's birth, space science has continued to be a major focus of the Agency's programs.[2]

NASA launched 30 space science missions during the decade from 1989 through 1998, almost twice as many as during the previous decade. The majority were launched from ELVs, although five space science missions were

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[1] "Declaration of Policy and Purpose," *National Aeronautics and Space Act of 1958*, Public Law 85-568, 85th Congress, 2nd sess., July 29, 1958, as amended.

[2] Space science missions are typically those that look outward from an orbiting spacecraft into space, investigating the space environment, space phenomena, and the various objects in space. Earth science missions generally look toward Earth from orbit or examine the atmosphere surrounding Earth.

deployed from the Space Shuttle during the decade. Several Space Shuttle missions carried on-board science payloads, and the crews conducted experiments as well as deployed and retrieved scientific satellites that flew freely in the vicinity of the Shuttle or carried out investigations while tethered to the Shuttle's robotic arm. In keeping with its mandate to cooperate with other nations and groups of nations, many of NASA's space science missions were international in scope, with NASA and other space agencies collaborating and sharing in the science investigations. In addition, NASA participated in space science missions launched by other countries and the DOD.

NASA's science missions were in the areas of astrophysics, space physics, interplanetary exploration, and solar physics. In addition, new technologies useful for space science missions were tested. Across all disciplines, these missions opened new vistas, adding immensely to the body of scientific knowledge about the cosmos and raising many new questions that remained to be investigated.

This chapter describes NASA's space science activities between 1989 and 1998. This chapter includes an overview of the decade and a brief summary of the previous decade's activities, budget data for the various programs, and a summary of the management structure and personnel. This chapter describes the individual missions launched during the decade, as well as those launched earlier but operated during this decade, and missions launched after 1998 but developed primarily by that year. For part of this decade, space science, Earth science, life sciences, and microgravity sciences were all included in one NASA administrative office. Only space science is addressed in this chapter. Earth science missions are included in chapter 2 of Volume VIII of the *NASA Historical Data Book*. Life sciences and microgravity sciences are included with human spaceflight in chapter 3 of this volume.

As is customary in these data books, most of the material in this chapter is based on primary NASA documents and Web-based materials produced by NASA. These include pre- and post-launch mission operation reports, press kits and press releases, key personnel announcements, and various reports and plans issued by the Agency. Where space science activities are Shuttle-based, the Space Shuttle mission archives and mission chronologies have been consulted. The NASA projects themselves have been plentiful sources of data. Most NASA projects have comprehensive Web sites, and many also publish information booklets and fact sheets. Partner agencies, such as the ESA, also publish printed and online material about their joint activities with NASA as do the academic and private-sector institutions and organizations that are the homes of researchers and investigators. Most budget material comes from the annual budget estimates generated by the NASA Office of the Chief Financial Officer and from federal budget legislation. Other government agencies and organizations including the GAO, Congressional Research Service, and NOAA also issue reports and documents used as reference material. Measurements are presented in the unit used in the original reference (metric or English); conversions are in parentheses.

The Last Decade Reviewed

During the 10-year period from 1979 to 1988, NASA launched 17 space science missions, increasing our scientific understanding of the nature and processes of the universe by observing the distant universe, exploring the near universe, and investigating Earth's space environment. Missions included those sponsored by NASA's Office of Space Science (OSS) or Office of Space Science and Applications, those launched for other U.S. government agencies, and those involving international partners. Most space science missions were in the areas of planetary exploration, astrophysics, or solar terrestrial studies. The Life Sciences Division participated heavily in Spacelab missions and other investigations. In addition, scientists continued to receive and analyze data from earlier launches and prepare for future missions.

The decade began in 1979 with the "year of the planets" in space exploration. The Voyager and Pioneer planetary exploration missions revealed new information about Jupiter and its satellites; Saturn and Titan, its largest moon; Venus; and Mars. The encounter with the comet Giacobini-Zinner by the International Cometary Explorer (ICE) was the first mission of its type, carrying out on-site investigation of the comet. Researchers investigated astronomical x-ray sources using data obtained on the High Energy Astronomical Observatory (HEAO) mission, receiving the first high-resolution images of x-ray sources and detecting x-ray sources 1,000 times fainter than any previously observed and 10 million times fainter than the first x-ray stars observed.[3] They used data from the Solar Maximum Mission (SMM) to investigate solar activity in the Sun's energy output, output which probably contributed to climate change on Earth.

The *Challenger* accident in January 1986 delayed the launch of scheduled Space Shuttle missions. Astro-1, the Hubble Space Telescope, and the planetary missions Galileo and Ulysses were deferred to the beginning of the next decade. NASA returned to a "Mixed Fleet Strategy," remanifesting some of the other missions that had been scheduled for the Shuttle onto ELVs.

In addition to dedicated free-flying space science missions, almost all Space Shuttle missions performed scientific investigations on board. The first three Spacelab missions took place during the decade. Spacelab was the largest international cooperative space project undertaken to that time. The missions involved numerous disciplines, including atmospheric physics and Earth observations; space plasma physics; solar physics; materials science; life sciences; infrared astronomy; high-energy physics; and technology. Other on-board science experiments also were multidisciplinary.

[3] "The Einstein Observatory (HEAO-2)," *http://heasarc.gsfc.nasa.gov/docs/einstein/heao2.html* (accessed May 8, 2006).

Space Science (1989–1998) Overview

During the 10-year period from 1989 to 1998, NASA launched 30 new space science missions (see Table 4–1). Five were launched from the Space Shuttle and the remainder from various ELVs. Eight missions focused on planetary investigations; 20 were physics and astronomy missions; and two were space science technology demonstrators, one with a significant planetary component. NASA also contributed an instrument to one Russian planetary mission, two Japanese missions, and partnered in a technology demonstration and space science DOD mission. Thirteen other space science missions were carried out on or near the Space Shuttle—as attached payloads, satellites flying freely near the Shuttle, or satellite servicing missions featuring ambitious spacewalks (see Table 4–2).[4]

These missions were highly productive and had an impressive success rate. Only one physics and astronomy mission, the dual HETE/SAC-B, failed entirely because of a launch vehicle malfunction, not because of an anomaly with the scientific payload. The planetary missions were less successful; three missions, all missions to Mars, failed. Among the attached and retrieved payloads, one deployment was unsuccessful and required a reflight. Many of the missions launched during the decade operated beyond their stated design life, and some were still operating in mid-2005. Some missions launched during the 1970s were still in use into the 1990s.

During the Agency's first two decades, NASA policy had called for a mixture of small explorers, medium-sized observatories, and large complex missions such as Viking and the Large Space Telescope to advance the state of technology and challenge the system. In the 1980s, the Agency moved toward an emphasis on large missions, reflecting the philosophy that it took as much time and energy to start a large mission as a small mission, and the science returns were greater.[5] As NASA's fourth decade began in 1989, it seemed as if the Agency would continue with large, complex, long-duration space science missions that characterized the program in the 1980s. Three major space science missions were approved between 1989 and 1991 while Richard Truly led the Agency: the Advanced X-ray Astronomical Facility (AXAF), the Comet Rendezvous-Asteroid Flyby (CRAF) mission, and a Saturn-bound mission named Cassini.[6] On October 4, 1989, President George H. W. Bush proclaimed the Space Exploration Initiative, an ambitious new mission to

[4] This adds to the Spacelab and SPACEHAB missions described in chapter 3, Human Spaceflight.

[5] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

[6] John E. Naugle and John M. Logsdon, "Space Science: Origins, Evolution, and Organization," in John M. Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V: Exploring the Cosmos* (Washington, DC: National Aeronautics and Space Administration Special Publication 2001-4407, 2001), p. 14.

return to the Moon and then travel to Mars.[7] It quickly became clear that this initiative was too expensive in a time of increasing budget deficits and an ailing economy, and the initiative did not receive congressional support.

By the time Daniel Goldin replaced Truly in April 1992, cost overruns, delays, and failures of some larger missions were already contributing to the trend toward smaller, more frequent missions. The new Administrator, recognizing the need to rein in escalating costs, accelerated the trend and directed office administrators to plan for a level budget in the future rather than continued growth.[8] Within six months after joining NASA, Goldin introduced the Agency to the concept of "faster, better, cheaper" for future missions. The rationale was that undertaking more missions at lower costs and with shorter development times would produce better science results, allow more scientists the opportunity to participate in NASA missions, and allow for an occasional failure.[9] Although applicable to the entire Agency, the organization most affected by this new direction was the Office of Space Science and Applications.

The Agency introduced the Discovery Program later in 1992 to carry out Goldin's directive in the area of planetary exploration. Discovery Program missions were a series of less costly missions with specific scientific, technical, and programmatic guidelines. These small planetary missions had strict schedule, size, and cost limits and would complement larger missions and keep the scientific community involved with a steady stream of new planetary data.[10] The first Discovery mission, the NEAR mission, flew in 1997. The Mars Pathfinder and Lunar Prospector followed.

The Explorer program was also restructured during the decade, and a small Explorer component was added even before Goldin's tenure began. According to a NASA brochure, small Explorer satellites were designed to produce "extraordinary performance while fully embracing the essence of 'smaller, faster, cheaper.'"[11] All four small Explorer missions launched by 1998 succeeded.

NASA's space science programs fell into two large categories: 1) planetary or solar system exploration and 2) physics and astronomy. The first solar system exploration missions since 1978, Magellan and Galileo, had been victims of *Challenger*-induced launch delays. Launched in 1989, they were NASA's only two interplanetary launches in the 1980s. Upon arriving at Venus, Magellan embarked on a mission that yielded outstanding scientific

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[7] W. Henry Lambright, "Transforming Government: Dan Goldin and the Remaking of NASA," Price Waterhouse, March 2001, pp.13–14.

[8] Committee on the Future of Space Science, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, *Managing the Space Sciences,* Chapter 3, The Changing Environment for Science at NASA, *http://www.nap.edu/html/ssb_html/Manage_Sp_Sci/fossch3.shtml* (accessed October 5, 2005).

[9] Naugle and Logsdon, p. 14.

[10] "Discovery Program Handbook," Document I-31 in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* p. 219.

[11] McCurdy, *Faster, Better, Cheaper,* p. 57.

results, revealing new information about the planet's surface. Galileo, despite a high-gain antenna that refused to unfurl, operated successfully and returned valuable scientific data on Jupiter and its moons.

The Mars missions of the 1990s had a mixed record. The Mars Observer, a scientifically ambitious and costly mission packed with expensive instruments, failed to regain contact with mission controllers after performing a maneuver to put it into orbit around Mars. In 1997, the relatively economical Mars Pathfinder mission demonstrated a less costly method of landing a spacecraft and science instruments on the Martian surface. The Pathfinder's small rover, named Sojourner, gathered an international following as it navigated the harsh Martian terrain. The Mars Global Surveyor also successfully reached Mars in 1997, conducting a successful mission. The next two Martian probes, the Mars Climate Orbiter and the Mars Polar Lander, failed. Both probes disappeared as they made their final approaches to the planet.[12]

One more planetary mission launched during the 1990s. The NEAR mission, the first of NASA's lower-cost Discovery missions, performed the first sustained examination of a near-Earth asteroid. The mission tested scientific theories on the formation of the solar system and management theories on cost reduction.[13]

NASA's physics and astronomy missions were in the areas of astrophysics, space physics, and solar physics; they ranged from large, complicated missions to small missions limited in scope. Two "Great Observatories" were launched during the decade. The first, the Hubble Space Telescope, launched in 1990, turned out to have blurred vision caused by spherical aberration introduced during manufacturing of the primary mirror. The telescope also had excessive jitter caused by expansion and contraction of the solar arrays related to temperature changes. The telescope's first servicing mission in 1993 installed corrective mirrors to sharpen the telescope's vision and replaced the solar arrays. This servicing mission was critical to regaining the Agency's credibility as well as the optical sensitivity that allowed the Hubble Space Telescope to produce the expected high-quality images.

The second Great Observatory, the CGRO, was one of several missions devoted to investigating gamma-ray bursts. The CGRO showed that gamma-ray bursts were evenly distributed over the sky. The mission was extremely productive, with investigations ranging from the solar system to distant regions of the universe. Another mission, the 1996 Italian-Dutch satellite, Beppo-SAX, launched on a U.S. launch vehicle from Cape Canaveral, Florida revealed that a gamma ray burst was followed by an optical image, permitting identification of the source.[14]

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[12] Amy Paige Snyder, "NASA and Planetary Exploration," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* pp. 291–298.

[13] Howard McCurdy, *Low-Cost Innovation in Spaceflight: The Near Earth Asteroid Rendezvous (NEAR) Shoemaker Mission,* Monographs in Aerospace History no. 36 (Washington, DC: National Aeronautics and Space Administration Special Publication 2005-4536, 2005), p. 3.

[14] Nancy Grace Roman, "Exploring the Universe: Space-Based Astronomy and Astrophysics," in Logsdon, ed., *Exploring the Unknown, Vol. V,* pp. 515–516, 539.

NASA carried out several x-ray and UV studies during the decade, some with other countries. In 1982, NASA arranged to work with Germany and the United Kingdom on the ROSAT, an x-ray observatory launched in 1990 by the United States. NASA and the Massachusetts Institute of Technology (MIT) flew instruments on the Japanese ASCA. NASA's first satellite dedicated to the EUV, the EUVE was launched and operated until 2000 when NASA decided to deorbit the spacecraft because of budget constraints. The RXTE, the last large Explorer mission, continues to measure the variability over time in the emission of x-ray sources in a wide energy range. AXAF, renamed Chandra, launched in 1999 after 20 years of development.[15]

NASA launched several solar physics missions during this decade, beginning with Ulysses in 1990. This collaboration with the ESA produced a number of years of valuable heliospheric data as it flew over the solar poles. Another solar physics mission, the TRACE, a small Explorer mission with international participation and a "faster, better, cheaper" approach was developed in less than four years to refine knowledge of the relationship between solar magnetic fields and coronal heating. Launched on a U.S. launch vehicle, the SOHO (sometimes classified as a space physics rather than a solar physics mission) was an international mission built by the ESA carrying instruments from 14 countries and NASA. Despite battery difficulties, the SOHO sent back critical information about the Sun, contributing to the understanding of the Sun's internal dynamic structure and the onset of coronal bursts and mass ejections affecting solar-terrestrial relations.[16]

The discipline of space physics has been central to NASA's science program since discovery of what became known as the Van Allen belts in 1958. From 1989–1998, the ISTP and GGS programs formed the framework for a number of space physics missions, including NASA's Wind and Polar spacecraft, the ESA's SOHO and Cluster spacecraft, and Japan's Geotail spacecraft. The NASA portion of the CRRES, a joint NASA-U.S. Air Force mission, also was planned to be part of the ISTP program.

NASA's space physics program benefited from the Explorer program restructuring, which called for launching two Explorer missions per year and included a Principal Investigator (PI)-mode, a mode in which the PI took full responsibility for all aspects of the mission. A number of small, focused science missions complemented NASA's GGS program. Between 1989 and 1998, these missions included the SAMPEX, launched in 1992; the FAST, launched in 1996; the ACE, launched in 1997; and TRACE (a solar physics mission), launched in 1998.[17]

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[15] Roman in Logsdon, ed. pp. 517–521, 540.

[16] David H. DeVorkin, "Solar Physics from Space," in John M. Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume VI: Space and Earth Science* (Washington, DC: National Aeronautics and Space Administration Special Publication 2004-4407, 2004), pp. 35–36.

[17] James Green and Brian Dewhurst, "Space Physics," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume VI*, pp. 157, 168–173.

At the close of the decade, a new concept was introduced in which space physics missions would perform the scientific research necessary to support a variety of practical applications relating to space weather and its effect on human society and life. Named Living With a Star, the initiative, under the leadership of George Withbroe, added a practical dimension to the traditional rationale for space science: increase understanding and apply that understanding in useful ways. The initiative focused on human radiation exposure related to spaceflight and high-altitude flight; the impact on space assets; satellite operations; communication systems; terrestrial power grids; and the effects of solar variability on terrestrial climate change. Supported by Goldin, it was presented to the Clinton administration as an "add-on" to the FY 2001 budget, where it became a NASA initiative in FY 2001.[18]

Management of NASA's Space Science Program

The organizational structure and responsibilities of NASA's space science program office are similar to those found in program offices throughout the Agency.[19] The OSSA (or the OSS later in the decade) was headed by an Associate Administrator, located at NASA Headquarters, who was responsible for "the overall planning, direction, execution, and evaluation of the NASA programs concerned with space science . . ." The Associate Administrator also had institutional management of NASA's Goddard Space Flight Center and the Jet Propulsion Laboratory.[20] These NASA Centers were the "lead centers" for the Agency's space science missions and the location of the missions' project offices with responsibility for mission implementation.

The heads of several discipline areas or programs, usually called divisions, reported to the Associate Administrator. These program areas changed over time but generally included the areas of physics, astronomy, and planetary exploration. Each division was responsible for specific scientific missions consisting of one or more spacecraft, instruments, and a number of scientific experiments. A PI was responsible for each instrument and for analyzing and publishing data from the instrument. The PI also was responsible for placing the data in a data center accessible to other scientists.

In most cases, the project office at the lead Center was responsible for the design and development or procurement of the mission's hardware as well as testing the hardware, integrating it with the launch vehicle, operating the spacecraft, and delivering the data to the PI.[21] The project manager headed the project office, and the project scientist was usually collocated in the project

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[18] Green and Dewhurst in Logsdon, pp. 174–175.
[19] Midway during this decade, NASA moved from a program office structure to a strategic enterprise structure, headed by an Enterprise Associate Administrator.
[20] *NASA Management Instruction 1102.1H,* "Role and Responsibilities–Associate Administrator for Space Science and Applications," July 30, 1992.
[21] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

office and the science directorate at the project's lead Center. International missions, and missions managed jointly with other U.S. agencies, might have different arrangements.

At the beginning of the 1989–1998 decade, the OSSA managed space science missions, referred to within NASA as Code E. This combined organization had been established in November 1981. The divisions within OSSA relating to space science were Space Physics, Solar System Exploration, and Astrophysics (see figure 4–1). The remaining divisions not involved with space science were Space Earth Sciences and Applications, Microgravity Science and Applications, Communications and Information Systems, and Life Sciences. Lennard A. Fisk was Associate Administrator of the OSSA; Stanley Shawhan headed the Space Physics Division; Geoffrey Briggs headed the Solar System Exploration Division; and Charles J. Pellerin headed the Astrophysics Division.

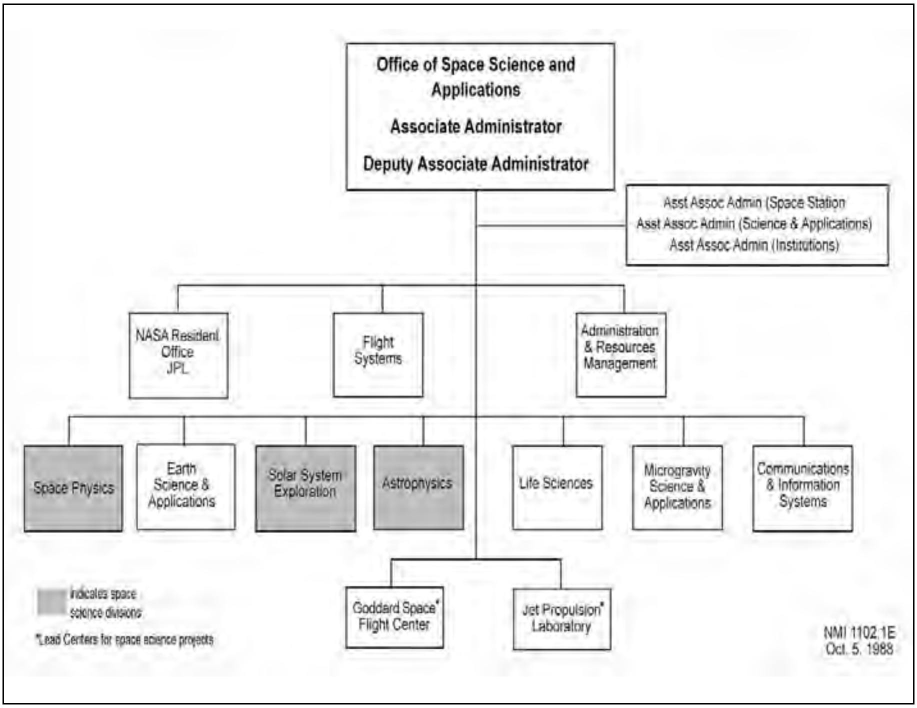

Figure 4–1. Office of Space Science and Applications, 1981–1993

In April 1990, an administrative action changed the letter designation for OSSA to Code S, but the functions and organization remained the same. In June 1990, Shawhan died of a sudden heart attack. His deputy, Thomas Perry, became acting Director of the Space Physics Division.[22] In July 1990, Wesley Huntress, Jr., replaced Briggs as head of the Solar System Exploration Division. In spring 1991, George L. Withbroe became Director of the Space Physics Division.

[22] George Withbroe, e-mail to author, October 3, 2005.

In July 1992, the roles and responsibilities assigned to the OSSA changed to include responsibility for "planning, development, and operation of NASA missions that used the Space Shuttle, Spacelab, other Shuttle-attached payload carriers, and Space Station *Freedom* . . . " The OSSA also assumed responsibility for managing and directing the ELV and upper stages launch service program, including "planning, requirements, acquisition strategy, operations, and oversight . . . ."[23]

In October 1992, Administrator Goldin announced an Agency-wide reorganization to "better focus NASA's programs, to streamline how we do business so we can meet the challenges ahead" that affected the management of space science missions.[24] The OSSA split into two organizations, one to manage space science missions and the second to manage Earth science and applications missions. The temporarily renamed Office of Planetary Science and Astrophysics (Code S) managed space science missions. Applications missions went to the new Mission to Planet Earth (Code Y) office. At the time, neither life sciences nor microgravity science was mentioned.[25] Huntress became acting Associate Administrator of the reconfigured space science organization, replacing Fisk, who did not agree with the Administrator's "faster, better, cheaper" policy and was reassigned to the position of Agency Chief Scientist.[26] William L. Piotrowski replaced Huntress as acting head of the Solar System Exploration Division. These changes became effective in March 1993.

At the same time, the OLMSA (Code U) was established. This office was formed from the offices within the old OSSA that dealt with life sciences and microgravity.[27] Before the end of the month, the Office of Planetary Sciences and Astrophysics changed its name to the simpler OSS. Activities previously managed by the Office of Exploration, headed by Michael Griffin, were also absorbed by the OSS, and the Exploration Office was disbanded.[28] See Figure 4–2 for the new OSS structure.

Pellerin left as head of the Astrophysics Division in June 1993. The position remained vacant until April 1994 when Daniel Weedman was appointed to the position.

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[23] NASA Management Instruction 1102.1H "Role and Responsibilities–Associate Administrator for Space Science and Applications," (July 30, 1992).

[24] "Goldin Announces Changes in NASA Organization To Focus and Strengthen Programs and Management," *NASA News* Release 92-172, October 15, 1992, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1992/92-172.txt* (accessed April 18, 2006).

[25] Committee on the Future of Space Science, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, *Managing the Space Sciences*, chapter 1, Introduction, *http://www.nap.edu/html/ssb_html/Manage_Sp_Sci/fossch1.shtml* (accessed October 5, 2005).

[26] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

[27] "Assignment of Key Personnel and Establishment of New Offices," NASA Special Announcement, March 11, 1993. OLMSA is discussed in chapter 3.

[28] "Exploration Effort Shifted to Office of Space Science," *NASA News* Release 93-54, March 25, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-054.txt* (accessed July 9, 2005).

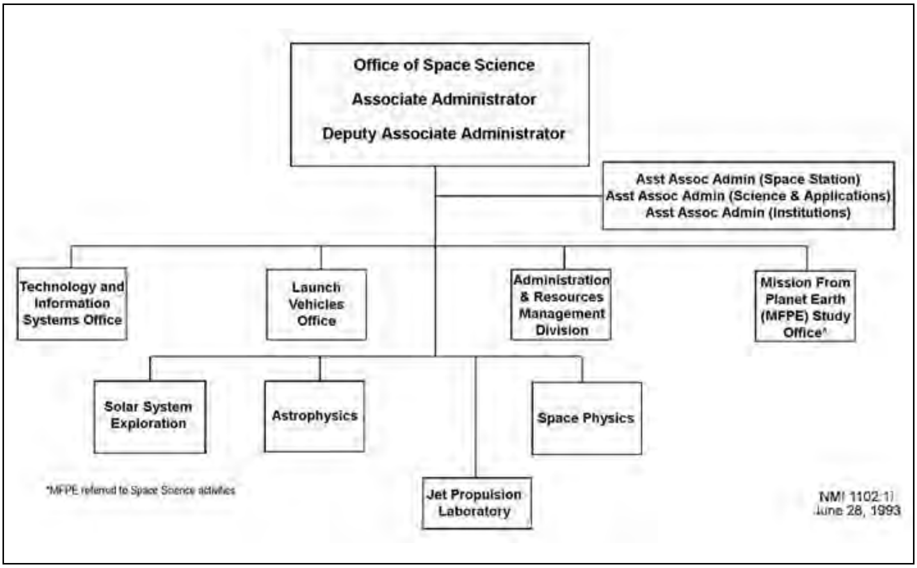

Figure 4–2. Office of Space Science (1993)

In September 1994, the OSS published the Office of Space Science Strategic Plan for 1995–2000. The vision of space science, as stated in the plan, was to "explore and seek to understand the Sun, the Solar System, the Galaxy, and the Universe, for the benefit of humanity."[29] The plan identified four central science themes: the Galaxy and the Universe, the Sun-Earth-Heliosphere Connection, Planetary System Origin and Evolution, and Origin and Distribution of Life in the Universe. Each theme had intellectual questions that current and future projects sought to answer and strategies for accomplishing near-term and long-term objectives relating to the theme. Each program, whether currently operating, in development, or planned for the future, was identified with one or more themes. The plan recognized that declining budget expectations for space science required a different approach for future missions, using smaller spacecraft and new technologies to reduce spacecraft development and launch costs and to distribute risk.

In the spring of 1995, NASA again took steps to reduce costs and increase organizational efficiency. The Agency released a new Strategic Plan in May 1995 with five "strategic enterprises" forming the framework for strategic planning at NASA. OSS projects and research programs were in the Space Science Enterprise. At the same time, a key decision was made to assign each field Center a clearly defined primary mission, structured along a series of strategic enterprises and functional responsibilities. "Centers of Excellence" for each discipline area already existed, with missions in particular disciplines managed by Centers with specific expertise. This step formalized the process.

[29] National Aeronautics and Space Administration Office of Space Science, *Space Science for the 21st Century: Strategic Plan for 1995–2000*, September 1994.

In the area of space science, two Centers were involved. The "mission" of Goddard Space Flight Center, the Center of Excellence for scientific research, was Earth science and physics and astronomy. The "mission" of the Jet Propulsion Laboratory, the Center of Excellence for deep space systems, was planetary science and exploration.[30]

Around the same time, Jurgen Rahe was appointed to head the Solar System Exploration Division, which Piotrowski had led on an acting basis. Rahe led the division for two years, until his sudden death in June 1997.

Six months later, in November 1995, Goldin again reorganized the OSS. Associate Administrator Huntress stated in a memo that the changes were made to "meet the drastically reduced staffing levels prescribed in the President's initiative, while preserving both the excellence in managing NASA's space science program and its strong bond with the science community."[31] He listed four science themes: Galaxy and Universe, Astronomical Search for Origins and Planetary Systems, Solar System Exploration, and the Sun-Earth Connection. These four themes were almost identical to those introduced a year earlier in the Office of Space Science Strategic Plan. The existing discipline divisions and their branches within the OSS transformed into programs corresponding to these themes. The programs were led by program directors who provided an integrated scientific perspective for each theme and collectively functioned much like a chief scientist for the OSS.[32] Space Physics became the Sun-Earth Connection, still headed by Withbroe. Solar System Exploration kept the same name, with Jurgen Rahe as the head. Weedman left the disbanded Astrophysics Division, which was restructured into two programs: the Astronomical Search for Origins and Planetary Systems, led by Edward J. Weiler, former chief of the Ultraviolet and Visible Astrophysics Branch; and Structure and Evolution of the Universe, led by Alan Bunner, former chief of the High Energy Astrophysics Branch.[33] With the abolishment of the discipline divisions and their associated branches while their functions moved to the Goddard Space Flight Center or Jet Propulsion Laboratory, space science staffing at NASA Headquarters was reduced from more than 200 civil servants to less than 70 persons.[34]

As well as the thematic programs, the restructured OSS had the following three functionally oriented operating divisions: Research Program Management, led by Henry Brinton, housed all the program scientists and was where scientific research was accomplished, fundamental questions defined, measurements required from the space missions specified, and data analyzed.

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[30] "Review Team Proposes Sweeping Management, Organizational Changes at NASA," *NASA News* Release 95-72, May 19, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-73.txt* (accessed April 25, 2005).

[31] Wesley Huntress, Jr., to multiple addresses, "NHB 1101.3 NASA Organization Handbook," November 9, 1995.

[32] George Withbroe, e-mail to author, October 3, 2005.

[33] Weedman left NASA and returned to a faculty position at Pennsylvania State University.

[34] Green and Dewhurst, "Space Physics," in Logsdon, p. 174.

Advanced Technology and Mission Studies, led by Peter Ulrich, was where the tools to carry out the space missions were developed and tested. The Mission and Payload Development Division, led by Kenneth Ledbetter, was where flight missions were developed. The Mission and Payload Development Division housed all of the engineers and program managers. Figure 4–3 shows the new structure.

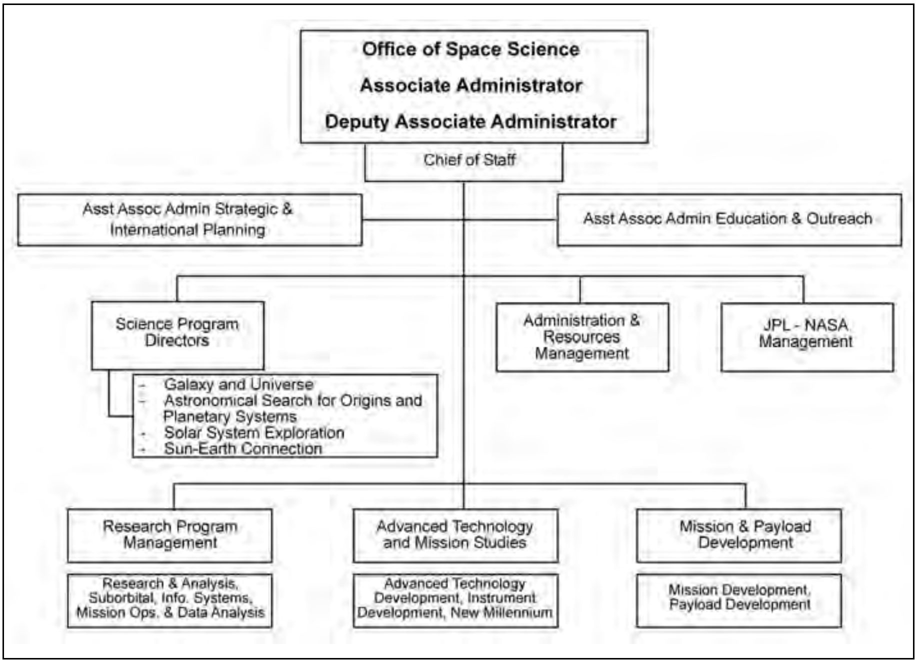

Figure 4–3. Office of Space Science (November 1995)

Carl Pilcher, Office of Space Science Assistant Associate Administrator for strategic and international planning, assumed the position of acting head of the Solar System Exploration Division upon the death of Rahe in 1997 and became head in 1998.

In February 1998, Huntress announced that he would leave NASA. In November, Weiler, who had served as acting OSS Associate Administrator since September 28 and led the Astronomical Search for Origins and Planetary Systems program, was appointed to the position.

Money for Space Science

The R&D appropriation through FY 1994 and the SAT appropriation beginning in FY 1995 funded NASA's space science activities. From FY 1989 to FY 1996, NASA's space science funds were divided into the following two major discipline categories within the broader space science category:[35] 1)

[35] Funding associated with Life Sciences can be found in chapter 3, Human Space Flight.

Physics and Astronomy, and 2) Planetary Exploration. Each of these discipline categories funded every mission under development in the discipline, mission operations and data analysis for missions that had been launched and were operational, and research and analysis. More specifically, mission operations and data analysis funded in-flight operation of spacecraft and the analysis of data from those missions. Research and analysis funds ensured that data and samples returned from flight missions were fully exploited; undertook complementary laboratory and theoretical efforts; defined the science rationale; and developed the technology needed to undertake future missions.

To fund a space science program, the director of the proposed program first defended the program to the space science Associate Administrator, then to the NASA Administrator, and finally to the OMB as part of the annual budget submission. The OMB then submits the President's budget to Congress for approval. A description of the budget process is in chapter 1, Introduction, of this data book.

In FY 1993, NASA restructured the OSS and moved programs dealing with life sciences to a new program office, the OLMSA. The new structure was reflected in the FY 1994 budget request (see chapter 3, Human Spaceflight).

In FY 1997, the OSS combined its Physics and Astronomy and Planetary Exploration budget categories and listed all projects in a single Space Science budget category. In the Space Science budget category, missions under development were still listed separately by name but with only one mission operations and data analysis budget category and one research and analysis budget category rather than two (as in previous years).

Also beginning with the FY 1997 budget request, NASA started moving toward implementing "full-cost accounting," a method in which all costs associated with a project were included in the project budget. Starting with projected FY 1997 costs, NASA showed budget figures using both the traditional method (being phased out) and the new "full-cost" method, shown as "budget authority," or the amount appropriated by Congress.[36] FY 1995 and the prior years' budget authority were recalculations reflecting the full cost of all elements associated with a project. For space science missions, the full cost of a mission typically included costs for development of the spacecraft and experiments, postlaunch mission operations and data analysis, launch support, and tracking and data acquisition support.[37] Previously, only the development cost was associated with a mission budget, and it was necessary to search for

[36] Budget authority represents the amounts appropriated by Congress in a given fiscal year that provide NASA with the authority to obligate funds. Obligation of funds legally commits NASA to pay contractors and other service providers for materials and services. The ensuing obligations, cost incurrence, and expenditures (outlays) based on the budget authority can occur in a different fiscal year from the year in which Congress provides the budget authority.

[37] The cost of civil service labor is not included in these figures, although it would be included in complete "full-cost" figures.

the costs for mission operations, launch, and tracking in other parts of the budget and determine the amounts applicable to a particular mission. In the following tables where an amount for "budget authority" is shown, the phasing of both actual costs and projected budget authority come from the FY 1998 Budget Estimate. Phasing of funds may have been somewhat different in the FY 1997 Budget Estimate and earlier, but the final cost to complete a project would have been roughly the same. Also, the full-cost figures stated here do not include amounts contributed by international participants or costs for the use of non-program-unique government facilities and general and administrative support used to carry out research and development activities or for early definition phase activities.

From 1989–1998, NASA's Space Science budget generally rose, although typically at a modest pace, usually barely outpacing the rate of inflation. In FY 1991, the amount Congress authorized for space science did not exceed the rate of inflation, and in FY 1998, the amount for space science fell.[38] Starting with the FY 1993 budget and continuing for three years, the amount authorized for physics and astronomy missions also fell. However, the amount authorized for planetary missions rose significantly during the same period, and the total amount for space science missions increased until FY 1998 (see Table 4–3).

For most of the decade, the programmed amounts (reflecting what NASA actually had available to spend) increased (see Table 4–4). In 7 of 10 years, the programmed budget for space science activities grew less than 10 percent but still more than the rate of inflation. In FY 1991, the programmed amount grew slightly more than 15 percent, capping a three-year period in which three large programs were approved. In FY 1994, the programmed budget increased 27 percent over the prior year. The programmed amount dropped in the following two years: FY 1993 by 3.8 percent, reflecting an effort by the administration to reduce the federal deficit, and FY 1997, by 9.4 percent. However, in FY 1994, a 27.1 percent increase made up for the decrease of the prior year. The modest 3.8 percent increase in FY 1998, however, did not cover the drop of the previous year, increasing the budget to only slightly more than the FY 1995 level.

Beginning in 1992, the Agency implemented Daniel Goldin's "faster, better, cheaper" approach. The Discovery Program, New Millennium Program, Mars Surveyor Program, Small Explorer Program, and Small Satellite Technology Initiative sponsored a greater number of smaller, more

[38] In most years, annual appropriations legislation did not designate an amount specifically for space science. The authorization bill and committee proceedings provided guidance as to Congress's intent and formed the basis for the Agency's annual operating plan. An authorization act authorizes the enactment of appropriations and specifies how appropriated funds are to be used. In some years, no authorization bill was passed. The annual appropriations act provides funds for federal agencies to make payments out of the Treasury for specified purposes. In years when there was an authorization act, the act's text was typically more specific than in the appropriations act, which provides direction for only major budget appropriations categories (U.S. Senate Glossary), *http://www.senate.gov/pagelayout/reference/b_three_sections_with_teasers/glossary.htm* (accessed July 14, 2006).

frequent projects.[39] The Agency also reduced costs through greater international cooperation on new flight programs, involving the space agencies of other countries as full partners that contributed instruments and other key components as well as sharing in the science results. The number of missions NASA successfully flew during this decade and the wide range of scientific discoveries made in diverse disciplines demonstrated the success of this approach.

Tables 4–5 to 4–35 show budget requests and programmed amounts for the programs in space science. If Congress indicated an authorized amount for a program, that amount is indicated.[40] Since NASA typically submits an original and revised budget request before Congress acts on a budget, both amounts are indicated and separated by a forward slash. Where no amount appears, there was no submission. Programmed amounts are determined after the end of a fiscal year and reflect the amounts actually available to be spent. Occasionally, a budget category was established during a fiscal year. When that happened, there is a programmed amount shown but no budget request for that activity. Funds for these introduced activities generally were taken out of another project's budget through a "reprogramming" of funds. All amounts stated come from the annual budget requests prepared by the NASA Office of the Chief Financial Officer.

Space Science Missions

Overview

NASA's space science missions fit into the following three discipline areas: space physics, astrophysics, and solar system exploration. During the first part of the decade, three corresponding divisions managed these discipline areas. The Space Physics Division supported investigations into the origin, evolution, and interactions of particulate matter and electromagnetic fields in a wide variety of space plasmas. Missions managed by this division studied the upper atmospheres, ionospheres, and magnetospheres of Earth and other planets; the Sun as a star and as a source of solar system energy, plasma, and energetic particles; and the acceleration, transport, and interactions of energetic particles and plasmas throughout the solar system and the galaxy. Observations, theory, modeling, simulations, laboratory studies, interactive data analysis, instrument development, and active experiments were aspects of the Space Physics program. The division included research programs in ionospheric, magnetospheric, solar, and cosmic and heliospheric physics. The Suborbital Research program was also part of the Space Physics Division.

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[39] Small Satellite Technology Initiative projects fell into the category of space applications and are addressed in the Space Applications chapter in Volume VIII of the *NASA Historical Data Book*.

[40] Usually Congress stated authorized amounts only for major budget categories or programs of great visibility.

Missions managed by the Astrophysics Division studied the origin and evolution of the universe, the fundamental physical laws of nature, and the birth of stars, planets, and ultimately life. Because these subjects required some observations at wavelengths absorbed by Earth's atmosphere, observations needed to take place from space-borne instruments. This program centered on the four Great Observatories; a series of smaller spacecraft; and suborbital rockets, balloons, and aircraft. The Great Observatories—the Hubble Space Telescope, GRO, AXAF, and SIRTF—each provided significantly improved sensitivity and resolution over their selected region of the electromagnetic spectrum. The Explorer spacecraft performed exploratory work, all-sky surveys, specific studies, and unique investigations not suited to the Great Observatories. Suborbital vehicles provided the means to make preliminary observations, conduct selected investigations at lower cost, test instrumental concepts, and nurture groups capable of developing instruments for future space missions.

The Solar System Division was responsible for all of NASA's deep space missions and for the exploration of all the planets and other solar system constituents such as asteroids, comets, and the interplanetary medium.[41] This division's investigations included the search for planetary systems around other stars, conducting comparative planetary studies, and establishing the scientific and technical database required to support major human activities on other planets.[42]

In 1995, NASA gave its space science organization a more multidisciplinary focus. For funding purposes, however, NASA's space science missions remained in two categories: physics and astronomy, which encompassed both space physics and astrophysics missions as well as planetary exploration. Missions addressed in this chapter are arranged in these two categories.

The descriptions of missions in this chapter launched during the decade 1989–1998 include both narrative material and mission tables. If the mission continued to operate past 1998, it is noted in the table; but most events occurring after 1998 are not described. If a mission launched before 1989 but continued to operate into the decade addressed here, the description focuses on events beginning in 1989. When mission development occurred primarily between 1989 and 1998 but the mission did not launch until after 1998, events occurring through 1998 are addressed.

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[41] "Guide to NASA's Office of Space Science & Applications," prepared by the NASA Headquarters Office of Communications, Office of Space Science and Applications Public Affairs Office, July 5, 1988.

[42] Office of Space Science and Applications, *Strategic Plan 1991,* p. 7 (NASA History Office Folder 18431).

Role of the Principal Investigator

Typically, NASA's space science missions draw heavily on the participation and contributions of their PIs. These scientists, who often work with teams of researchers of varying sizes, come from NASA, other U.S. and foreign agencies, academia, research organizations, and the private sector. The PI frequently participates in instrument development and the determination of science objectives and is responsible for the instrument's calibration before launch and for much of the science program after launch.

During the 1990s, NASA shifted the degree of PI responsibility. On older space science missions, PIs took responsibility for the science instruments and data analysis with NASA managing the project and developing the spacecraft. Beginning in the mid-1990s, NASA moved toward missions offering scientists the opportunity to lead their own space science missions, termed PI-led missions.[43] A mission characterized as PI-led "entrusts the scientific, technical, and fiscal management to a single PI and his or her teams. The PI has responsibility for defining the mission concept and controlling its cost, schedule, and targeted scientific investigation."[44] PI-led missions differ from NASA's "core" missions, which are defined in NASA's strategic plans, because the scientist's involvement in a core mission occurs first when defining the mission, then as a competitively selected instrument provider, and then during data analysis and interpretation. Also, in a core mission, NASA usually takes responsibility for the spacecraft and often provides significant help with the experiment.[45] PI-led missions, on the other hand, are conceived and promoted by smaller groups in the scientific and technical communities to carry out space-based measurements that core missions do not cover. On a PI-led mission, PIs choose and organize their implementation team and decide how best to use project resources to accomplish the mission's scientific goals. In general, PI-led missions include the following:

- Operate under a cost cap.
- Are led by a single PI affiliated with a range of possible types of institutions.
- Designate the PI responsible for *all* aspects of the mission, including development, management, risk management, and termination if the science objectives are no longer likely to be met within cost and schedule reserves.
- Allow the PI control over organizational and management specifics with "only essential NASA oversight."[46]

Examples of PI-led missions include some Explorer missions and missions in NASA's Discovery Program.[47]

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[43] Committee on Principal-Investigator-Led Missions in the Space Sciences, Space Studies Board Division on Engineering and Physical Sciences, National Research Council, *Principal-Investigator-Led Missions in the Space Sciences* (Washington, DC: The National Academies Press, 2006), p. 1 (PDF available at *http://darwin.nap.edu/books/0309100704/html/*) (accessed May 5, 2006).
[44] *Principal-Investigator-Led Missions in the Space Sciences,* pp. 10–11.
[45] Nancy Roman, e-mail to author May 20, 2006.
[46] *Principal-Investigator-Led Missions in the Space Sciences*, p. 91.
[47] *Principal-Investigator-Led Missions in the Space Sciences*, pp. 16–17.

Physics and Astronomy Missions

Space science missions funded by the Physics and Astronomy program included the Explorer missions, the Great Observatories, a series of smaller spacecraft, and suborbital balloons and rockets.

Explorers Program

NASA's Explorers Program provided frequent, less costly access to space for physics and astronomy investigations that could be accommodated with small to midsized spacecraft. The program supported investigations in all space physics and astrophysics disciplines that were usually of an exploratory or survey nature or had specific objectives not requiring the capabilities of a major observatory. Since the first Explorer launch in 1958, Explorer missions have discovered radiation trapped within Earth's magnetic field, investigated the solar wind and its interaction with Earth, studied upper atmosphere dynamics and chemistry, mapped our galaxy in radio waves and gamma rays, and determined properties of the interstellar medium through UV observations.[48] The missions also have performed active plasma experiments on the magnetosphere, made *in situ* measurements of the comet Giacobini-Zinner, and completed the first high sensitivity, all-sky survey in infrared, discovering more than 300,000 sources.[49] The Explorers Program also helped develop instruments for "payload-of-opportunity" missions, such as those involving other federal agencies or international collaboration.

In 1988, the Explorers Program began developing a group of "small class" explorers. These Small Explorer missions, called SMEX, provided frequent flight opportunities for highly focused and relatively inexpensive space science missions in the disciplines of astrophysics and space physics. The program conducted focused investigations probing conditions in unique parts of space, complementing major missions, proving new scientific concepts, and making other significant contributions to space science. The first three SMEX missions, selected from 51 candidates, were announced on April 4, 1989. The SAMPEX missions launched in 1992; the FAST launched in 1996; and the SWAS launched in 1998. All of these missions studied important questions in space physics, astrophysics, and upper atmosphere science.

The second SMEX mission set, announced on September 14, 1994, chose two science missions. The first of the newly selected missions, the TRACE, observed the Sun to study the connection between its magnetic fields and the heating of the Sun's corona. The TRACE launched in April 1998. The second spacecraft, the Wide-Field Infrared Explorer (WIRE), launched in 1999 to

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[48] Riccardo Giacconi received the Nobel Prize in large part because of research he did with the first Explorer, Uhuru. (John Naugle)

[49] "Explorer Development," Office of Space Science and Applications, Research and Development Fiscal Year 1992 Estimates, Budget Summary, p. RD-3-17.

study the evolution of galaxies using a cryogenically cooled telescope and arrays of highly sensitive infrared detectors for the studies.

Unlike larger missions, SMEX team members worked on more than one mission at a time. SMEX missions overlapped and staggered their schedules so that the program launched a satellite every one to one and one-half years. Development typically took approximately three and one-half years. The program was structured to accept increased risk, reduce costs, and increase the flight rate. By having a short development time, SMEX missions also provided training opportunities for the next generation of scientists and engineers. The Engineering Directorate at Goddard Space Flight Center managed the SMEX program.[50]

In the mid-1990s, to enable more frequent flights, NASA initiated the Medium-class Explorer (MIDEX) program. MIDEX missions were larger than SMEX missions but smaller and less expensive than Delta-class missions. They were to be launched aboard a new Med-Lite class launch vehicle. This new launch vehicle was not developed, however, and the first mission intended for this program, the Far Ultraviolet Spectroscopy Explorer (FUSE), launched on a Delta II in 1999. NASA chose the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) and Microwave Anisotropy Probe (MAP) in 1996 as MIDEX missions. IMAGE launched in 2000 and MAP in 2001, both on Delta IIs.

The STEDI Program was a three-year pilot program under the Explorer umbrella that aimed to demonstrate that high-quality space science and technology missions could be carried out with small, less costly, free-flying satellites on a timescale of two years from go-ahead to launch. The STEDI program hoped to make science in orbit available to universities and other small users for research, graduate education, and training of entry-level professionals.

The STEDI announcement of opportunity was released on May 12, 1994, and 66 proposals were received in response. Six of these were selected for further study and development. In February 1995, two of these projects, the Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS), led by Boston University, and the SNOE, led by the University of Colorado, were chosen for fully funded flight development. A third project led by the University of New Hampshire, the Cooperative Astrophysics and Technology Satellite (CATSAT), was selected as an alternate. In 1996, additional funding was secured to fully fund the CATSAT mission.

Each of the three teams received about $4.5 million to cover design, manufacture, and one full year of science operations. Launch procured under the NASA Ultralite Expendable Launch Vehicle procurement was provided on an Orbital Sciences Pegasus XL rocket. The STEDI spacecraft were dual manifested as the primary payload—Orbital had the option of booking a secondary payload. Following launch to low Earth orbit (550 kilometers), the

[50] "SMEX Project History," *http://sunland.gsfc.nasa.gov/smex/history/miss1.html* (accessed September 27, 2005).

missions would collect data for up to one year.[51] SNOE launched in 1998; TERRIERS in 1999. CATSAT did not launch because no launch vehicle was available. The STEDI program was terminated in 2001.[52]

Although not an Explorer mission, the Explorers Program provided the U.S. instrument flown on the ROSAT, a U.S.-German cooperative mission conducting the first detailed all-sky x-ray survey and performing in-depth studies of selected objects. The program also managed the CRRES, a joint NASA-DOD mission launched into geosynchronous orbit that released trace chemicals whose transport in the magnetosphere could be observed from ground-based and airborne instruments. Explorer missions launched during 1989–1998 are listed in Table 4–36.

Cosmic Background Explorer

Goddard Space Flight Center developed the COBE to investigate the origin and dynamics of the universe, including the theory that the universe began about 15 billion years ago with a cataclysmic explosion—the Big Bang. COBE mission activities included a definitive exploration and study of the diffuse radiation of the universe between the wavelengths of 1 micrometer and 9.6 millimeters. This region included the 3 K (-270°C) cosmic background radiation, the residual radiation from the Big Bang presumed to have started the expansion of the universe, and also included the 1-micrometer to 300-micrometer infrared region.[53]

The spacecraft was launched November 18, 1989. It comprised an instrument module carrying three instruments and their associated electronics and a base module with the spacecraft operational subsystems (see Figure 4–4). The instruments included a Diffuse Infrared Background Experiment (DIRBE) to search for cosmic infrared background radiation, a Differential Microwave Radiometer (DMR) to sensitively map cosmic radiation, and a Far Infrared Absolute Spectrophotometer (FIRAS) to compare the spectrum of the cosmic microwave background radiation with a precise blackbody. The three instruments were all located inside a deployable shield in the top half of the spacecraft. The shield protected them from the heat and light of the Sun and Earth, from terrestrial radiation, and from the spacecraft telemetry antenna at the bottom of the spacecraft.[54] A superfluid helium dewar (cryostat), also mounted on the instrument module core structure and similar to that used on the Infrared Astronomical Satellite, housed and cooled the FIRAS and DIRBE

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[51] "STEDI: Student Explorer Demonstration Initiative," Mission and Spacecraft Library, Jet Propulsion Laboratory, *http://msl.jpl.nasa.gov/Programs/stedi.html* (accessed September 30, 2005).

[52] "CATSAT, University of New Hampshire," Space Operations Programs, *http://www.sop.usra.edu/catsat.html* (accessed September 30, 2005).

[53] "COBE, Cosmic Background Explorer," *http://library01.gsfc.nasa.gov/gdprojs/projinfo/cobe.pdf* (accessed August 4, 2005).

[54] J.C. Mather et al, "Early Results from the Cosmic Background Explorer (COBE)," COSPAR Conference Proceedings (NASA History Office Folder 5893).

instruments to 1.5 K (-271.7°C). COBE carried the first cryogenic scientific instruments with moving parts to fly in a satellite.

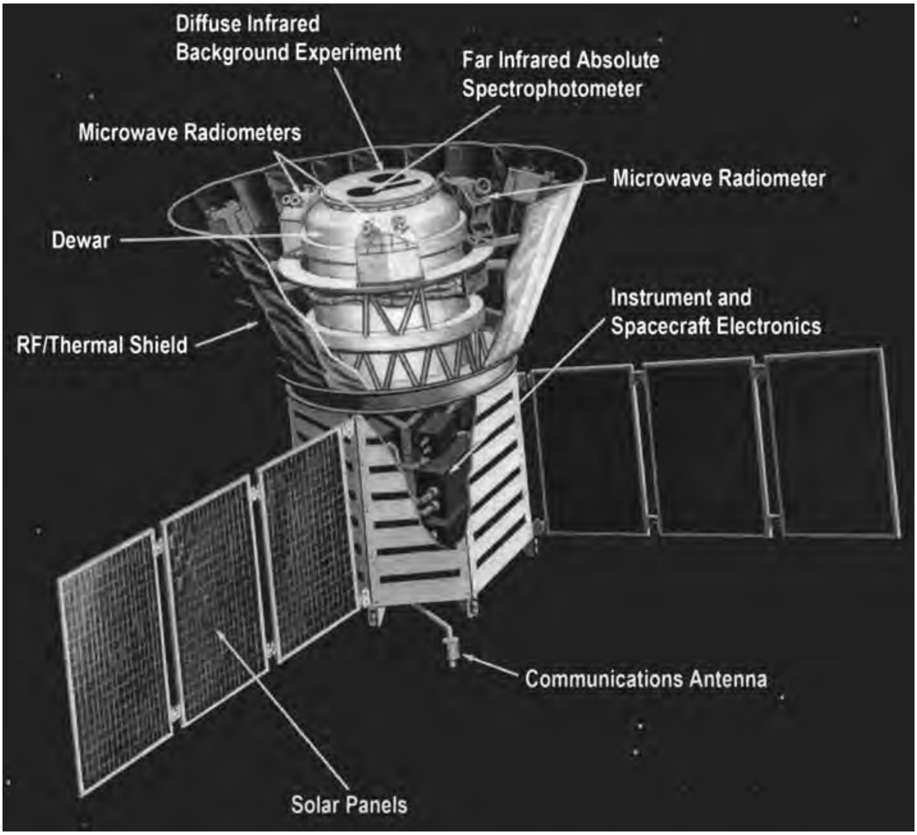

Figure 4–4. COBE Configuration. (CMB Astrophysics Research Program, University of California, Berkeley)

The base module contained the power, communications, and attitude control systems. The orientation of the spin axis was maintained anti-Earth and at 94 degrees to the Sun-Earth line. The operational orbit was dawn-dusk Sun-synchronous so that the Sun remained to the side and the instruments were shielded from it. With this orbit and orientation, the instruments performed a complete scan of the celestial sphere every six months.

COBE was originally planned for a Space Shuttle launch, but the *Challenger* accident, which occurred just before COBE-Shuttle integration was to begin, made this launch impossible. After much study, NASA decided on a West Coast launch into polar orbit using a Delta ELV even though it meant decreasing the weight and volume of the spacecraft by 50 percent to fit within the Delta size and weight constraints.[55]

[55] A polar orbit was necessary for a survey of the celestial sphere. Dennis McCarthy, "The Cosmic Background Explorer Mission," *1992 Goddard Space Flight Center Research and Technology*, p. 6.

COBE's primary science mission requirement called for one year of observations. In September 1990, the liquid helium supply needed to cool the FIRAS and DIRBE to a temperature below 2 K (-271°C) because full sensitivity became exhausted. During the following months, the temperature inside of the dewar that held the cryogen increased, preventing the FIRAS from operating. DIRBE could still function in the near infrared bands. (The DMR did not require cryogenic cooling and continued remapping the sky to further increase the sensitivity of its measurements.) COBE ended all operations on December 23, 1993, when the DMR was turned off. Beginning in January 1994,[56] Wallops Flight Facility was to use the spacecraft as an engineering training and test satellite.

COBE addressed basic questions of modern cosmology such as how the universe began, how it evolved to its present state, and what forces governed this evolution. According to the Big Bang theory, the universe was created about 15 billion years ago in a violent cosmic explosion that hurled matter in all directions. COBE became well known for its very precise measurements (confirming the Big Bang) and detection of the largest and oldest objects discovered to date. Figure 4–5 shows maps of the full sky in COBE's infrared view of the universe. See Table 4–37 for further mission details.

Extreme Ultraviolet Explorer

The EUVE was the first dedicated EUV mission, conducting the first EUV survey of the sky. The mission carried out extensive spectroscopy observations at EUV wavelengths to help investigators understand the least studied portion of the electromagnetic spectrum.

The EUVE conducted an all-sky, photometric six-month survey (0.1-degree resolution) and a concurrent high-sensitivity photometric survey covering a 2-degree by 180-degree strip along the ecliptic. It carried out spectroscopic observations of bright EUV point sources from 70 angstroms to 760 angstroms. The EUVE also conducted pointed spectroscopy observations of targets identified by guest observers; identified the emission physics of EUV sources such as hot white dwarfs and late-type coronal stars; studied the interstellar medium; and probed whether compelling science could be performed with increased sensitivity in the EUV region.

The spacecraft consisted of four grazing incidence, EUV-sensitive telescopes. Three of the telescopes were co-aligned scanning telescopes mounted perpendicular to the spin axis, and one was a deep survey and spectroscopy telescope oriented along the spin axis. The science payload was attached to a multimission modular spacecraft. The University of California, Berkeley had primary responsibility for the EUVE science payload. See Figure 4–6 for a drawing of the spacecraft.

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[56] "NASA Ends COBE Operations," *NASA News* Release 93-228, December 23, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-228.txt* (accessed August 4, 2005).

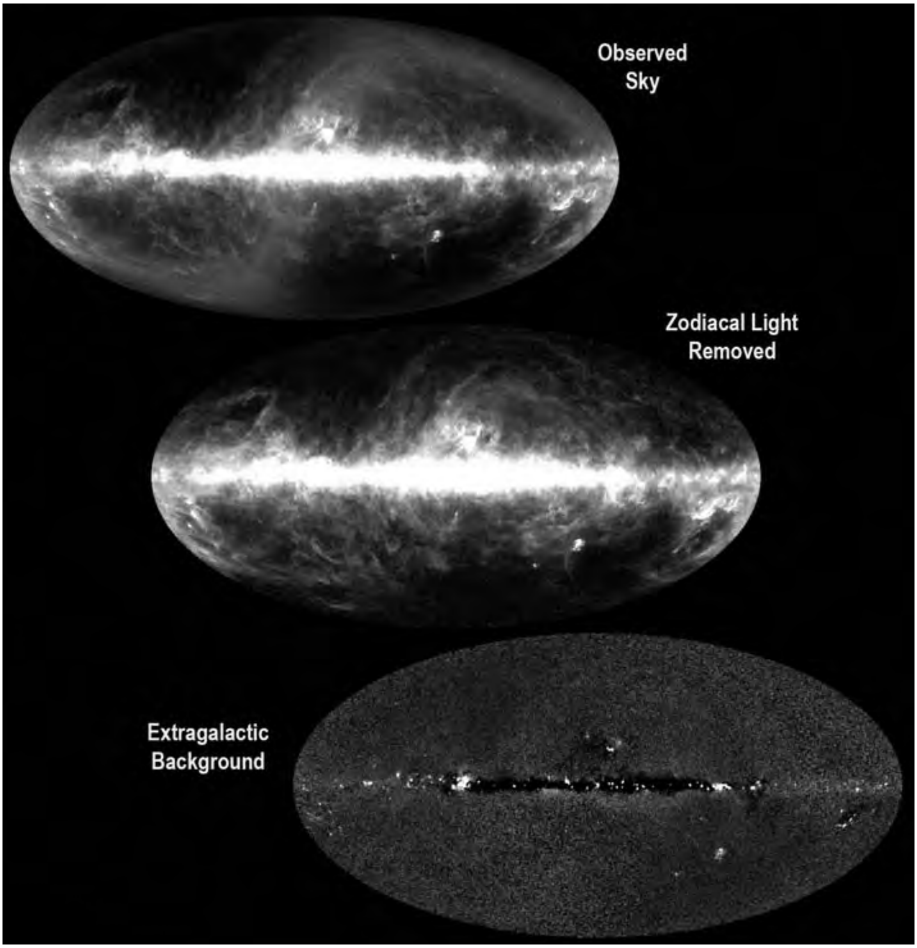

Figure 4–5. COBE's infrared view of the universe. These three pictures are maps of the full sky as seen in infrared light. They were compiled from data taken between December 1989 and September 1990 by COBE's diffuse infrared background experiment. (STScI-PRC 1998-01. Michael Hauser, STScI, the COBE/DIRBE Science Team, and NASA)

The EUVE was launched by a Delta rocket from Cape Canaveral on June 6, 1992, after several launch delays. The spinning spacecraft rotated about the Earth-Sun line. During its early years, the EUVE was operated from Goddard Space Flight Center. A guest observer program, initiated on January 22, 1993, and lasting more than 36 months, followed the initial survey. In 1997, control of the EUVE moved from Goddard Space Flight Center to the University of California, Berkeley, where it remained until the program's end in 2001. Planned to operate for only three years, the EUVE operated for eight years. NASA extended the EUVE's scientific mission twice, but cost and scientific merit issues led NASA to decide to end the mission.[57]

[57] "EUVE," NSSDC Master Catalog, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-031A* (accessed April 20, 2006).

Figure 4–6. EUVE Spacecraft.

In the summer of 2000, NASA decided to end the EUVE mission operations within a few months. The EUVE science operations ended on January 26, 2001, followed by several days of end-of-life mission engineering tests of the never-used backup high-voltage supplies and checking of the remaining battery capacity. The EUVE was stabilized pointing away from the Sun and sent into safehold at 23:59 Universal Time on January 31, 2001. The transmitters were commanded off on February 2, 2001.

The EUVE did not have an on-board propulsion system to allow engineers to control its reentry into Earth's atmosphere. Consequently, although the exact place of reentry into Earth's atmosphere was expected to be somewhere along the spacecraft's orbit track, the precise location was not known until approximately 12 hours before impact. After the transmitters were commanded off in February 2001, the spacecraft was left in a 424-kilometer by 433-kilometer (263-mile by 269-mile) by 28.4-degree orbit. This slowly decayed, and the spacecraft started to break up when it fell to within 80 kilometers (50 miles) of Earth. The EUVE finally reentered Earth's atmosphere over central Egypt on January 30, 2002, and it burned up in the atmosphere.[58] See Table 4–38 for further details.

[58] "EUVE Spacecraft Re-enters Earth's Atmosphere," *NASA News* Release 02-019, January 31, 2002, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-019.txt* (accessed April 20, 2006). The spacecraft entered the atmosphere at 11:15 p.m. Eastern Standard Time on January 30 or 0415 Universal Time on January 31.

Solar Anomalous and Magnetospheric Particle Explorer

The SAMPEX, launched on a Scout rocket in 1992, was the first mission in the SMEX program. NASA engineers at Goddard Space Flight Center designed and built the spacecraft in three years following selection of the mission. The mission studied solar energetic particles, anomalous cosmic rays, galactic cosmic rays, and magnetospheric electrons, and it successfully investigated the composition of local interstellar and solar material and the transport of magnetospheric charged particles into Earth's atmosphere. Dr. Glenn M. Mason of the University of Maryland, College Park, and 10 co-investigators from U.S. and German institutions proposed the SAMPEX study.

The SAMPEX carried four scientific instruments from the University of Maryland, California Institute of Technology, the Aerospace Corporation, and the Max-Planck-Institut für extraterrestrische Physik (Max Planck Institute for Extraterrestrial Physics (MPE)) in Germany. The four instruments, which occupied most of the upper half of the spacecraft, were a complementary set of high-resolution, high-sensitivity, particle detectors studying solar, anomalous, galactic, and magnetospheric energetic particles (see Figure 4–7). The instrument hardware was integrated throughout the primary structure, which consisted of three sensor assemblies, an 8-bit instrument interface microprocessor, and a tank of isobutane for use by one of the sensors.

The SAMPEX was a momentum-biased, Sun-pointed spacecraft that maintained the experiment-view axis in a zenith direction as much as possible, especially while crossing the polar regions of Earth. The SAMPEX pointed its solar array at the Sun by aiming the momentum vector toward the Sun and rotating the spacecraft one revolution per orbit about the Sun/spacecraft axis.[59] See Table 4–39 for further details.

The SAMPEX was the first mission to use the Small Explorer Data System, developed entirely through the SMEX project at Goddard Space Flight Center. The system used advanced computer technology and solid-state memory (in place of a tape recorder) to store engineering and scientific data and operate the spacecraft autonomously. It provided primary command and control of experiments and spacecraft subsystems, interfaces with the spacecraft communications system, and, with the attitude control system, controlled the spacecraft attitude.[60] The system used a fiber optic data bus to connect the subsystems. Two hemispherical coverage quadrifilar helix antennae were used for ground communication. The average science data rate for the mission was 3 kbps. The spacecraft was configured to operate with two ground contacts per day, each typically lasting 10 minutes. Stored data was transferred to ground stations at a downlink data rate of 900 kbps. Commands were uplinked at 2 kbps.[61]

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59 "SAMPEX," *http://sunland.gsfc.nasa.gov/smex/sampex/* (accessed July 18, 2006).

60 "Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) Mission Operation Report," Report no. S-864-92-01, NASA Office of Space Science and Applications, p. 15 (NASA History Office Folder 5895).

61 "SAMPEX," *http://sunland.gsfc.nasa.gov/smex/sampex/index.html* (accessed August 11, 2005).

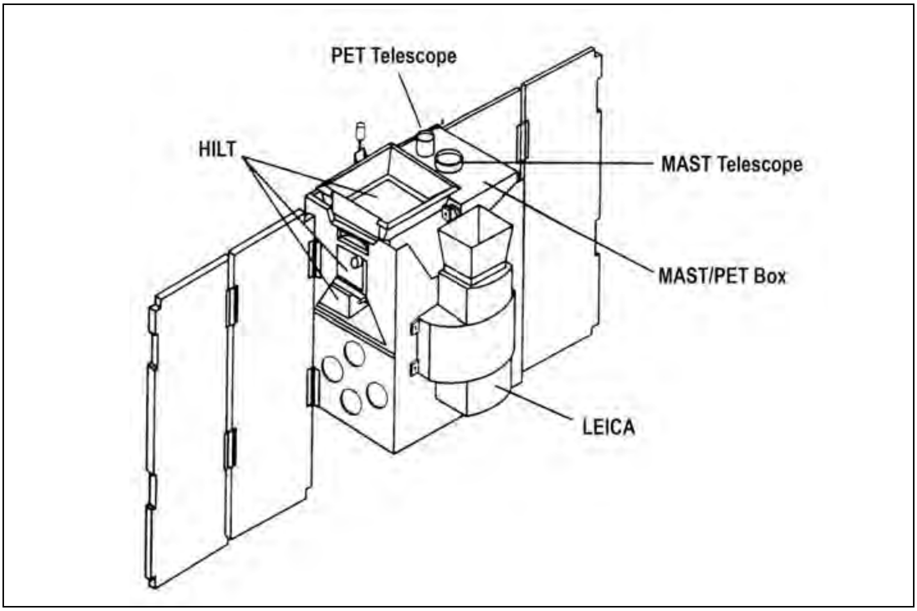

Figure 4–7. SAMPEX Spacecraft.

Rossi X-ray Timing Explorer

The RXTE was designed and built at NASA's Goddard Space Flight Center. Originally called the X-ray Timing Explorer, it was renamed the Bruno B. Rossi X-ray Timing Explorer in February 1996 after astronomer Bruno Rossi, a pioneer in both x-ray astronomy and space plasma physics who discovered the first non-solar source of x-rays. He died in 1993.[62]

The RXTE had three unprecedented capabilities for an x-ray satellite:

1. It measured x-ray flux changes in less than one ten-thousandth of a second. Therefore, the RXTE could track the evolution of material moving at relativistic speeds near neutron stars and black holes.
2. The RXTE detectors had the largest collecting area yet flown and spanned the energy range from 2 keV to 200 keV.
3. The spacecraft and instrument designs allowed the RXTE to change observing plans quickly, so it could usually observe the desired target.

The RXTE spacecraft contained a number of innovations when compared to the Explorer platform that was originally going to serve the XTE mission. These innovations included the following:

[62] "Who Is Bruno Rossi," The Rossi X-ray Timing Explorer Learning Center, *http://heasarc.nasa.gov/docs/xte/learning_center/name.html* (accessed May 11, 2006).

- A 1-gigabit solid-state memory instead of tape recorders for storing telemetry. This memory allowed a variable telemetry rate.
- A communication system that included two high gain antennae, allowing an almost continuous telemetry stream using the TDRS' Multiple Access mode.
- Consultative Committee for Space Data Systems (CCSDS) packet-based communications.
- Two modern charge coupled device (CCD) star trackers that allowed simultaneous tracking of up to five stars per a star tracker.
- A high-powered Spacecraft Data System requiring the Flight Operations Team to do far less work.[63]

The RXTE carried three instruments: the Proportional Counter Array (PCA), the High Energy Timing Experiment (HEXTE), and the All Sky Monitor (ASM). The power and uniqueness of the RXTE came largely from the synergism of these three instruments and the spacecraft. The spacecraft permitted rapid pointing to almost any point on the sky. The instruments addressed a single objective: the timing and broadband spectra of x-ray sources from 2 keV to 200 keV. The PCA and HEXTE measured short-term variability to microsecond levels. The PCA covered the lower part of the energy range, while the HEXTE covered the upper energy range. The ASM scanned about 80 percent of the sky with every orbit, allowing the ASM to monitor light sources at time scales of 90 minutes or longer. Long-term variability of faint sources could be monitored with repeated brief PCA and HEXTE observations. Data from the PCA and ASM were processed on board by the Experiment Data System.[64] Figure 4–8 shows the spacecraft.

Goddard Space Flight Center operated the RXTE for the astrophysics community. Scientific planning and data processing took place at the RXTE Science Operations Center (SOC). The SOC consisted of the Science Operations Facility, which ran the satellite observatory, and the Guest Observer Facility, which provided scientific services to astronomers using the RXTE. Astronomers at more than 70 universities and laboratories have made observations with the satellite.

The RXTE transmitted data alternately to one of the two NASA TDRSs flying in geosynchronous orbit. A TDRS was in the RXTE's view for 80 percent of its orbit around Earth. The TDRS rebroadcast data to White Sands, New Mexico, which then sent the data to Goddard Space Flight Center. See Table 4–40 for the RXTE mission characteristics.

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[63] "X-Ray Timing Experiment Spacecraft," *http://heasarc.gsfc.nasa.gov/docs/xte/XTEsc.html* (accessed October 20, 2005).

[64] "Taking the Pulse of the Universe," RXTE Brochure, *http://xte.mit.edu/xte_pulse.html* (accessed October 20, 2005). Also "Rossi X-Ray Timing Explorer (RXTE): December 1995–," *http://heasarc.gsfc.nasa.gov/docs/xte/XTE.html* (accessed May 6, 2006).

Fast Auroral Snapshot Explorer

The FAST was the second SMEX mission. It complemented ISTP program investigations. While traversing through the auroral regions, the FAST took high data rate snapshots with electric and magnetic fields sensors and plasma particle instruments to investigate the plasma physics of the auroral phenomena occurring around both poles of Earth. The science investigation made extremely temporal and spatial resolution measurements of the auroral plasma at apogee altitude. The FAST launched in 1996.

The spacecraft orbited in a near-polar, highly elliptical orbit. Apsoidal rotation caused by this orbit configuration positioned the apogee over the North Pole approximately four months after launch. The FAST measurements addressed a broad range of scientific objectives in areas including:

- Electron and ion acceleration by parallel E-fields
- Wave heating of ions-ion conics
- Electrostatic double layers
- Field-aligned currents
- Kilometric radiation
- General wave/particle interactions[65]

The FAST observatory, provided by NASA's Goddard Space Flight Center, was a spin-stabilized spacecraft rotating at 12 revolutions per minute with its spin axis oriented parallel to the orbit axis. The spin rate and spin-axis orientation were maintained by two magnetic torquer coils, one spinning Sun sensor, one horizon crossing indicator, and a spacecraft magnetometer. The attitude control system provided closed-loop spin-rate control.

The body-mounted solar array contained 5.6 square meters (60.3 square feet) of solar cells that could distribute 52 watts of orbit average power to the spacecraft and instruments. The spacecraft hardware consumed an average of 33 watts of power on orbit. The instruments consumed an average of 19 watts of power on orbit, 39 watts when operating. The instruments were frequently powered off to maintain a positive energy balance. See Figure 4–9 for a diagram of the spacecraft.

[65] "NASA Small Explorer Program–FAST Mission," *http://sunland.gsfc.nasa.gov/smex/fast/mission/* (accessed September 22, 2005).

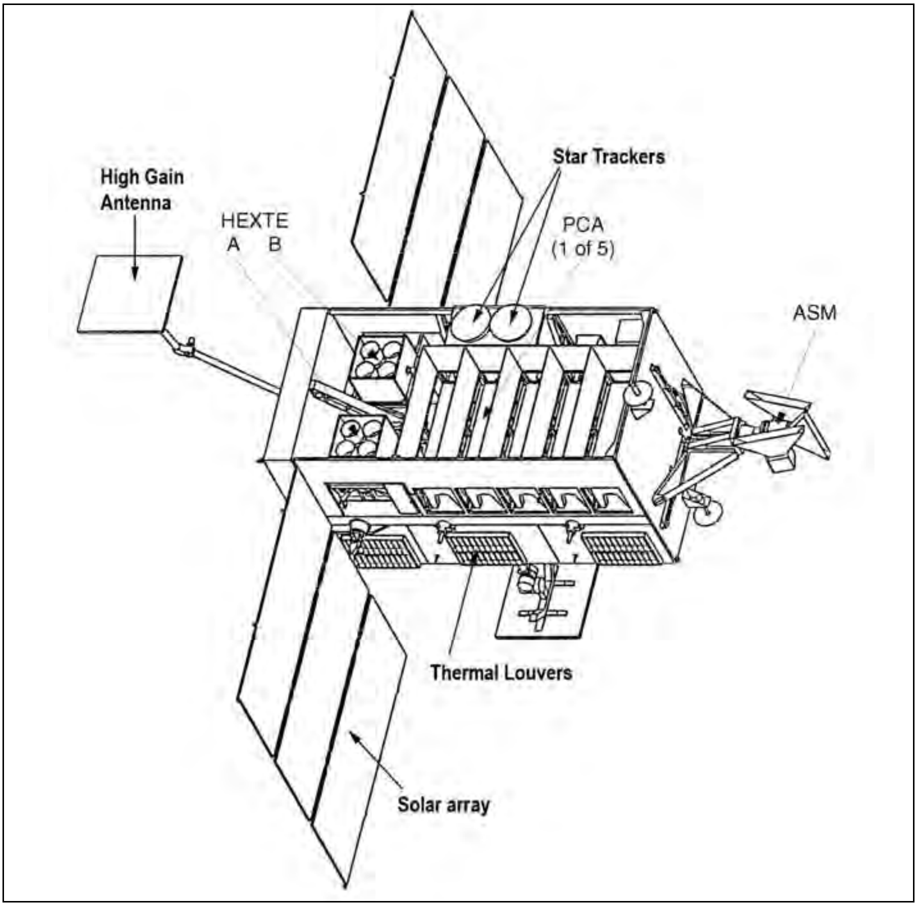

Figure 4–8. Rossi X-Ray Timing Explorer.

The FAST instrument hardware consisted of the sensor assemblies and an instrument data processor. There were 16 electrostatic analyzers, four electric-field Langmuir probes suspended on 30-meter wire booms, two electric-field Langmuir probes on 3-meter (9.8-feet) extendible booms, searchcoil and flux-gate magnetometers, and a time-of-flight mass spectrometer. The instrument electronics included a 32-bit data processing unit performing science data processing and recording in a one gigabit, solid-state memory. The stored data was transferred to the ground at one of three selectable high data rates of 900 kbps, 1.5 Mbps, or 2.25 Mbps. An average volume of 4 gigabytes to 5 gigabytes per day could be transmitted to Earth during a campaign. While participating in campaigns, the FAST telemetered high-resolution data to the ground on every orbit. Health and safety data was telemetered to the ground at 4 kbps. From the ground stations, the data was moved to Goddard Space Flight Center and then on to the Mission and Science Operations Center at Berkeley, California. The FAST produced nearly 1 terabyte of data in its first two years. During a campaign, the FAST observations were coordinated with those from ground-based equipment, other spacecraft, or aircraft.

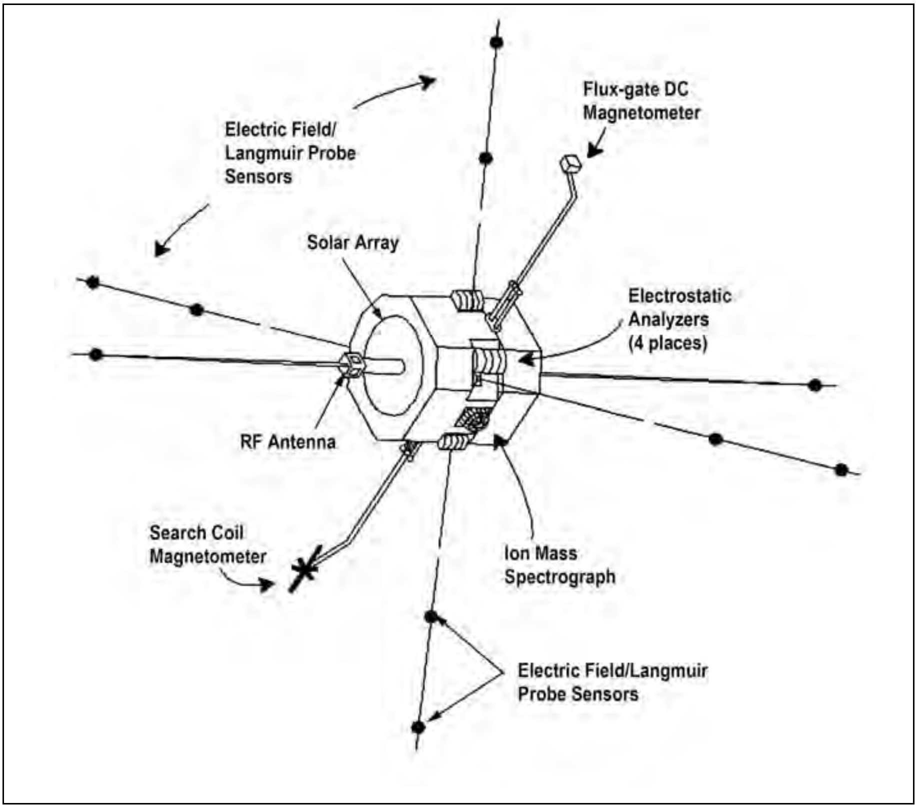

Figure 4–9. FAST Small Explorer Satellite was made up of particle detectors and magnetic and electric field sensors.

The FAST data system consisted of dual 8085 8-bit spacecraft computers. The spacecraft computers performed health and safety functions, power distribution, data encoding/decoding, and launch vehicle interface. An antenna mounted on a boom above the spacecraft supported ground communications. Commands were uplinked at 2 kbps. A transportable orbital tracking station (TOTS) in Alaska collected real-time science telemetry while the spacecraft was passing through the northern aurora. The TOTS was highly automated and portable; it had an 8-meter antenna with 200 watts of uplink power and could be packed for shipment in three containers.[66] See Table 4–41 for mission details.

[66] "FAST," *http://sunland.gsfc.nasa.gov/smex/fast* (accessed August 11, 2005).

Advanced Composition Explorer

The ACE spacecraft studied the composition of particles in the solar wind, the local interstellar medium, and galactic matter to better understand the formation and evolution of the solar system. ACE's observations spanned a wide range of energy and intensities, including low-energy particles of solar origin and high-energy galactic particles, with 10 to 1,000 times greater collecting power than past missions. The ACE measured all solar elements from carbon to zinc and determined the masses of individual atomic nuclei over a wide range of velocities.

The ACE was launched in August 1997 during solar minimum conditions, and it observed the transition to solar maximum. During this period, the number of solar flares and coronal mass ejections increased. To escape the effects of Earth's magnetic field, the ACE traveled almost 1 million miles (1.5 million kilometers) from Earth to the Earth-Sun libration point (L1).[67] By orbiting the L1 point, the ACE stayed in a relatively constant position with respect to Earth while Earth revolved around the Sun. Figure 4–10 shows the ACE orbit.

The spacecraft spun about its axis at about five revolutions per minute so that one end always pointed toward the Sun and the other toward Earth.[68] Most of the instruments were located on the top (sunward) deck (see Figure 4–11). The ACE transmitted data to Earth with a highly directional parabolic dish antenna mounted on the aft deck of the spacecraft. Four other broadbeam antennae, capable of transmitting data at lower rates, were also available if needed. Twenty-four hours worth of science and housekeeping data (about 1 gigabit) recorded on one of two solid-state recorders were transmitted to Earth in one 3 to 4-hour telemetry pass each day. A star tracker and digital Sun sensors provided spacecraft attitude. The solar arrays generated about 500 watts of power.

Eight scientific instruments measuring a variety of particle types were mounted on the spacecraft. Booms attached to two of the solar panels carried the ninth instrument—a pair of magnetometers. The ACE instruments covered an unprecedented range of particle types and energy; simultaneous measurements from the instruments were coordinated to create a comprehensive picture of the energetic particles pervading the inner solar system. The nine scientific instruments on the ACE performed comprehensive and coordinated composition determinations and observations spanning a broad dynamic range. They could also provide approximately 1 hour's notice of an impending geomagnetic storm from the Sun. See Table 4–42 for further details.

The ACE was conceived in a meeting on June 19, 1983, at the University of Maryland. This meeting was preceded by preliminary documentation from The Johns Hopkins University Applied Physics Laboratory and the University of Maryland under the proposal name of Cosmic Composition

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[67] "Advanced Composition Explorer (ACE) Mission and Spacecraft Characteristics," *http://www.srl.caltech.edu/ACE/ace_mission.html* (accessed August 11, 2005).

[68] "Advanced Composition Explorer," *http://helios.gsfc.nasa.gov/ACEbrochure-2nd-ed_final.pdf* (accessed August 11, 2005).

Explorer. An unsolicited proposal was assembled and forwarded to the NASA Explorers Program Office later in the year but was not acted upon. The proposal was resurrected and officially resubmitted to NASA in 1986 as part of the Explorer Concept Study Program. In 1988, the ACE mission was selected for a one-year "Phase A" (Concept) Study. This study was a collaborative effort between spacecraft design and science teams.

The ACE mission officially began on April 22, 1991, when the contract between Goddard Space Flight Center and the California Institute of Technology was signed. The Applied Physics Laboratory, designer and builder of the ACE spacecraft, was involved in planning for the definition phase that officially began in August 1992. The early ACE spacecraft effort (April to July 1991) was primarily for ACE mission support, spacecraft system specification, and ACE instrument support and interface definition.

The Mission Preliminary Design Review was held in November 1993. The design and development phase began soon after.[69] The ACE was launched on a Delta II rocket on August 25, 1997. As of 2002, the ACE had sufficient hydrazine to remain in an L1 orbit until 2019, depending on details of the orbit.[70]

Student Nitric Oxide Explorer

The SNOE was the first satellite launched in NASA's STEDI program. STEDI, managed for NASA by the Universities Space Research Association (USRA), was a pilot program to demonstrate that high-quality space science was possible with small, less costly ($4.4 million), free-flying satellites within two years from go-ahead to launch.[71] The spacecraft and its instruments were designed and built at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. The spacecraft was one of the first NASA satellites entirely operated and controlled by a university. The SMEX, which gathered data on ozone and solar radiation variability from 1981 to 1988, also was controlled at the University of Colorado, Boulder.

Students were involved in all aspects of the SNOE project. Under the supervision of the LASP, they worked on the design study; built the spacecraft and instruments; wrote the flight software; integrated and tested the instruments and subsystems; and integrated the satellite with the launch vehicle. A team of students and mission operations professionals operated the SNOE from the LASP Space Technology Research Building. Advanced undergraduates and graduate students analyzed the data.[72]

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[69] "Advanced Composition Explorer (ACE) Mission Overview," *http://www.srl.caltech.edu/ACE/ace_mission.html* (accessed August 11, 2005).

[70] "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

[71] "SNOE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-012A* (accessed August 31, 2005).

[72] "SNOE Mission Overview," *http://lasp.colorado.edu/snoe/overview.html* (accessed August 31, 2005).

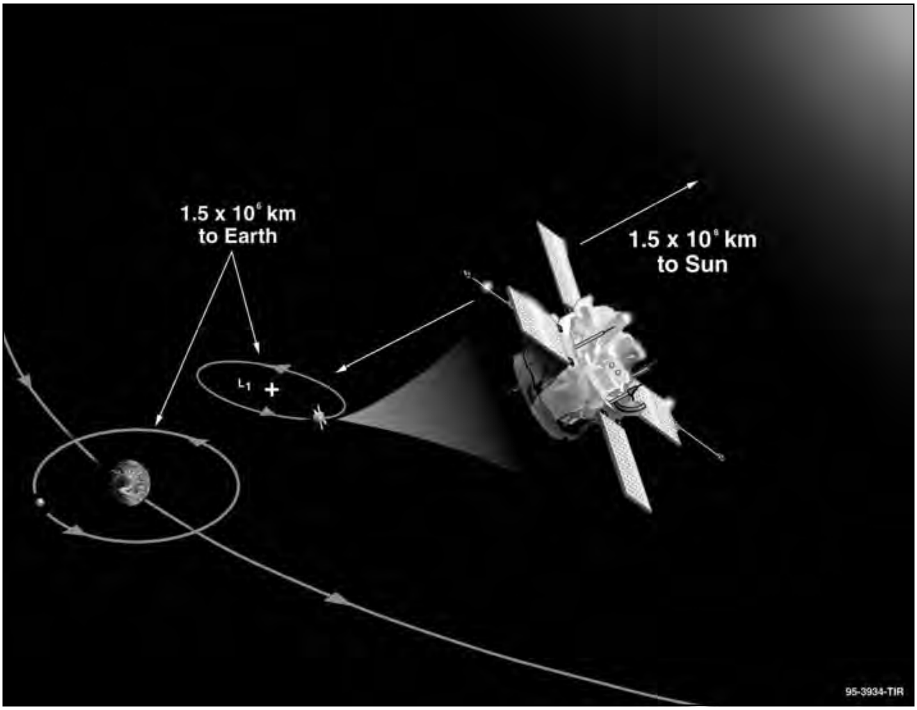

Figure 4–10. ACE L1 Orbit Between Earth and the Sun.

The SNOE measured the effects of energy from the Sun and the magnetosphere on the density of nitric oxide in Earth's upper atmosphere. Nitric oxide is produced when solar x-rays are absorbed into the atmosphere; the substance destroys naturally produced ozone when injected into the stratosphere 30 miles to 50 miles (48 kilometers to 80 kilometers) above Earth.[73]

The compact, hexagonal scientific spacecraft was launched on February 26, 1998, into a Sun synchronous circular orbit; it began returning science data on March 10. The SNOE spun at five revolutions per minute with the spin axis normal to the orbit plane. The SNOE carried three instruments: a UV spectrometer to measure nitric oxide altitude profiles, a two-channel auroral photometer to measure auroral emissions beneath the spacecraft, and a five-channel solar soft x-ray photometer. The SNOE also carried a special GPS technology investigation built by the Jet Propulsion Laboratory. The spacecraft consumed an average of 35 watts power on orbit, and its data rate was 6 Mb per day. Figure 4–12 shows a computer-generated diagram of the spacecraft structure. See Table 4–43 for additional details. The SNOE reentered the atmosphere on December 13, 2003, descending over the Pacific Ocean west of Peru.

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[73] "CU's 'Little Satellite That Did' Set for Re-entry in Coming Days," *Colorado*, University of Colorado at Boulder News Release, December 1, 2003, *http://www.colorado.edu/news/releases/2003/454.html* (accessed August 31, 2005).

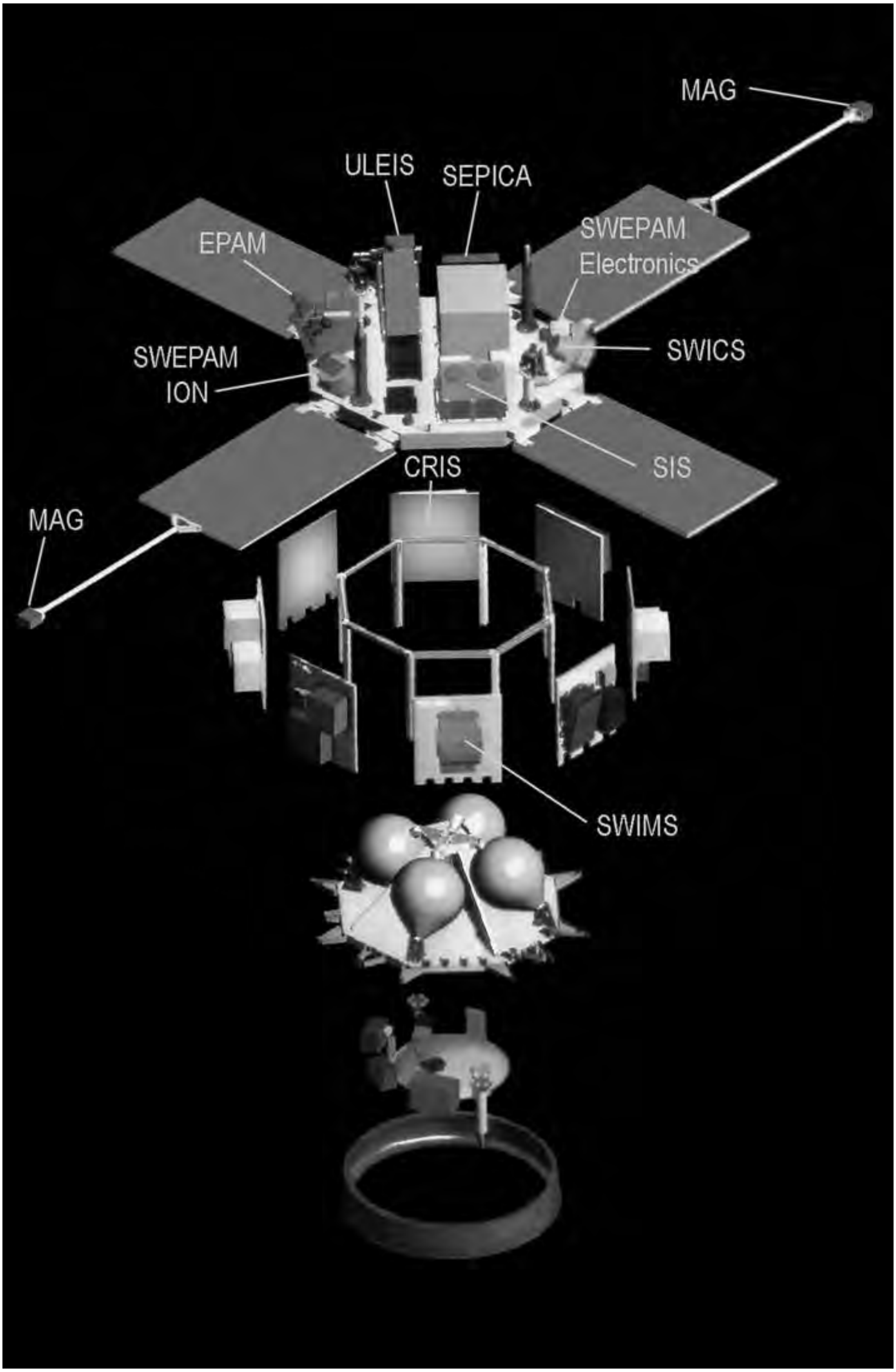

Figure 4–11. Expanded View of ACE.

Transition Region and Coronal Explorer

The TRACE was a NASA SMEX mission to image the solar corona and transition region at high angular and temporal resolution. It was a key component of NASA's Sun-Earth Connection theme and was the first U.S. solar research mission since the 1980 Solar Maximum Mission.[74] The spacecraft joined a multinational fleet of spacecraft in the ISTP program studying the Sun during a period when solar activity was approaching the peak of its 11-year solar cycle. The mission's science team included scientists from the United States, Sweden, the United Kingdom, and the Netherlands.

The mission was the first U.S. research project with a completely open data policy. All data obtained by the TRACE was available to other scientists, students, and the general public soon after it became available to the primary science team.[75]

The TRACE explored the magnetic field in the solar atmosphere by studying the three-dimensional field structure, the field's temporal evolution in response to photospheric flows, the time-dependent coronal fine structure, and the coronal and transition region thermal topology.[76] The trace observed the Sun to study the connections between fine-scale magnetic fields and the associated plasma structures on the Sun in a quantitative way by observing the photosphere, the transition region, and the corona. With the TRACE, these temperature domains were observed nearly simultaneously (with delays as short as 1 second between different wavelengths), with a spatial resolution of 1 arc second. This was accomplished by obtaining precisely coaligned image sequences of the photosphere, transition region, and corona with high spatial resolution and uninterrupted viewing of the Sun for up to eight months.

The power of the TRACE telescope to perform detailed studies of the solar atmosphere made this observatory unique among the current group of spacecraft studying the Sun. The spacecraft had roughly 10 times the temporal resolution and 5 times the spatial resolution of previously launched solar spacecraft. The telescope's Sun-synchronous orbit was uninterrupted by Earth's shadow for eight months at a time, allowing the telescope the greatest chance to observe the random processes leading to flares and massive eruptions in the Sun's atmosphere. Figure 4–13 shows an image produced by the TRACE.

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[74] "Spacecraft Images Capture Magnetic Energy Burst on Sun," *NASA News* Release 98-92, May 29, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-092.txt* (accessed September 27, 2005).

[75] "Transition Region and Coronal Explorer (TRACE): Exploring the Upper Regions of the Solar Atmosphere," NASA Fact Sheet, FS-1998-01-001-GSFC, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/trace.htm* (accessed September 27, 2005).

[76] "TRACE Science Objectives," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

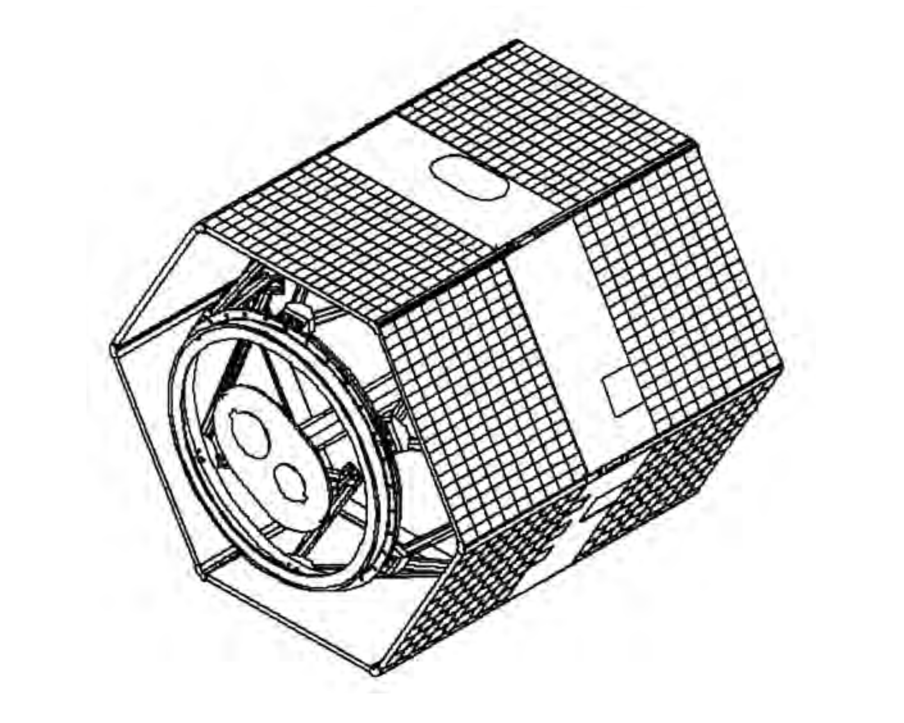

Figure 4–12. SNOE Spacecraft Structure. (Laboratory for Atmospheric and Space Physics)

The TRACE launch was scheduled to allow joint observations with the SOHO during the rising phase of the solar cycle to sunspot maximum. No transition region or coronal imager had ever witnessed the onset and rise of a solar cycle. The two satellites provided complementary observations: TRACE produced high spatial and temporal resolution images, while SOHO yielded images and spectral data out to 30 solar radii at much lower spatial and temporal resolution. Jointly they provided the opportunity to obtain simultaneous digital measurements of all the temperature regimes of the solar atmosphere, in both high-resolution imaging and spectroscopy.[77]

Coordination with the SOHO provided an opportunity to follow the emergence of magnetic flux from the base of the convection zone deep inside the Sun through the photosphere, chromosphere, and transitional region, and then to the low-beta outer corona, while observing the effects of this emergence (such as coronal mass ejections) with high spatial and temporal resolution.[78]

The TRACE was a three-axis stabilized spacecraft with a single telescope. The spacecraft attitude control system used three magnetic-torquer coils; a digital Sun sensor; six coarse Sun sensors; a three-axis magnetometer; four reaction wheels; and three two-axis inertial gyros to maintain pointing. Four

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[77] "TRACE Mission," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

[78] "TRACE Mission," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

panels of Ga-As solar cells provided power to the spacecraft. A 9 amp-hour nickel cadmium battery provided energy when the spacecraft was in Earth's shadow. Communications were provided via a 5-watt S-band transponder, providing up to 2.25 Mbps downlink data transmission and 2 kbps uplink. Data was transmitted up to six times daily. Data was stored on board using a solid-state recorder capable of holding up to 300 MB. The command and data handling system used a 32-bit 80386/80387 processor.[79]

In science mode, the spacecraft used an instrument-provided guide telescope as a fine guidance sensor to provide pointing accuracy of less than 5 arc seconds. The telescope's mirrors were individually coated in four distinct ways to allow light from different bandwidths to be captured and analyzed. It could detect and examine regions of the Sun ranging in temperatures from 16,000°F to 16,000,000°F (roughly 8,861°C to 8,900,000°C). A CCD detector collected images over a 3,600-mile by 3,600-mile (5,794-kilometer by 5,794-kilometer) FOV, which represented about 25 percent of the Sun's disk or outer edge. A powerful data-handling computer enabled very flexible use of the CCD array, including adaptive target selection, data compression, and image stabilization. Further details are provided in Table 4–44.

Submillimeter Wave Astronomy Satellite

The overall goal of the SWAS Small Explorer mission was to gain a greater understanding of star formation by determining the composition of interstellar clouds and how those clouds cooled as they collapsed to form stars and planets. The observatory looked at the water and molecular oxygen thought to dominate the chemistry of interstellar clouds. and it looked at carbon monoxide and atomic carbon believed to be major reservoirs of carbon in those clouds. The SWAS measured water, molecular oxygen, atomic carbon, and isotopic carbon monoxide spectral line emissions from galactic interstellar clouds in the 540-micrometer to 616-micrometer wavelength range. Such submillimeter wave radiation could not be detected from the ground because of atmospheric attenuation.

The SWAS measurements provided new information about the physical conditions (density and temperature) and chemistry in star-forming molecular clouds.[80] The SWAS focused on the following spectral lines:

- Water (H_2O) at 556.936 gigahertz
- Molecular oxygen (O_2) at 487.249 gigahertz
- Neutral carbon (CI) at 492.161 gigahertz

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[79] "TRACE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-020A* (accessed September 27, 2005).

[80] "Submillimeter Wave Telescope," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-071A&ex=** (accessed August 18, 2005).

Figure 4–13. TRACE observed this filament eruption on September 30, 1998. It shows a filament very early in its eruption, appearing dark against the backdrop of an arcade of loops; the big, dark filament is rising into interplanetary space with an increasing velocity that already exceeds 100 km/sec. These brightly glowing loops are the result of an earlier flare, cooling down from temperatures of several million degrees. As the loops cool, material drains from them, streaming back toward the solar surface under the influence of gravity. This appears in the image as thin, dark strands of gas at approximately 10,000°C (18,032°F) that absorb EUV emission from other, hotter gases behind them.

- Isotopic carbon monoxide (^{13}CO) at 550.927 gigahertz
- Isotopic water ($H_2{}^{18}O$) at 548.676 gigahertz

The SWAS was a three-axis-stabilized, stellar-pointed observatory with a pointing accuracy of 38 arc seconds and jitter of less than 19 arc seconds. The spacecraft typically pointed its science instrument at three to five targets per orbit. Target selection was constrained so the solar arrays always faced within plus or minus 15 degrees of the Sun except during an eclipse. The SWAS submillimeter wave telescope incorporated dual radiometers and an acousto-optical spectrometer (see Figure 4–14).

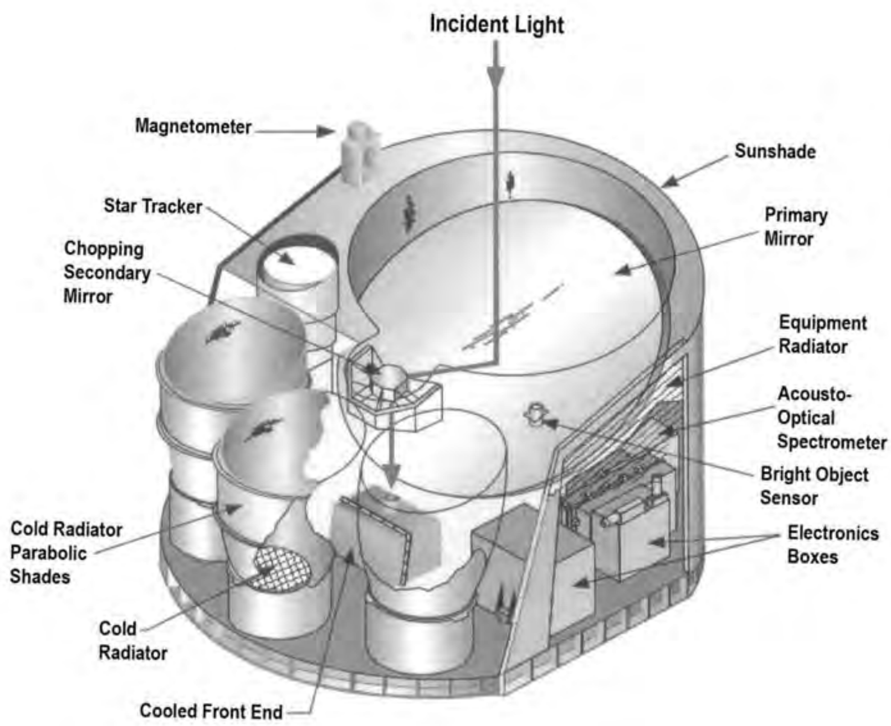

Figure 4–14. SWAS Telescope.

Using PI-selected navigation guide stars and an observation timetable generated by the PI, the spacecraft, without ground intervention, "nodded" from an on-source target position to an off-source instrument calibration position up to three degrees away. This nodding occurred approximately every 40 seconds. Attitude control, including pointing and nodding, was accomplished by using three magnetic-torquer coils; one digital Sun sensor; six course Sun sensors; four reaction wheels; one magnetometer; three inertial gyros; and a high accuracy charge coupled device star tracker.

Four deployable, fixed solar panels and one body-mounted panel contained 3.4 square meters (36.6 square feet) of solar cells and provided an average of 230 watts of power on orbit that was distributed to the spacecraft and instrument. The orbit average power consumption of the spacecraft hardware was 150 watts. The instrument consumed 59 watts. See Table 4–45 for further details.

Far Ultraviolet Spectroscopic Explorer

The FUSE did not launch until June 24, 1999, but the Explorer's development took place during the decade ending in 1998. The FUSE was originally proposed in 1982 to answer a set of fundamental questions about the nature of the universe posed by the Astronomy Survey Committee of the National Academy of Sciences.[81] The mission began as a NASA-managed Explorer project in the mid-1980s. At the time, it was conceived as a midsized mission to explore interplanetary space and study extragalactic light sources. It was to use high-resolution spectroscopy at wavelengths below 1,200 angstroms to measure faint sources both throughout the Milky Way galaxy and at very large extragalactic distances. It would be attached to the Explorer Platform after reaching orbit on the Space Shuttle.

But when the budget ballooned to more than $300 million, NASA looked for a way to restructure the project, and FUSE was extensively redesigned as part of a general restructuring of the Explorers Program. In 1995, The Johns Hopkins University proposed to NASA a way to build the satellite "faster, cheaper, and better" than previously conceived—at a cost of about $100 million and ready to launch two years earlier than originally planned.[82] The Johns Hopkins University proposal was accepted and in November 1995, the FUSE was selected for development leading up to launch on an ELV in October 1998 at a cost of $108 million. The mission was to study the origin and evolution of hydrogen and deuterium, created shortly after the Big Bang, and the forces and processes involved in the evolution of galaxies, stars, and planetary systems.[83]

The FUSE was the first large-scale space mission fully planned and operated by an academic department of a university. The Johns Hopkins University designed and developed it with a global team of corporate and academic partners, including the University of Colorado, the University of California, Berkeley, and the space agencies of Canada and France. The Johns Hopkins University would take control of the scientific mission about 100 minutes after launch and manage it from a mission center in the Center for Physics and Astronomy on the university campus.[84]

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[81] D.J. Sahnow et al, "The Far Ultraviolet Spectroscopic Explorer Mission," poster paper presented at the 1995 American Astronomical Society meeting in Pittsburgh, Pennsylvania, *http://fuse.pha.jhu.edu/papers/technical/aas95/aas95.html* (accessed October 21, 2005).

[82] "FUSE Moves Closer to Launch; Scientists Hope Satellite Uncovers Mysteries of Big Bang's Immediate Aftermath," Headlines@Hopkins News Release, The Johns Hopkins University, August 26, 1998, *http://www.jhu.edu/news_info/news/home98/aug98/fuse.html* (accessed September 28, 2005).

[83] "NASA's Restructured FUSE Program Costs Less, Flies Earlier," *NASA News* Release 95-33, March 21, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-33.txt* (accessed September 28, 2005). Also "NASA Selects FUSE Mission for Development," *NASA News* Release 95-206, November 13, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-206.txt* (accessed September 28, 2005).

[84] "FUSE Moves Closer to Launch; Scientists Hope Satellite Uncovers Mysteries of Big Bang's Immediate Aftermath," Headlines@Hopkins News Release, The Johns Hopkins University, August 26, 1998, *http://www.jhu.edu/news_info/news/home98/aug98/fuse.html* (accessed September 28, 2005).

The FUSE was designed for a very specialized and unique task that complemented other NASA missions. It looked at light in the far UV portion of the electromagnetic spectrum (approximately 90 nanometers to 120 nanometers), observing these wavelengths with much greater sensitivity and resolving power than other instruments that studied light in this range.[85] Astronomers were to use FUSE observations to:

- Understand the origin and history of the chemical elements in the Milky Way galaxy and other nearby galaxies, especially the Large and Small Magellanic Clouds.
- Help trace the history of deuterium, a special form of hydrogen, back to its origin in the Big Bang.
- Explore the origin and circulation of hot and cold gas in the Milky Way and the relationship of these gases with the formation of new generations of stars.
- Provide insight into the origin and evolution of our galaxy by studying a wide range of astronomical objects including hot stars; solar-type stars; remnants of supernova explosions; active nuclei of galaxies and quasars; and planets and comets in the solar system.[86]

The FUSE satellite consisted of two primary parts: the spacecraft and the science instrument. The spacecraft contained all the elements needed to power and point the satellite: the attitude control system, the solar panels, communications electronics, and antennae. The observatory was approximately 7.6 meters (25 feet) long with its baffle fully deployed. The spacecraft and the science instrument each had their own computers, which together coordinated the activities of the satellite.[87] S-band transponders of 5-watt output capacity allowed transmission of the scientific data at a rate of 40 kbps. A complete spectrum could be read in about 7 minutes. Spacecraft housekeeping data and compressed data was downlinked at 2 kbps.

The satellite carried four coaligned telescope mirrors; four focal plane assemblies, each of which contained four apertures; four spherical, aberration-corrected, holographically-recorded diffraction gratings; and two microchannel plate detectors with delay line anodes. A visible light fine error sensor maintained subarcsecond pointing of the entire spacecraft. A composite structure maintained the positions of the optical elements to the several-micron level while the temperature was controlled to 1°C (33.8°F).[88]

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[85] "FUSE Mission Overview," *http://fuse.pha.jhu.edu/overview/mission_ov.html* (accessed September 28, 2005).

[86] "FUSE: Will Further 'Explore' the Big Bang," FS-1999 (03)-008-GSFC, NASA Facts On-Line, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/fuse.htm* (accessed September 28, 2005).

[87] "FUSE Mission Overview," *http://fuse.pha.jhu.edu/overview/mission_ov.html* (accessed September 28, 2005).

[88] D.J. Sahnow et al, "The Far Ultraviolet Spectroscopic Explorer Mission," poster paper.

The PI responsible for developing the overall mission was H. Warren Moos from The Johns Hopkins University. The FUSE was a joint project of NASA and The Johns Hopkins University in collaboration with the French Centre National d'Etudes Spatiales (CNES), the Canadian Space Agency, the University of Colorado, and the University of California, Berkeley.

Explorers Support

The ROSAT and the CRRES missions were not Explorer missions, but they received support or were managed by the Explorers Program.

Roentgen Satellite

The ROSAT was an x-ray observatory developed through a cooperative program between NASA, the United Kingdom, and Germany. NASA viewed the observatory as a stepping stone toward the AXAF, which launched in 1999. Designed, built, and operated by Germany, the ROSAT resulted from a 1975 proposal made by the MPE to the Bundesministeriium für Forschung und Technologie (BMFT) (Federal Ministry for Research and Technology). The original version of the project entailed an all-sky x-ray survey to be carried out with a moderate angular resolution imaging telescope. Between 1977 and 1982, German space companies conducted extensive studies of the project. At the same time, the Carl Zeiss Company began to develop a large x-ray mirror system and the MPE began to develop the focal plane instrumentation. In 1979, to comply with ESA regulations, Germany offered collaboration on the ROSAT to ESA member states. The University of Leicester proposed a wide-field EUV camera to be flown with the main x-ray telescope (XRT) to extend the spectral bandpass to lower energies.[89] The XRT covered the ~6-angstrom to 100-angstrom band, and the wide field camera (WFC) covered the ~60-angstrom to 300-angstrom band. (See Figure 4–15 for a drawing of the ROSAT.)

In 1982, NASA and Germany reached an agreement regarding U.S. participation in the ROSAT project. In return for making 50 percent of pointed observing time available to the PIs from the United States, NASA would provide a high-resolution imager (HRI) for the focal plane of the XRT and launch the satellite on the Space Shuttle. In 1983, Germany and Britain's Science and Engineering Research Council agreed that 12 percent of pointing time would be available to British PIs, and Britain would supply the WFC and associated subsystems. Germany agreed to design, fabricate, test, and integrate the spacecraft and provide the XRT and the two position-sensitive proportional counters (PSPCs) at the focal plane of the telescope. Germany would also handle mission control, tracking, and data acquisition after separation from the Shuttle, as well as initial reduction and distribution of

[89] Mission Operation Report, "Roentgensatellit (ROSAT)," Report no. E-876-90-03, p. 6 (NASA History Office Folder 30959).

data. In 1983, NASA awarded a sole source contract to the Smithsonian Astrophysical Observatory (SAO) to build flight and engineering model high-resolution imagers and provide integration and launch support. In May 1985, NASA transferred this contract to the Explorers Program at Goddard Space Flight Center for administration and implementation.

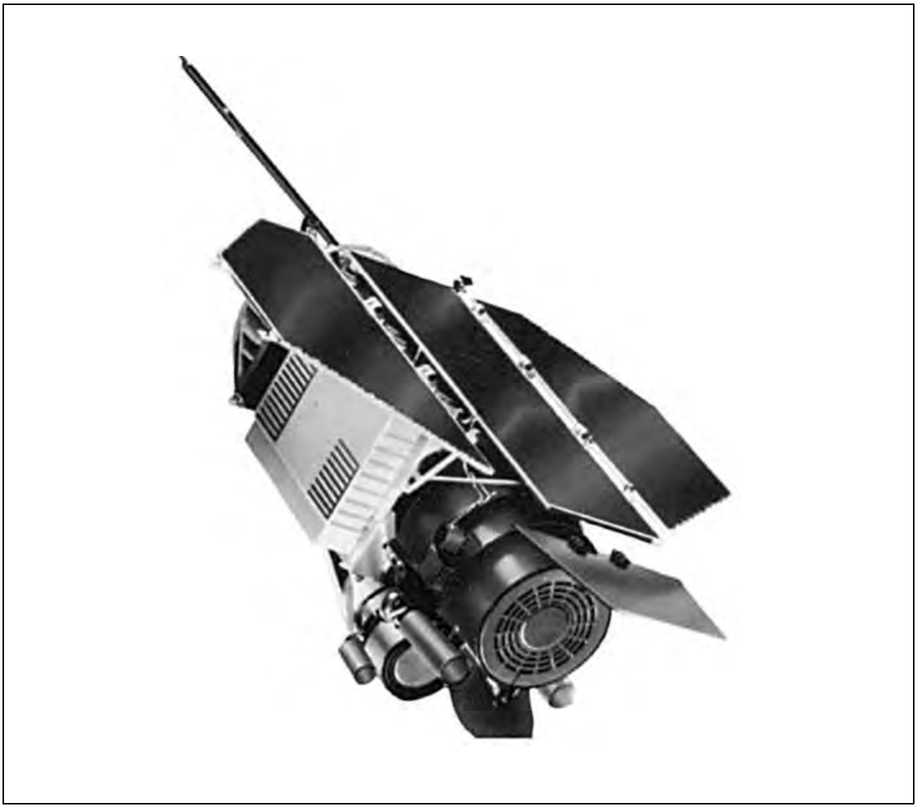

Figure 4–15. ROSAT. (Max-Planck-Institut für Extraterrestrische Physik)

The *Challenger* accident led to significant changes in the spacecraft design and a launch delay. In December 1987, the decision was made to launch the ROSAT on a Delta II ELV.[90] Germany subsequently modified the spacecraft design and its test and integration procedures to be compatible with the Delta launch vehicle. The United States developed a new 10-foot (3-meter) diameter fairing for the Delta nose section to accommodate the ROSAT's cross-sectional dimension determined by the mounting of the WFC.

The ROSAT was a three-axis stabilized satellite designed for pointing at celestial targets, for slewing between targets, and for performing scanning observations on great circles perpendicular to the plane of the ecliptic. The scientific payload,

[90] Max Planck Institut Für Extraterrestrische Physik, *ROSAT User's Handbook*, *http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

comprising about two-thirds of the satellite's total weight, was based on two coaligned imaging telescopes. The large XRT was the primary telescope. It measured "soft" x-rays in the energy range from 0.1 keV to 2 keV (corresponding to wavelengths of 100 angstroms to 6 angstroms). The WFC extended the measuring range to the EUV region by covering the energy range from 0.04 keV to 0.2 keV (300 angstroms to 60 angstroms). (See Figure 4–16 for a diagram of the satellite.)

The German Space Operations Center in Oberpfaffenhofen, Germany, operated the satellite using the German Deep Space Station near Weilheim, Germany, for command functions and receipt of data from the on-board tape recorders. NASA tracking station support was limited to launch preparations, early mission operations, and backup in emergencies.

The mission consisted of two phases: a six-month all-sky survey phase conducted by German scientists using the PSPC, and a pointed phase (also called the Guest Observer phase) that began in February 1991. The all-sky survey with imaging x-ray and EUV telescopes resulted in the most sensitive, complete x-ray and map of the sky to date. This survey led to the discovery of about 80,000 x-ray and 500 EUV sources from which observers could choose targets during the Guest Observer phase.

During the guest observer program, which spanned 7.5 years and involved some 650 PIs from 26 countries, about 9,000 fields in the sky were observed. Numerous discoveries were made, and more than 4,000 scientists published more than 3,000 scientific articles and reports. The program ended in November 1998 after the HRI, an x-ray camera built by the SAO under contract to NASA, accidentally scanned too close to the Sun on September 20, causing irreversible damage to its collecting plate. This was an unavoidable event after ROSAT engineers in April lost control of the satellite's navigational system, which had deteriorated after eight years in space. Scientists made two final days of observations starting on December 7 by using reserved gas and the PSPC. The PSPC naturally exhausted its xenon gas supply in 1994 and has been inactive ever since. The two-day reserve gas allowed the PSPC to turn on and make one last observation of a few important astrophysical objects such as Supernova 1987A, which had been the ROSAT's very first target in 1990.

The ROSAT's discoveries spanned subjects as diverse as the relatively nearby Moon and comets to the most distant high redshift quasars, from tiny neutron stars to clusters of galaxies, the largest physical objects in the universe.[91] The ROSAT was the first observatory to detect x-rays from the Moon. In the distant universe, the spacecraft resolved virtually all of the cosmic x-ray background into discrete quasars and galaxies. See Table 4–46 for further mission details.

[91] "End of the ROSAT Guest Observer Programme," ROSAT Status Report #175: ROSAT News no. 67 (November 3, 1998) *http://heasarc.gsfc.nasa.gov/mail_archive/rosnews/msg00118.html* (accessed August 8, 2005).

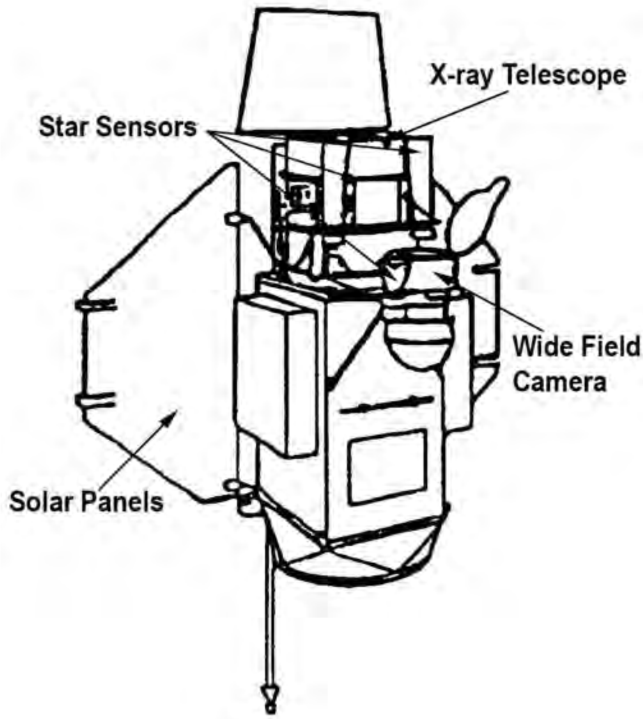

Figure 4–16. ROSAT Configuration.

Combined Release and Radiation Effects Satellite

The CRRES was a joint project of NASA and the U.S. Air Force. The Explorer Program managed the NASA portion of the mission. The CRRES was launched on July 25, 1990, into a highly elliptical geosynchronous transfer orbit (GTO) to conduct complex scientific research in "Earthspace," the space environment just above Earth's atmosphere that included the ionosphere and magnetosphere with its invisible magnetic and electrical fields and particles.[92] The CRRES carried five payloads of experiments on high-efficiency solar cells, ionospheric structure and chemistry, and radiation effects on microelectronic devices. The satellite also contained a NASA chemical payload comprising 24 chemical canisters ejected from the main spacecraft and releasing chemicals at specific times during the mission.

[92] "Combined Release and Radiation Effects Satellite (CRRES) Press Kit," General Release, p. 2, *http://www.lightwatcher.com/chemtrails/CRRES_%20Presskit.html* (accessed August 5, 2005).

The CRRES program began in 1983 as a joint NASA-U.S. Air Force project resulting from two separate programs, NASA's Chemical Release Module (CREM) program and the Air Force's Space Radiation program. Originally, the dual-mission spacecraft was to carry 48 canisters of chemicals to release after the spacecraft had been deployed from the Space Shuttle in low-Earth-orbit (LEO) at 215 miles (346 kilometers) altitude. At LEO, the spacecraft would have performed chemical release experiments for 90 days. Following the LEO mission, a trans-stage motor would have placed the CRRES into GTO, where additional chemical releases and the primary DOD mission would take place.

The loss of *Challenger* in January 1986 forced a major restructuring of the CRRES program. In June 1987, NASA decided to launch the CRRES directly to GTO on an Atlas-Centaur ELV carrying 24 canisters, complemented by a program of sounding rocket launches to perform some of the experiments excluded from the original 48-canister CRRES mission. Modifications also included the removal of a large orbit transfer stage, replacement of the orbiter cradle with a payload adapter to mate with the Centaur upper stage, and relocation of the solar panels to fit into the Atlas I fairing.

The 24 chemical canisters were ejected from the satellite during the first 13 months of the mission. The 16 large and 8 small canisters released clouds of metal vapor about 100 kilometers (62 miles) in diameter that interacted with the ionospheric and magnetospheric plasma and Earth's magnetic field. The vapors were released approximately 25 minutes after the canisters were ejected to avoid contaminating the spacecraft. The canisters performed 14 experiments. Seven experiments took place at altitudes ranging from 1,200 miles to 21,000 miles (1,931 kilometers to 33,800 kilometers); the remaining seven were undertaken near perigee at altitudes between 240 miles and 300 miles (386 kilometers and 483 kilometers). In June 1991, contact was lost with the CRRES, and the mission ended before the sounding rocket experiments could take place.

NASA's experiments were in four areas:

- Magnetospheric Ion Cloud Injections: This group of experiments artificially seeded the magnetosphere with plasma and, working with DOD particle and electromagnetic wave investigators, used ground-based optical and radar diagnostics to observe large-scale changes in the cloud. *In situ* CRRES measurements examined smaller local phenomena. The CRRES instruments also determined the state of the magnetosphere, providing valuable data to allow determination of optimal conditions for releases (experiments G-1 through G-7, G-10).
- Ionospheric Modifications: This group of experiments introduced disturbances into the ionosphere to study friction forces from the interaction of high-speed injected plasmas and the ionosphere. Scientists also injected neutral atoms at orbital velocities to understand why

unusually efficient ionization occurred when a fast beam of neutral gas passed through magnetized plasma. Scientists compared the observed behavior of the injected plasmas with computer models (experiments G-8, G-9, G-13, G-14).

- Electric Fields and Ion Transport: This group of experiments studied the low-latitude electric fields and the movement of ions along magnetic field lines into the ionosphere in response to these electric fields (experiments G-11, G-12).
- Ionospheric Irregularity Simulators: These experiments were to produce large-scale releases of chemicals to study irregularities in the ionosphere and the effects of the ionosphere on the propagation of high-frequency waves. This was the sounding rocket portion of the mission, and this portion did not take place because contact was lost with the spacecraft in October 1991, before these experiments were scheduled to begin (experiments AA-1 through AA-7).

Further details can be found in Table 4–47.

The Great Observatories

The Great Observatories were a series of four space-borne observatories designed to conduct astronomical studies over many different wavelengths (visible, gamma rays, x-rays, and infrared). Each Great Observatory focused on a different part of the spectrum. Their overlapping operations phases enabled astronomers to make contemporaneous observations of an object at different spectral wavelengths. During the 1989–1998 decade, NASA launched two of four Great Observatories, launched the third in 1999, and also largely developed the fourth.

Hubble Space Telescope

The Hubble Space Telescope was the first Great Observatory. The Hubble Space Telescope was deployed by Space Shuttle *Discovery* on April 25, 1990. Subsequent Shuttle missions serviced the Hubble Space Telescope, recovering the full capability of its imperfect mirror and adding additional capabilities. The telescope observes the universe at UV, visible, and near-infrared wavelengths.

The Hubble Space Telescope is a large Earth-orbiting astronomical telescope that observes the heavens above and without the interference and turbulence of Earth's atmosphere. The idea for a "large orbital telescope" originated in 1946 when Lyman Spitzer, a world-renowned theoretical astrophysicist, wrote "Astronomical Advantages of an Extra-terrestrial Observatory," discussing the advantages of an orbiting observatory over a ground-based telescope.[93] After the

[93] Lyman S. Spitzer, Jr., "History of the Space Telescope," *Quarterly Journal of the Royal Astronomical Society* (March 20, 1979): pp. 29–36.

success of NASA's Orbiting Astronomical Observatories in the late 1960s and early 1970s, NASA developed plans for a Large Orbiting Telescope to launch in 1970. Regular "manned maintenance missions" were part of the plan for the telescope to ensure a long and useful life. During the 1970s, astronomers and other proponents of the telescope lobbied Congress for project funding. In 1977, Congress approved funding for the Large Space Telescope, soon to be named the Hubble Space Telescope after Edwin Hubble.[94]

The original plan for the Large Space Telescope program called for the telescope's return to Earth, refurbishment, and relaunch every five years, with on-orbit servicing every two and one-half years. Hardware lifetimes and reliability requirements were based on such an interval between servicing missions. In 1985, contamination and structural loading concerns associated with return to Earth aboard the Shuttle eliminated the idea of the telescope's ground return. NASA decided that on-orbit servicing might be adequate to maintain the Hubble Space Telescope's 15-year design life and adopted a three-year cycle of on-orbit servicing.[95]

The Hubble Space Telescope was scheduled for a 1986 launch, but the destruction of *Challenger* in 1986 delayed launch until 1990. Between 1986 and launch in 1990, engineers intensively tested and evaluated the spacecraft, assuring the greatest possible reliability. An exhaustive series of end-to-end tests involving the Space Telescope Science Institute (STScI), Goddard Space Flight Center, the TDRS System, and the spacecraft were performed, resulting in overall improvements in system reliability.

In October 1989, the telescope was shipped by a U.S. Air Force C5A aircraft from the Lockheed Martin plant in Sunnyvale, California, to the launch site at Kennedy Space Center. The spacecraft was installed in *Discovery*'s payload bay on March 29, 1990.

The Hubble Space Telescope was launched on April 24, 1990, and it began approximately six months of orbital-systems checkout and calibration. On May 20, at 11:12 a.m. Eastern Daylight Time, the telescope transmitted its first image, or "first light," a 1-second exposure of open-star cluster NGC 3532 from the telescope's WFPC. A second, 30-second exposure was taken at 11:14 a.m. The image in Figure 4–17 compares the first Hubble Space Telescope image to an image from a ground-based telescope of the same portion of the sky.

Despite great NASA and astronomer celebration, it was clear that there were problems with the images. Astronomers noticed "hairy tendrils" and "spiderlike tentacles emanating like spokes from the center of each of the bright stars" in the images. Additional WFPC images acquired about 10 days later had similar features. The first images taken with the European-built Faint Object Camera (FOC) on June 17 also seemed "strangely unfocused" and showed the "same kind of irksome halo . . . with the same spidery tendrils and other odd

[94] Spitzer, "History of the Space Telescope" : p. 34.
[95] "Overview of the Hubble Space Telescope," Space Telescope Science Institute, *http://www.stsci.edu/hst/HST_overview/* (accessed September 5, 2005).

radial structure surrounding each star's pointlike cusp of light." The unclear image was indicative of "spherical aberration, an optical flaw that invariably blurs part of a star's light energy over a larger area than expected, . . . a condition that could be caused only by a mirror of the wrong shape."[96]

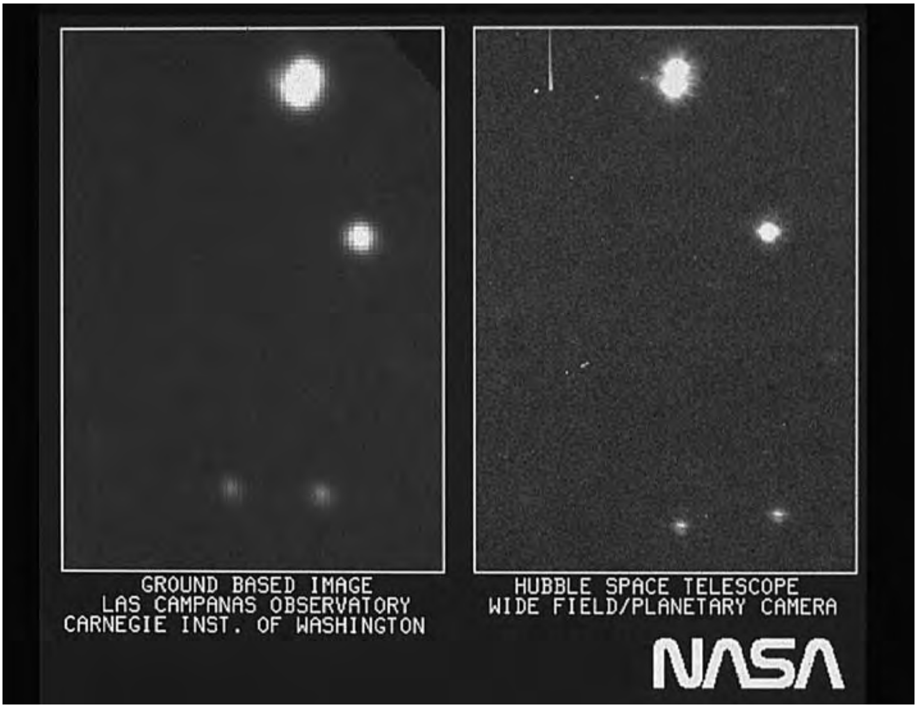

Figure 4–17. Hubble Space Telescope's "First Light," May 20, 1990. On the right is part of the first image taken with Hubble Space Telescope's Wide Field/Planetary Camera. The left shows a ground-based picture from the Las Campanas, Chile, Observatory of the same region of the sky taken with a 100-inch telescope. It is typical of high-quality pictures obtained from the ground. The images of the stars in the ground-based picture are fuzzy and, in some cases, overlap because of smearing by Earth's atmosphere. The same stars in the Hubble Space Telescope frame are sharper and well resolved, as shown by the double star at the top of the image. (STScI-PRC90-04)

Elation quickly turned to dismay, and on June 21 the Hubble Space Telescope's project manager announced the telescope's inability to focus properly. On June 25, spherical aberration was discovered in the telescope's primary mirror.[97] On July 2, NASA Associate Administrator for Space Science and Applications, Dr. Lennard A. Fisk, appointed a Hubble Space Telescope Optical Systems Board of Investigation, headed by Dr. Lew Allen, director of JPL, to review, analyze, and evaluate the facts and circumstances regarding the manufacture, development, and testing of the Hubble Space

[96] Eric J. Chaisson, *The Hubble Wars* (New York: Harper Collins Publishers, 1994), pp. 137–138, 143, 166.
[97] "Historical Timeline," *http://hubble.nasa.gov/overview/timeline.php* (accessed September 20, 2005).

Telescope Optical Telescope Assembly.[98] During the next five months, the board met and determined that the problem resulted from a flawed measuring device at the Perkin-Elmer plant where the telescope's mirrors had been made. A mirror defect 1/50 the width of a human hair prevented the telescope from focusing all light at a single point.[99]

Although many believed the spherical aberration, which was not detected during manufacturing, would cripple the telescope, scientists quickly found a way to use computer enhancement to work around the abnormality. Targets were revised to give priority to UV astronomy in front of visible light astronomy.[100] Even with the flaw, the Hubble Space Telescope saw objects at 5 billion to 10 billion light-years away with as much detail as objects at 1 billion light years seen with telescopes on Earth.[101]

A second major defect also was discovered. Problems with the solar panels caused degradation in the spacecraft's pointing stability. When passing in and out of the orbital shadow, thermal expansion and contraction from heating and cooling of the arrays caused the panels to undergo a transient distortion. This induced a jitter strong enough for the telescope's pointing and control system to lose lock on the target stars.[102] A final serious telescope problem, premature failure of the gyroscopes, also needed to be remedied.[103]

Because of these serious problems, NASA changed the primary objective of the 1993 first servicing mission from replacing the WFPC with an improved camera and performing routine maintenance to correcting the Hubble Space Telescope's primary mirror spherical aberration, replacing the faulty solar arrays, and installing new gyroscopes to replace faulty ones.[104] The repair mission aboard STS-61 in December 1993 successfully replaced the gyroscopes and solar panels and installed corrective lenses, greatly improving image quality and restoring much of NASA's credibility. Details of the servicing mission can be found later in this section. Figure 4–18 shows the M100 galaxy before and after the first servicing mission.

The Hubble Space Telescope weighs approximately 24,500 pounds (11,110 kilograms) and is 43.5 feet (13.3 meters) long and 14 feet (4.3 meters) in diameter at its widest point, roughly the size of a railroad tank car or bus. Many of the telescope's components are modular so they may be removed and replaced on orbit by astronauts. It is the first spacecraft specifically designed for on-orbit servicing.

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[98] "Hubble Board of Investigation Named," *NASA News* Release 90-091, July 2, 1990, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1990/90-091.txt* (accessed September 20, 2005).

[99] "Did You Know," *Goddard News* Special Edition (1993): 4. (NASA History Office Folder 005989).

[100] Randee Exler, "HST Promises 'Excellent Science,'" *Goddard News* 36 (July 1990): 1, 8.

[101] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Office of Space Science, Report no. X 458-61-93-02, November 1993, p. 2 (NASA History Office Folder 005989).

[102] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," pp. 1–2.

[103] Gyroscopes sense changes in orientation so the spacecraft can be "pointed" in the desired direction. Chaisson, pp. 58–59.

[104] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission." Report no. X 458-61-93-02, pp. 1–2.

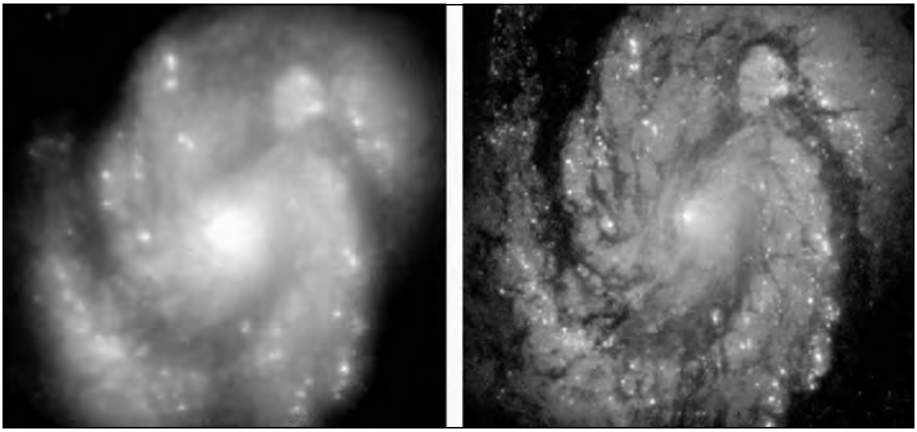

Figure 4–18. These images of Spiral Galaxy M100 were taken before and after the Hubble Space Telescope's first servicing mission. The image on the left was obtained with the original Wide Field/Planetary Camera. The image on the right was obtained with the Wide Field and Planetary Camera 2 that was installed on the servicing mission. Both the new device and the COSTAR were designed to compensate for the primary mirror's incorrect shape. (NASA and STScI-PRC1995-49e)

The Hubble Space Telescope has three major elements: the support systems module, the optical telescope assembly, and the scientific instruments. The support systems module consists of the exterior structure and the various systems that enable the optical telescope assembly and scientific instruments to operate. Foil-like multilayer insulation wraps the telescope. To keep it from overheating, the metallic silver surface reflects much of the direct sunlight striking the telescope. Tiny heaters attached to many telescope components warm them during the "eclipse" phase of orbit, when in Earth's shadow. The insulation blankets and solar-powered heaters maintain the mirror temperature at 70°F (21°C). Solar arrays, built by the ESA, convert the Sun's energy to electricity during the portion of orbit when the telescope is exposed to sunlight. These two "wings" contain 48,000 solar cells. Power is stored in six nickel-hydrogen batteries to support the telescope during eclipse.

A series of gyroscopes, star trackers, reaction wheels, fine guidance sensors, and electromagnets form the pointing control system. When conducting an observation, the pointing control system rotates the space telescope to the proper orientation, points it to the desired star, and locks the telescope in place. The gyroscopes and reaction wheels produce a course pointing toward the star. Star trackers (or fine guidance sensors) fine-tune the course pointing. These sensors can locate and lock onto a position in the sky to within 0.01 arc second and can hold that pointing without varying more than 0.007 arc second for as long as 24 hours while the Hubble Space Telescope continues to orbit Earth at 17,500 miles per hour (28,163 kilometers per hour).

The three fine guidance sensors on the Hubble Space Telescope are located at 90-degree intervals around the telescope's circumference. They serve a dual purpose. Two fine guidance sensors point the telescope at an astronomical target and then hold the target in a scientific instrument's FOV. The third fine guidance sensor can also be used as a scientific instrument to obtain highly accurate celestial positions (astrometry).

Other systems include a computer that controls the overall spacecraft; high-gain antennae that receive ground commands and transmit data back to Earth; an electrical power system; the spacecraft structure and mechanical parts; and the safing system, which controls the telescope to protect it from damage in case of serious computer problems or loss of communication with ground controllers.

The telescope assembly contains two mirrors that collect and focus light from the celestial objects being studied. The 94-inch (239-centimeter) primary mirror is near the center of the telescope. The precision-ground glass has an aluminum reflecting surface and is the smoothest large mirror ever made. To reduce weight, the front and back plates are fused to a honeycomb core. The 13-inch (33-centimeter) secondary mirror is located 16 feet (4.9 meters) in front of the primary mirror. It is set far enough inside the open end of the telescope to assure that stray light does not interfere with the image being studied. Three baffles surround the path of light to block out unwanted rays. To resist the expansion and contraction of the mirrors resulting from exposure to the temperature extremes of space, the mirrors are made from a kind of glass that resists expansion and contraction. An extremely strong, lightweight structure holds the mirrors at a precise distance from each other. The truss is made from graphite epoxy, a material resistant to expansion and contraction in temperature extremes.[105]

During observations, light from a celestial source travels through the tube of the telescope to the large primary mirror. The light is then reflected from the primary mirror back to the secondary mirror. From there, the beam narrows, then passes through a hole in the center of the primary mirror to a focal plane where the scientific instruments are located almost 5 feet (1.5 meters) behind the primary mirror.[106] (Figure 4–19 shows the light path for the main telescope.)

The Hubble Space Telescope's science instruments work together and individually to view the farthest reaches of space. Originally, the telescope accommodated five science instruments and three fine guidance sensors. Each instrument was contained in a separate module and operated on 110 watts to 150 watts of power. Four instruments were aligned with the main optical axis and were mounted just behind the primary mirror. At deployment, these axial instruments were the Goddard High Resolution Spectrograph (GHRS); the Faint Object Spectrograph (FOS); the FOC; and the High Speed Photometer (HSP). The fifth science instrument, the WFPC, was located in the radial bay.[107] Figure 4–20 shows the overall Hubble Space Telescope configuration.

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[105] "Space Shuttle Mission STS-31 Press Kit," April 1990, pp. 6, 9, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_035_STS-031R_Press_Kit.pdf* (accessed September 5, 2005).

[106] "Space Shuttle Mission STS-31 Press Kit," April 1990, p. 15.

[107] "Hubble's Science Instruments," *http://hubble.nasa.gov/technology/instruments.php* (accessed September 12, 2005).

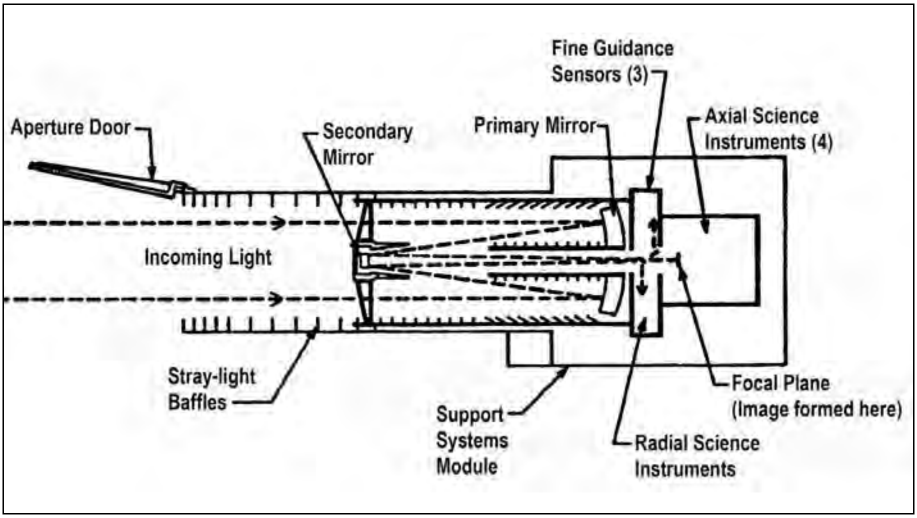

Figure 4–19. Light Path for the Main Telescope. (STS-61 Press Kit)

The Hubble Space Telescope was a collaborative effort. Marshall Space Flight Center was responsible for the telescope's design, development, fabrication, and assembly. The Center also conducted orbital verification of the observatory's systems after launch. Project management for the telescope was transferred from Marshall Space Flight Center to Goddard Space Flight Center when the orbital verification phase was almost complete. Goddard Space Flight Center was responsible for developing four of the scientific instruments and the telescope's ground data system, which included management and oversight of the Space Telescope Science Institute at The Johns Hopkins University in Baltimore (later called the STScI). The STScI conducts and coordinates the telescope's science operations. The Association of Universities for Research in Astronomy, Inc. (AURA) operates the STScI for NASA. The ESA played a significant role in telescope development by providing the electrical power-producing solar arrays and the FOC.

Johnson Space Center directs the Space Shuttle mission operations phase of the servicing mission. It supplies the Shuttle and all Shuttle-associated hardware and trains astronaut crews to rendezvous with the Hubble Space Telescope and repair and/or replace instruments and spacecraft hardware. Kennedy Space Center readies the Shuttle for launch, supervises placement of the telescope's payload elements in the Shuttle cargo bay, and provides Shuttle launch services.

Hubble Space Telescope Servicing

The Hubble Space Telescope was the first scientific mission specifically designed for routine on-orbit servicing by spacewalking astronauts. The modular design allowed astronauts to disassemble it, replace worn-out equipment, and upgrade instruments. These periodic servicings ensured that the Hubble Space Telescope continued to produce first-class science using the latest and most advanced technology. Each time a Hubble Space Telescope science instrument was replaced, it increased the telescope's scientific power by a factor of 10 or greater.[108]

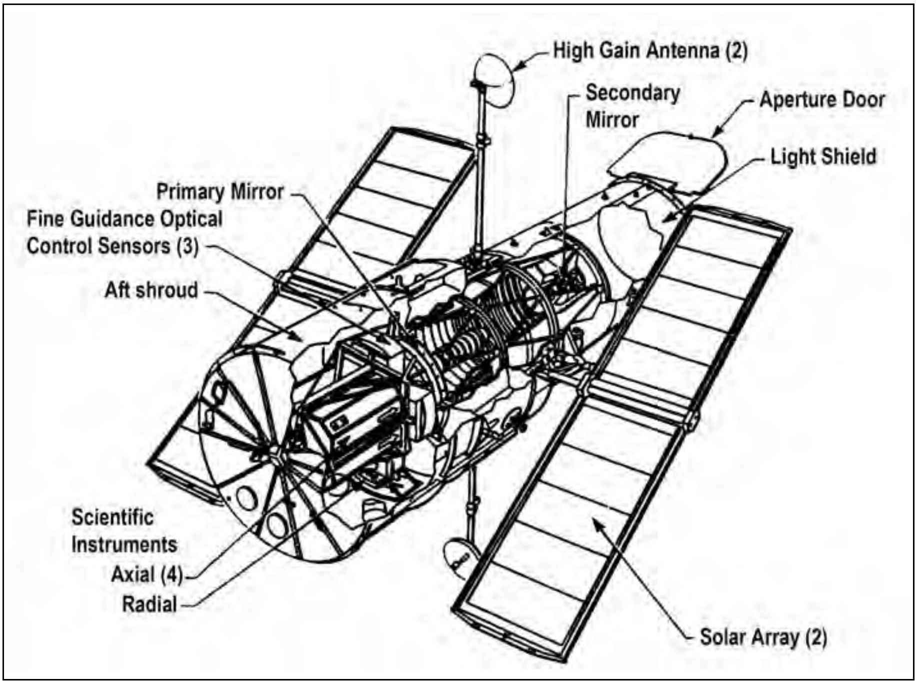

Figure 4–20. Hubble Space Telescope Configuration. (STS-31 Press Kit)

Servicing Mission 1 (SM1). Before Hubble Space Telescope's 1990 launch, a planned servicing mission had been scheduled for 1993 to install an updated Wide Field and Planetary Camera 2 (WFPC2) and perform general maintenance. But when problems with the telescope's mirror, solar arrays, and gyroscopes surfaced on orbit, NASA established additional requirements for the first servicing mission. The primary mission objectives became correcting spherical aberration in the telescope's primary mirror and replacing the spacecraft's faulty solar arrays and inoperative gyroscopes.

The COSTAR, built by Ball Electro-Optics and Cryogenics Division for installation on SM1, corrected spherical aberration of the main mirror by better focusing the light sources for the axial instruments. (The WFPC2 had its own corrective optics.) To install the COSTAR, one of Hubble Space Telescope's four axial instruments had to be removed. Because the HSP did

[108] "Hubble Space Telescope: An Introduction," *http://hubble.nasa.gov/overview/intro.php* (accessed September 6, 2005).

proportionately less science than the other instruments, NASA decided that astronauts would replace the 200-kilogram (441-pound), phone-booth-sized HSP by pulling it out through a servicing bay door and installing the COSTAR in its place. The COSTAR had no cameras or detectors. It used 10 precisely shaped corrective mirrors (each about the size of a quarter) placed with mechanical arms in front of openings on each of the three remaining observing instruments, to refocus the light relayed from the flawed primary mirror before it entered the instruments, much like "putting a pair of glasses on the Space Telescope."[109]

The WFPC2 was a spare instrument developed in 1985 by JPL; it was to be installed as a replacement during the first servicing mission. TheWFPC2 had new sensors that improved sensitivity, particularly in the UV portion of the spectrum. When the primary mirror flaw was discovered soon after launch, NASA and the camera team immediately began work on an optical correction that could be built into the upgraded camera. The new design had corrective optics to compensate for the Hubble Space Telescope primary mirror flaw and small actuators to fine tune the position of its internal mirrors to ensure correct alignment. The astronauts would slide out the original 280-kilogram (670-pound) wedge-shaped WFPC and replace it with WFPC2.

The replacement solar arrays were the original flight spare arrays that the ESA modified to eliminate the jitter problem. The modifications included the addition of thermal shields to reduce temperature gradients on the solar blankets' deployment booms and the redesign of boom-length-compensation and blanket-tension mechanisms. When deployed, each solar array measured approximately 12 meters by 3 meters (40 feet by 10 feet).[110]

This mission was nearly the most challenging and complex human spaceflight operation ever attempted. STS-61 lifted off from Kennedy Space Center on December 2, 1993. The *Endeavour* crew captured the Hubble Space Telescope on December 4, grappling and berthing it in the Shuttle's cargo bay. Over the next five days, two teams of astronauts carried out the servicing tasks during a record five back-to-back EVAs totaling 35 hours, 28 minutes.

During the first EVA, Jeffrey Hoffman and F. Story Musgrave replaced two sets of remote sensing units containing the gyroscopes that helped the telescope point in the correct direction. They also replaced eight fuse plugs protecting the telescope's electrical circuits. Thomas Akers and Kathryn Thornton performed the second EVA, in which the astronauts replaced the telescope's two solar arrays. EVA 3, performed by Hoffman and Musgrave, replaced the WFPC with the new WFPC2 and also changed out two magnetometers (see figure 4–21). EVA 4, performed by Akers and Thornton, replaced the HSP with the COSTAR. They also upgraded the Hubble Space Telescope's on-board computer by bolting

[109] "Corrective Optics Contract for Hubble Telescope Awarded," *NASA News* Release C91-oo, October 16, 1991 (NASA History Office Folder 005989).
[110] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Report no. X 458-61-93-02, November 1993, p. 10 (NASA History Office Folder 005989).

on an electronics package containing additional computer memory and a coprocessor. The final EVA, performed by Hoffman and Musgrave, replaced the solar array drive electronics, fitted an electrical connection box on the GHRS, and installed covers on the magnetometers.

The flight control team for Hubble Space Telescope operations on SM1 was divided between Johnson Space Center and Goddard Space Flight Center. The Goddard Space Flight Center Mission Manager, located at Johnson Space Center, coordinated the activities at both Johnson Space Center and Goddard Space Flight Center. The Shuttle flight was controlled from the Johnson Mission Control Center where EVA and payload-trained specialists assisted the normal complement of Shuttle flight controllers. At Goddard Space Flight Center, teams of engineers and scientists provided operational control of the Hubble Space Telescope until it docked with *Endeavour*. They conducted real-time commanding of the telescope to safe systems before EVAs, accomplished aliveness and functional tests on in-flight-serviced hardware, and provided troubleshooting expertise when required.

The Hubble Space Telescope was disconnected and moved from the Shuttle on December 9. Once released from *Endeavour*, Hubble Space Telescope command and control reverted solely to Goddard Space Flight Center, and a three and one-half-month period of observatory verification began. During that time, systems and subsystems were checked out and scientific instruments were aligned to the telescope's optical axis and calibrated to the characteristics of the newly installed corrective optics.

The verification period demonstrated the success of the SM1 repairs and replacements. Change-out or installation of all items on the entire servicing task list was accomplished and scientific capabilities were restored. Post-mission images proved the effectiveness of the optical corrections, and vehicle systems were restored to a fully redundant status. The mission proved the concept of on-orbit servicing as the way to keep the Hubble Space Telescope fully functional and performing cutting-edge astronomy.[111]

Key science enabled by the corrected image quality yielded the following:

- An accurate measurement of the expansion rate of the universe (the Hubble constant).
- The deepest look ever at the properties of galaxies in the early universe (the Hubble Deep Field).
- Initial spectroscopic detections of massive black holes in the centers of galaxies.
- The first detection of helium in the intergalactic medium.
- Unprecedented views of star formation and the late stages of stellar evolution (e.g., Orion protoplanetary disks, SN1989a).[112]

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[111] "Post-Launch Mission Operation Report for the Hubble Space Telescope First Servicing Mission," April 28, 1994 (NASA History Office Folder 30976).

[112] "The Evolving Role of Satellite Servicing at NASA," presented by Frank Cepollina to the Association of Space Explorers, USA, June 22, 2004, Houston, Texas.

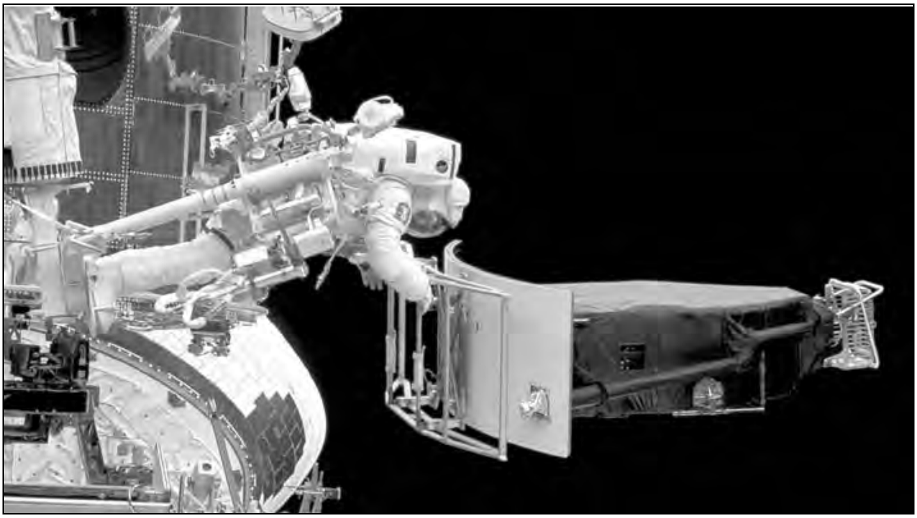

Figure 4–21. Replacing the Wide Field Planetary Camera During the Hubble Space Telescope's First Servicing Mission. (NASA Photo, 1993, http://imgsrc.hubblesite.org/hu/gallery/db/spacecraft/15/formats/15_print.jpg*)*

Servicing Mission 2 (SM2). On the Hubble Space Telescope's second servicing mission, which launched from Kennedy Space Center on February 11, 1997, the six-member STS-82/*Discovery* crew completed servicing and upgrading of the Hubble Space Telescope during four planned EVAs and then performed a fifth unscheduled spacewalk to repair telescope insulation. Astronauts upgraded the telescope's scientific capabilities by installing two new instruments—the STIS and NICMOS—and performed telescope maintenance. The telescope received a refurbished fine guidance sensor, a solid-state recorder to replace one of the reel-to-reel tape recorders, and a refurbished spare reaction wheel assembly (RWA) to replace one of the on-board assemblies.

The STIS replaced the GHRS. The new instrument included all the major capabilities of the GHRS and FOS, and added new technological capability. The STIS optical design featured internal corrective optics to compensate for the Hubble Space Telescope's primary mirror spherical aberration and did not use the COSTAR. The NICMOS replaced the FOS. Like STIS, the NICMOS design featured corrective optics to compensate for the primary mirror's spherical aberration. The addition of the STIS powerful general-purpose spectroscopic capability and the NICMOS near-infrared capability yielded the following:

- A systematic survey of black hole properties in galaxy nuclei.
- An infrared companion image to the Hubble Deep Field, showing even more distant galaxies.
- Spectroscopic detection of the atmosphere of a planet in another solar system.[113]

[113] "The Evolving Role of Satellite Servicing at NASA," presented by Frank Cepollina.

The Hubble Space Telescope's original data management system included three reel-to-reel tape recorders to store engineering and science data that could not be transmitted to the ground immediately. Unlike the reel-to-reel recorder, the new solid-state recorder had no reels, tape, or moving parts to wear out. It was about the same size as the reel-to-reel recorder, but it could store 10 times as much data in computer-like memory chips until the telescope's operators at Goddard Space Flight Center commanded the recorder to play it back; the new solid-state recorder stored 12 gigabits of data, while the tape recorder stored only 1.2 gigabits.

The Hubble Space Telescope communicated with the ground through NASA's orbiting TDRS System. Engineering information from the spacecraft systems and science data from the astronomical instruments could either be sent directly to the Space Telescope Operations Control Center at Goddard Space Flight Center or recorded and played back later. The current procedure was to record all science data to ensure continuity and safeguard against any possible loss of unique information. Post-servicing mission plans were to use the solid-state recorder, with larger capacity and flexibility, exclusively for science data storage. This would accommodate the higher data rates from the new science instruments and promote greater operational efficiency.

By the second servicing mission, one of the fine guidance sensors in the Hubble Space Telescope's pointing control system was showing signs of mechanical wear and was due for replacement. The fine guidance sensor had a new mechanism to accomplish better optical alignment. When this spare replaced one of the original units, telescope operators could compensate for changes in on-orbit conditions and optimize its performance by keeping the fine guidance sensor more finely tuned.

Other replacements during SM2 included the following:

- Replacement of one of the telescope's four reaction wheel assemblies with a refurbished spare.
- Replacement of one of the four data interface units with a modified and upgraded spare unit that corrected original unit failures.
- Replacement of the solar array drive electronics unit, not replaced during SM1, with the unit returned from orbit on SM1. The unit was refurbished to correct for problems that resulted in transistor failures. The ESA provided the solar array drive electronics units.
- Installation of more durable covers for magnetic sensing system hardware because of degradation of materials in the space environment.
- Replacement of one of the three engineering and science tape recorders with a spare because one unit failed.
- Installation of an optical control electronics enhancement kit.

Astronaut Steven Hawley, one of the astronauts who originally deployed the telescope, operated *Discovery's* remote manipulator system arm on STS-82 to retrieve the Hubble Space Telescope for its second servicing on February 13, 1997, and positioned it in the payload bay less than half an hour later. Figure 4–22 shows a close-up of the Hubble Space Telescope taken by *Discovery's* still camera.

Relying on more than 150 tools and crew aids, Mark Lee and Steven Smith performed EVAs 1, 3, and 5, and Gregory Harbaugh and Joseph Tanner accomplished EVAs 2 and 4. The spacewalks on STS-82, which took place in more than five days, totaled 33 hours, 11 minutes, about 2 hours less than the total EVA time recorded on the telescope's first servicing mission.

On the first EVA, Lee and Smith removed two scientific instruments from the Hubble Space Telescope, the GHRS and FOS, and replaced them with the STIS and NICMOS, respectively. On EVA 2, Harbaugh and Tanner replaced a degraded fine guidance sensor and a failed engineering and science tape recorder with new units. They also installed an optical control electronics enhancement kit, which increased the capability of the fine guidance sensor. During this EVA, astronauts noted cracking and wear on thermal insulation on the side of the telescope facing the Sun and in the direction of travel.

During EVA 3, Lee and Smith removed and replaced a data interface unit as well as an old reel-to-reel tape recorder with a new digital solid-state recorder that allowed simultaneous recording and playback of data. They also changed out one of the four reaction wheel assembly units that used spin momentum to move the telescope toward a target and maintain it in a stable position. After this EVA, the mission managers decided to add EVA 5 to repair the Hubble Space Telescope's thermal insulation.

On EVA 4, Harbaugh and Tanner replaced a solar array drive electronics package controlling the positioning of the telescope's solar arrays. They also replaced covers over the telescope's magnetometers and placed thermal blankets of multilayer material over two areas of degraded insulation around the light shield portion of the telescope below the top of the observatory. Meanwhile, inside *Discovery*, Horowitz and Lee worked on the middeck to fabricate new insulation blankets for the Hubble Space Telescope.

On EVA 5, the final spacewalk, Lee and Smith attached several thermal insulation blankets to three equipment compartments at the top of the telescope's support systems module, which contained key data processing, electronics, and scientific instrument telemetry packages.

The Hubble Space Telescope redeployed on February 19 and moved into the highest altitude it had ever flown, a 335-nautical-mile by 321-nautical-mile (620-kilometer by 594-kilometer) orbit. Calibration of the two new science instruments took place during a period of several weeks with first images and data returned after about two months.

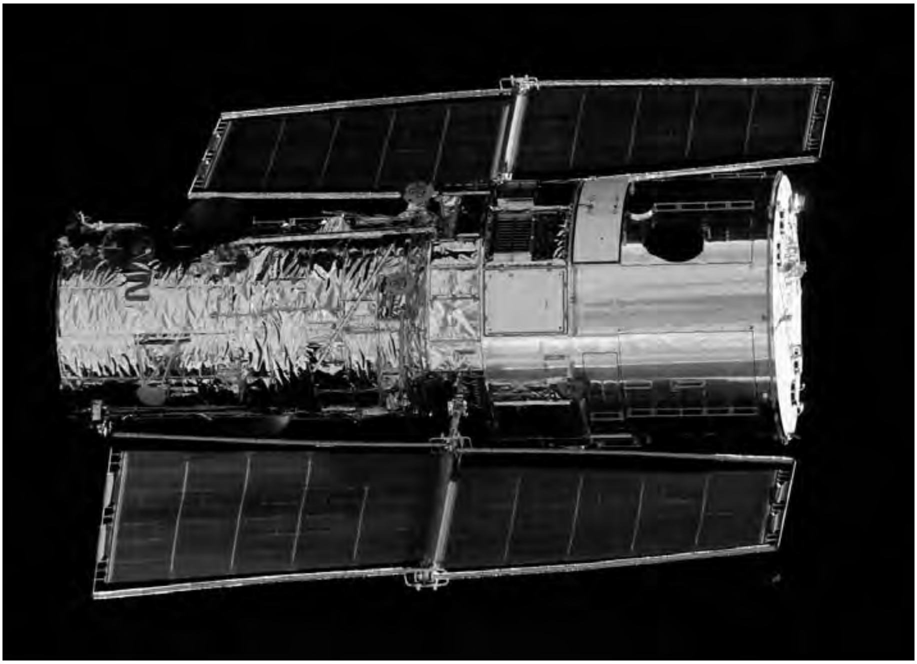

Figure 4–22. The first close-up look at the Hubble Space Telescope since 1993 was provided by the STS-82 electronic still camera during Discovery*'s rendezvous with the giant telescope. (NASA Photo No. STS82-E-5084)*

Hubble Orbiting Systems Test Mission

The HOST mission took place on STS-95 in October 1998. This Space Shuttle mission, dubbed "the John Glenn Mission" because of its famous crew member, tested key pieces of new Hubble hardware before installation on the Hubble Space Telescope. By flying in an orbit similar to the telescope's, the HOST allowed engineers to determine how new equipment on this flight would perform on the telescope.

HOST engineers monitored the effects of radiation on the telescope's new hardware, including an advanced computer, digital data recorder, and cryogenic cooling system. All the new technologies on the HOST mission performed as expected. Table 4–48 provides mission details.

Hubble Space Telescope Science

As stated in the announcement of opportunity released in 1977, the Hubble Space Telescope's main scientific objectives were to investigate the following:

- The constitution, physical characteristics, and dynamics of celestial bodies.
- The nature of processes occurring in the extreme physical conditions existing in and between astronomical objects.

- The history and evolution of the universe.
- Whether the laws of nature are universal in the space-time continuum.

From launch through 1998, the Hubble Space Telescope delivered a steady stream of new clues and discoveries to help solve the mysteries of the cosmos. Making great strides in achieving its scientific goals, the Hubble Space Telescope capitalized on its breadth of vision, which ranged from the UV to the near infrared, to help scientists answer some of the most puzzling questions of our universe while raising some new ones. The Hubble Space Telescope contributed significantly to most of the topics of current astronomical research, covering objects from our own solar system to the most distant galaxies. The following section describes some of the telescope's most significant discoveries. Material was drawn primarily from "The Hubble Space Telescope: Science in the First Decade," at the *HubbleSite* Web site.[114]

Cosmic Collision. The Hubble Space Telescope allowed astronomers an outstanding view of the impact of Comet Shoemaker-Levy 9 on Jupiter. During July 16–22, 1994, 21 fragments of the comet plunged into Jupiter, exploding with the force of millions of nuclear bombs. The telescope's high-resolution images provided acute details of the plumes' geometry, the growth and dispersion of the impact features, and the atmospheric waves expanding around the impact sites, even while the precise nature of these waves continued to generate debate. The comet impact was a relatively rare phenomenon, where a thousand years might pass before a similar event is observed again. Figure 4–23 shows eight impact sites on Jupiter.

Life Cycle of Stars. The Hubble Space Telescope documented in great detail the births and deaths of stars. The telescope visually demonstrated that protoplanetary dust disks around young stars are common, suggesting that at least the raw materials for planet formation are in place. The Hubble Space Telescope showed for the first time that jets in young stellar objects emanate from the centers of accretion disks (in objects such as Herbig Haro 30), thus turning what were previously theoretical expectations into observed reality. The Hubble Space Telescope provided many very detailed images of stellar deaths in the form of morphologies of planetary nebulae, a mysterious three-ring structure around Supernova 1987A, and corrugated bipolar lobes in the Luminous Blue Variable Eta Carinae (see figures 4–24 and 4–25). While some of the basic physics developed for these objects from earlier ground-based observations has not changed significantly, the realization that almost none of these objects are spherically symmetrical, but rather that bipolarity and point-symmetry was extremely common, stimulated much theoretical work on nebular shaping.

[114] "The Hubble Site," *http://hubblesite.org/discoveries/10th/vault/in-depth/science.shtml* (accessed September 9, 2005).

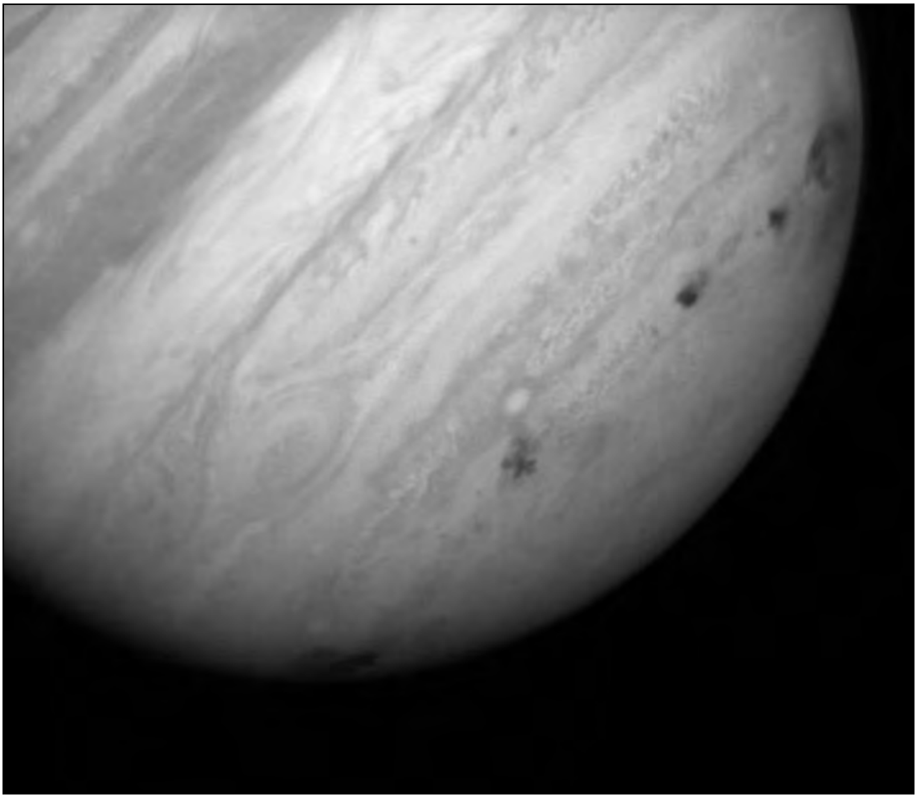

Figure 4–23. Image of Jupiter with Hubble's Wide Field and Planetary Camera 2. Eight impact sites are visible. (STScI-PRC1994-34. Hubble Space Telescope Comet Team and NASA)

Cosmic Collision. Observations of Supernova 1987A, the closest supernova in four centuries, provided details for the first time on the interaction of a blast wave from a supernova with its surrounding environment. The three-ring structure was an unexpected feature. The set of images in figure 4–26 shows Supernova 1987A and its neighborhood.

Probing Stars in Dense Regions. The Hubble Space Telescope's superb resolution was a major asset when observing dense stellar environments. The telescope produced many results on resolved stellar populations in globular clusters (galactic and in the Local Group), in field populations of nearby galaxies, and in stellar aggregates (clusters) in the Magellanic clouds. Figure 4–27 shows a view of the G1 globular cluster captured by the Hubble Space Telescope.

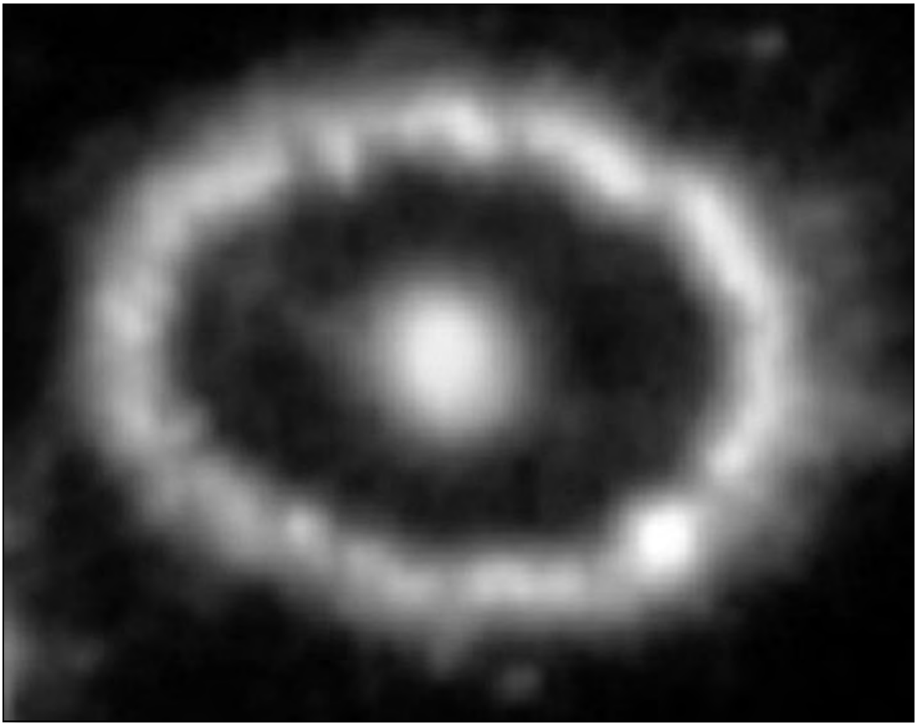

Figure 4–24. Ring Structure Around Supernova 1987A, February 6, 1996. (STScI 2004-09. NASA, P. Challis, R. Kirschner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI))

Hubble Space Telescope results included the following:

- The spread of ages among galactic globulars was relatively narrow, implying a short timescale for the formation of spheroidal components of galaxies.
- The horizontal branch morphology was determined in globulars as far as in M31 and M33, providing clues about the formation age of globulars in the Local Group.
- The first-time revelation of the sequence of cooling white dwarfs in several nearby globulars and exploration of the bottom of the main sequence.
- Star formation histories of resolved dwarf galaxies exhibited a wide variety of behaviors.
- Valuable information on star formation and the Initial Mass Function in the Magellanic clouds. This data suggests important implications for star formation in the early universe, a universe deficient in the heavier elements.

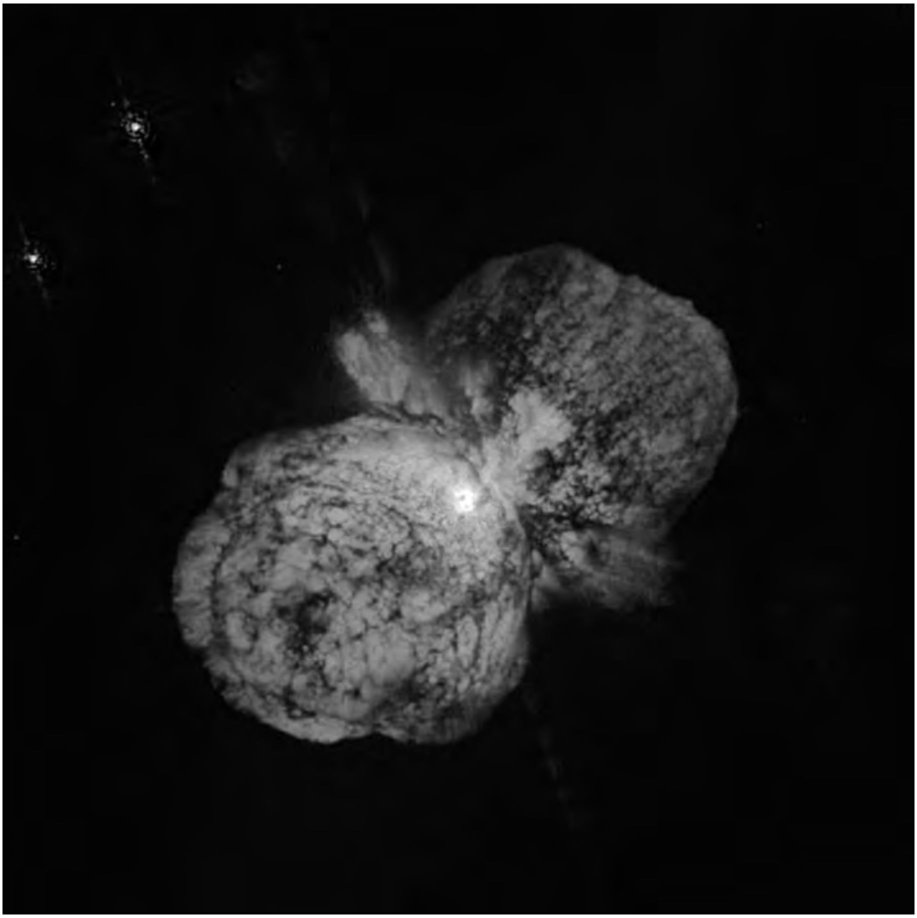

Figure 4–25. Hubble's Wide Field and Planetary Camera 2 observed Eta Carinae in September 1995. Images taken with red and near-infrared filters were subsequently combined to produce this color image. A sequence of eight exposures was necessary to cover the object's huge dynamic range. A giant outburst about 150 years ago produced two bipolar lobes, visible in this image. Estimated to be 100 times more massive than our Sun, Eta Carinae may be one of the most massive stars in our galaxy. It radiates about 5 million times more power than our Sun. (STScI-PRC1996-23a)

Black Holes a Common Occurrence. In the dense environments of galactic centers, the Hubble Space Telescope confirmed previous suspicions and provided decisive evidence showing that supermassive black holes resided in the centers of many (not necessarily active) galaxies. High-resolution images revealed the presence of dusty gas tori around the central object. The ability to spectroscopically determine velocities at multiple locations led to reliable determinations of the black hole masses. Figure 4–28 shows three black holes discovered by the Hubble Space Telescope.

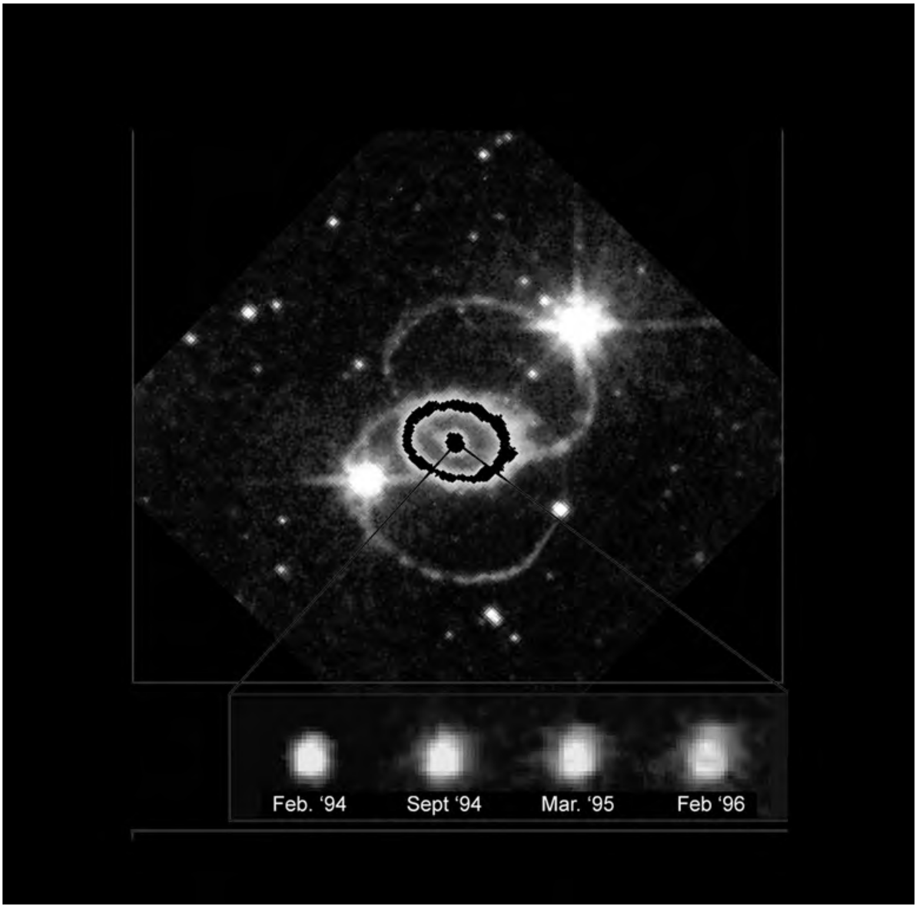

Figure 4–26. This image, taken by Hubble Space Telescope's Wide Field and Planetary Camera 2, shows the evolution of Supernova 1987A debris from February 1994 to February 1996. Material from the stellar interior was ejected into space during the supernova explosion in February 1987. The explosion debris was expanding at nearly 6 million miles per hour. (STScI-PRC1997-03. Chun Shing Jason Pun (NASA/GSFC), Robert P. Kirschner (Harvard-Smithsonian Center for Astrophysics), and NASA)

Galaxy Collisions. In the violent environment of colliding galaxies, the Hubble Space Telescope showed that young, massive, compact star clusters were formed when two galaxies collided or interacted strongly. The formation time was of the order of 10 million years or less, and these clusters might be the progenitors of globular clusters. Figure 4–29 shows the fireworks accompanying colliding galaxies. The Hubble Space Telescope has uncovered more than 1,000 bright young star clusters bursting to life as a result of galaxy collusions.

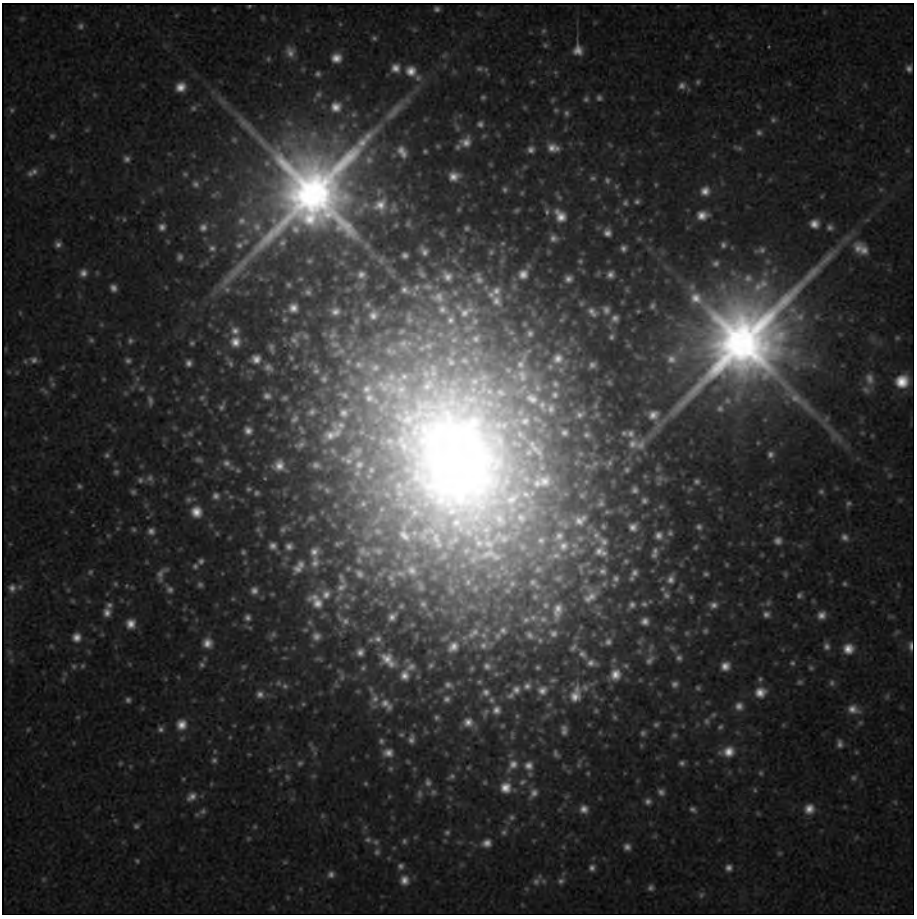

Figure 4–27. This globular cluster, called G1, orbits the Andromeda galaxy (M31), the nearest major spiral galaxy to our Milky Way. Located 130,000 light-years from Andromeda's nucleus, G1 is the brightest globular cluster in the Local Group of galaxies. The Local Group consists of about 20 nearby galaxies, including the Milky Way. (STScI-PRC1996-11. Michael Rich, Kenneth Mighell, and James D. Neill (Columbia University) and Wendy Freedman (Carnegie Observatories) and NASA)

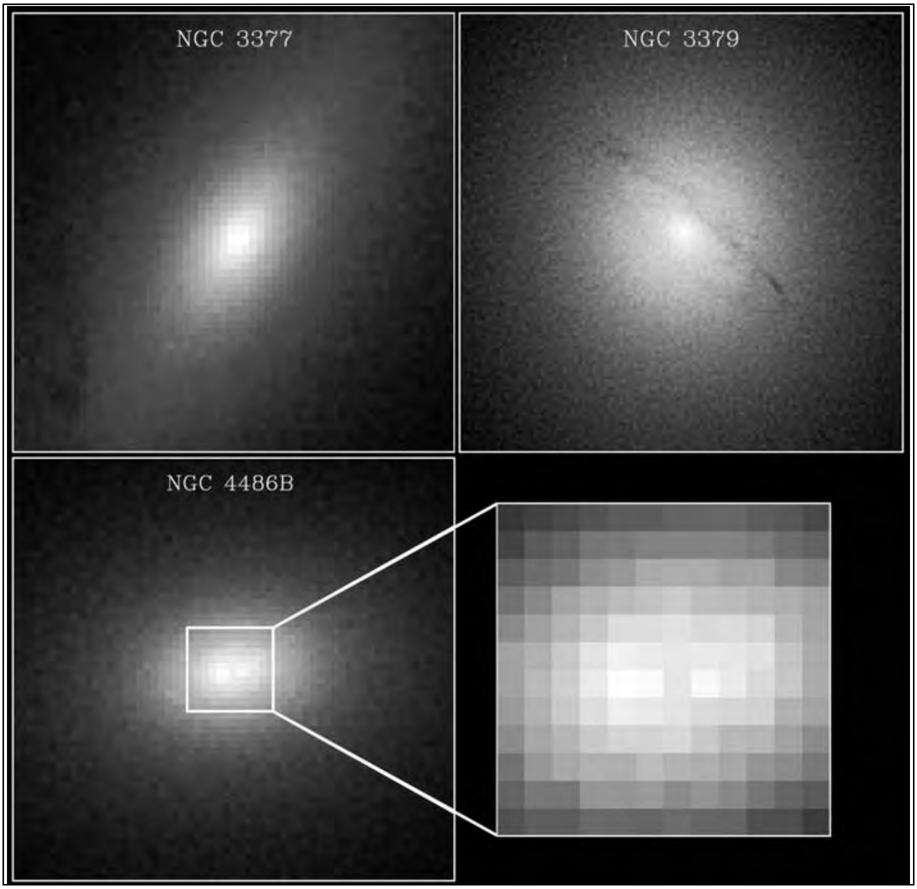

Figure 4–28. Announcing the discovery of three black holes in three normal galaxies in January 1997, astronomers suggested that nearly all galaxies may harbor supermassive black holes once powering quasars but now quiescent. The conclusion was based on a census of 27 nearby galaxies carried out by the Hubble telescope and ground-based observatories in Hawaii. (STScI-PRC1997-01. Karl Gebhardt, University of Michigan; Tod Lauer, National Optical Astronomy Observatory; and NASA)

Host Galaxies for Quasars. Findings from ground-based observations previously suggested that quasars reside in host galaxies; the Hubble Space Telescope confirmed this. And with superb resolution, the telescope demonstrated that a high fraction of the hosts are interacting galaxies. This information could be an important clue for how the central black hole is fed. Astronomers believe a quasar turns on when a massive black hole at the nucleus of a galaxy feeds on gas and stars. As the matter falls into the black hole, intense radiation is emitted. Eventually, the black hole stops emitting radiation when it consumes all nearby matter. Then it needs debris from a collision of galaxies or another process to provide more fuel. Figure 4–30 shows examples of different home sites of quasars.

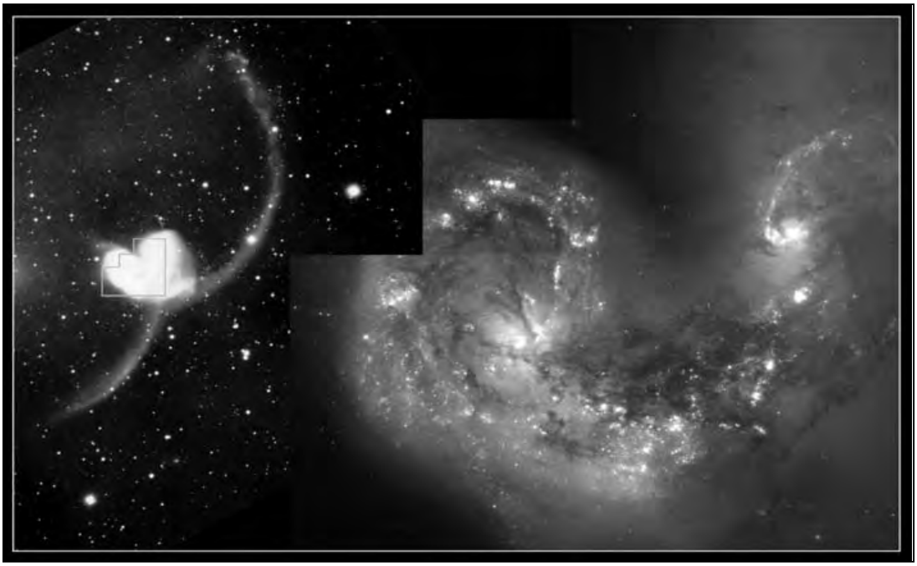

Figure 4–29. The image on the left shows two galaxies, called the Antenna. The green shape pinpoints the Hubble Space Telescope's view. The Hubble Space Telescope's close-up view on the right shows the "fireworks" at the center of the collision. The sweeping spiral-like patterns, traced by bright blue star clusters, result from a firestorm of star birth triggered by the collision. (STScI-PRC1997-34a. Brad Whitmore, STScI, and NASA)

An Expanding Universe. Ever since Edwin Hubble's discovery of the expansion of the universe in the late 1920s, measuring the value of the Hubble constant (indicative of the rate at which the universe is expanding and the age of the universe) was a prime target for observational cosmology. In May 1999, a Hubble Space Telescope project team announced the completion of a program aimed at measuring the distances to 18 galaxies, some as far as 20 megaparsecs away (in the Virgo cluster galaxies). By measuring the distance to the Cepheid variables in the Virgo clusters by a variety of methods, astronomers could reach a more accurate value for the Hubble constant, arriving at a value of 70 kilometers (43 miles) per second per megaparsec for the Hubble constant, with an uncertainty of about 10 percent. This project would have been impossible without the Hubble Space Telescope's resolution and depth. By calibrating the absolute magnitudes at maximum of a sample of Type Ia supernovae, another team determined the distances to galaxies in the Hubble flow, finding a value of 60 kilometers (37 miles) per second per megaparsec (with a 10 percent uncertainty) for the Hubble constant. Thus, the discrepancy among the values determined by different groups (and different methods) was finally being resolved. Before the Hubble Space Telescope, scientists placed the age of the universe at anywhere between 10 billion and 20 billion years; using the telescope, they agreed that approximately 12 billion to 15 billion years had elapsed since the Big Bang. Figure 4–31 shows spiral galaxy NGC 4603, the most distant galaxy in which Cepheid variables were found.

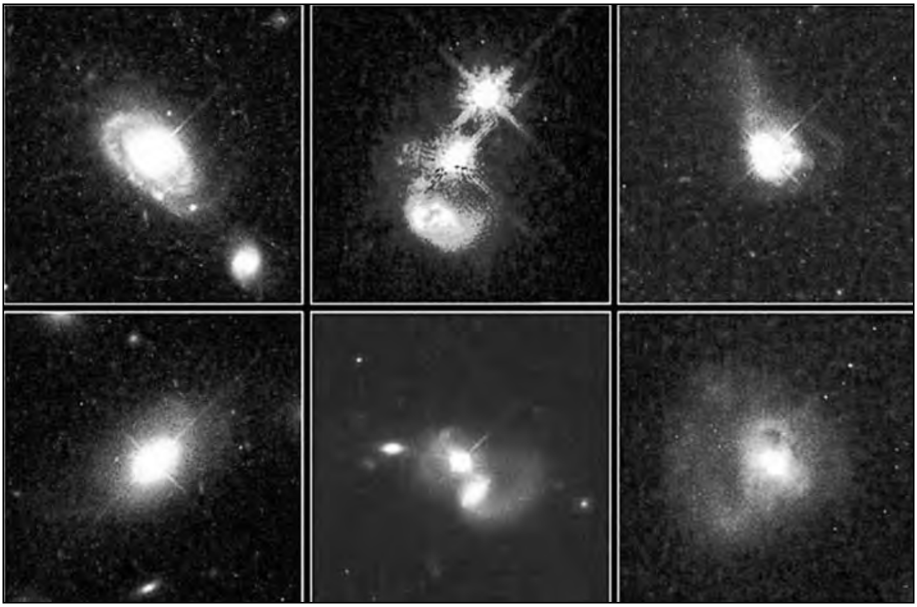

Figure 4–30. Quasar Host Galaxies. The column on the left represents normal galaxies, the center, colliding galaxies, and the right, peculiar galaxies. (PRC96-35a)

Figure 4–31. Spiral galaxy NGC 4603, the most distant galaxy in which a special class of pulsating stars, called Cepheid variables, have been found. The Hubble Space Telescope's Wide Field and Planetary Camera was used to observe this galaxy. (STScI-PRC1999-19. J. Newman University of California, Berkeley, NASA)

Cosmic Explosions. The Hubble Space Telescope teamed up with x-ray and gamma-ray satellites, as well as with ground-based optical telescopes, to understand gamma-ray burst sources. Gamma-ray bursts may represent the most powerful explosions in the universe since the Big Bang. Before 1997, astronomers were frustrated because, although more than 2,000 bursts had been observed, it was impossible to determine whether these fireballs occurred in our own galaxy's halo or at cosmological distances. The discovery of x-ray afterglows by the BeppoSAX satellite, followed by the discovery of optical transients (from the ground), led to a confirmation of the cosmological nature of at least a subclass of bursts. The telescope provided images showing unambiguously that gamma-ray bursts actually reside in galaxies that were forming stars at high rates. Furthermore, by pinpointing a burst's precise location, the Hubble Space Telescope showed that, at least in one case, the gamma-ray burst was probably not associated with an active galactic nucleus. Figure 4–32 shows a gamma-ray burst's visible light component.

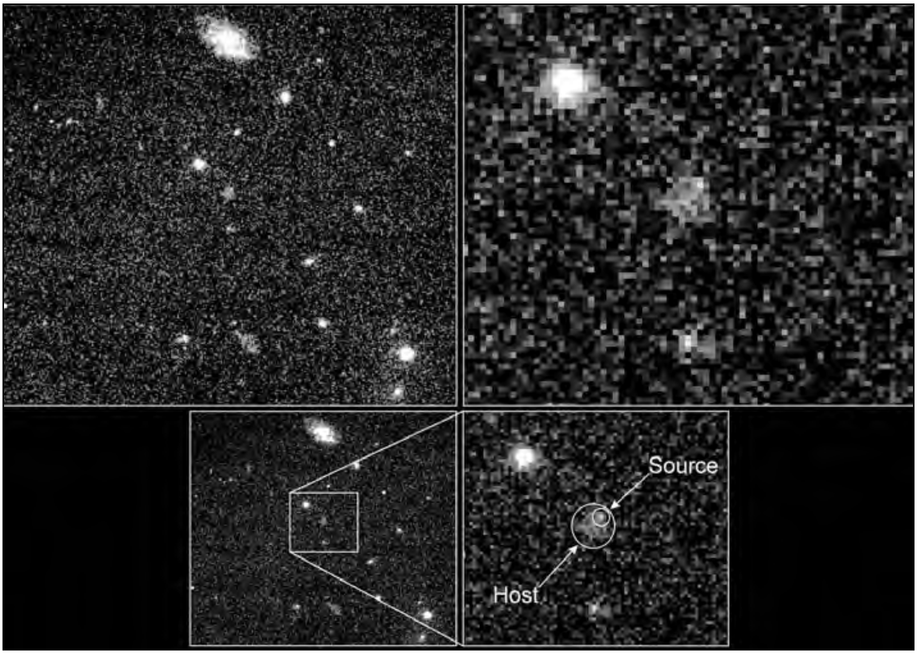

Figure 4–32. This image of gamma-ray burst GRB 970228 was acquired with the Space Telescope Imaging Spectrograph. In it, the fireball has faded to 1/500th its brightness since its discovery in March 1997 by ground-based telescopes. The Hubble Space Telescope continues to clearly see the fireball (center of picture) and a cloud of material surrounding it, considered to be its host galaxy. (PRC97-30. A. Fruchter, STScI, and NASA)

Cosmic Expansion Accelerating. In 1998, two teams independently found strong evidence that cosmic expansion was accelerating. This conclusion, based on distance measurements to Type Ia supernovae (if confirmed), also implied the existence of a cosmological constant, which contributed about 70 percent of the cosmic energy density. While many of the observations were made with the Keck telescope, the Hubble Space Telescope provided the resolution needed for the high-redshift supernovae, supernovae with light needing to be distinguished from that of the host galaxies. The Hubble Space Telescope's contribution was crucial in establishing that the more distant Type Ia supernovae are dimmer (by about 0.25 magnitude) than expected from the Hubble Law. Figure 4–33 shows Hubble Space Telescope images of three distant supernovae, stars which exploded and died billions of years ago.

Compton Gamma Ray Observatory

The CGRO was NASA's second orbiting Great Observatory. At more than 17 tons, the CGRO was the heaviest astrophysical payload ever flown at time of launch. The CGRO was the first satellite dedicated to observing gamma rays across a broad spectrum of energies. Scientists believe gamma rays are emitted during violent cosmic events, such as the formation of supernovae, quasars, and pulsars, and near black holes. NASA scientists used the CGRO to create a comprehensive map of celestial gamma-ray sources.[115]

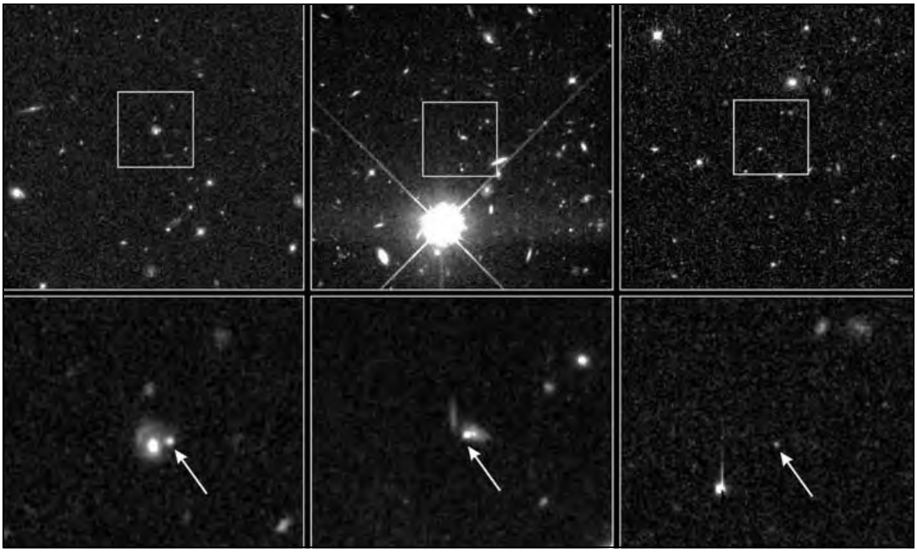

Figure 4–33. These images of distant supernovae, stars that exploded and died billions of years ago, were taken with the Hubble Space Telescope's Wide Field and Planetary Camera 2. Scientists use these faraway light sources to estimate if the universe was expanding at a faster rate long ago and is now slowing down. (PRC1998-02. P. Garnavich, Harvard-Smithsonian Center for Astrophysics, and NASA)

[115] Donna Drelick, "Compton Gamma Ray Observatory On Orbit Five Years," *Goddard News* 43 (April 1996): 3.

The project began in August 1977, when NASA released an announcement of opportunity for the Gamma Ray Observatory. In 1981, NASA selected TRW Inc. as the GRO contractor. Fabrication of flight components took place during 1985–1987, and in 1986, the GRO was designated a "Great Observatory." Detector module assembly took place during 1986–1988, and instrument integration during 1988–1989. The completed observatory was shipped to Kennedy Space Center in February 1990, to make final preparations for an April 1991 launch. On STS-37, the CGRO was launched April 5, 1991 on STS-37 aboard the Space Shuttle *Atlantis* and deployed on April 7 (see Figure 4–34). NASA renamed the observatory the Compton Gamma Ray Observatory on September 23, 1991, in honor of Dr. Arthur Holly Compton, winner of the Nobel Prize in physics for work on scattering of high-energy photons by electrons. This process was central to the gamma-ray detection techniques of all four of the observatory's instruments.

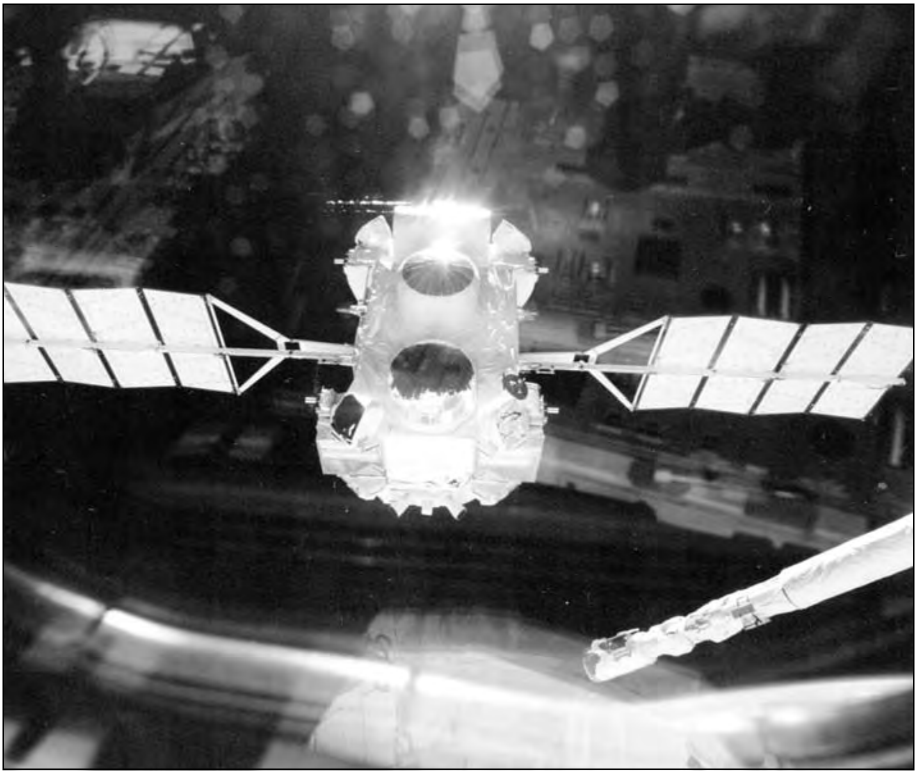

Figure 4–34. The Shuttle Atlantis *Remote Manipulator System releases the GRO during STS-37 deployment. Visible on the GRO as it drifts away from the robotic arm are its four instruments: the Energetic Gamma Ray Experiment (bottom), Imaging Compton Telescope (center), Oriented Scintillation Spectrometer Experiment (top), and Burst and Transient Source Experiment (at four corners). The GRO's solar array panels are extended and are in orbit configuration. The photo was taken through the aft flight deck window, which reflects some of the crew compartment interior. (NASA Photo No. STS-37-96-009)*

The CGRO was a NASA cooperative program. Germany had PI-responsibility for the Energetic Gamma Ray Experiment Telescope (EGRET), along with scientists at Goddard Space Flight Center, Stanford University, and Grumman Aerospace.[116] Germany also furnished hardware elements and provided co-investigator support for a second instrument, the imaging Compton Telescope (COMPTEL), developed as a joint venture of Germany, the Netherlands, the ESA, and the United States. Scientists at Marshall Space Flight Center developed the Burst and Transient Source Experiment (BATSE), and the U.S. Naval Research Laboratory developed the Oriented Scintillation Spectrometer Experiment (OSSE).

Dedicated to observing the high-energy universe, the CGRO was the heaviest astrophysical payload flown to date, weighing 35,000 pounds (15,875 kilograms) or 17.5 tons. The CGRO instruments alone weighed approximately 6 tons (5,400 kilograms) and were much larger and more sensitive than those on any gamma-ray telescope previously flown in space. The observatory's four instruments together detected a broad range of gamma rays. Their large size was necessary because the number of gamma-ray interactions that could be recorded was directly related to the mass of the detector. The number of gamma-ray photons from celestial sources was very small when compared to the number of optical photons. Large instruments were needed to detect a significant number of gamma rays in a reasonable amount of time. The combination of these instruments detected photon energies from 20,000 electron volts to more than 30 billion electron volts.[117] For each instrument, an improvement in sensitivity of more than a factor of 10 was realized compared to previous missions.[118] Figure 4–35 shows the location of the CGRO's instruments.

The CGRO mission objectives were to measure universe gamma radiation and to explore the fundamental physical processes powering this radiation. The following were the CGRO's observational objectives:

- Search for direct evidence of the synthesis of the chemical elements.
- Observe high-energy astrophysical processes occurring in supernovae, neutron stars, and near black holes.
- Locate gamma-ray burst sources.
- Measure the diffuse gamma-ray radiation for cosmological evidence of its origin.
- Search for unique gamma-ray-emitting objects.

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[116] "Compton Gamma Ray Observatory: Exploring the Mysteries of Time," NASA Facts On-Line, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/gro.htm* (accessed September 1, 2005).

[117] "About the Compton Gamma Ray Observatory," *http://heasarc.gsfc.nasa.gov/docs/cgro/cgro/* (accessed May 15, 2006).

[118] "NASA's Great Observatories," *http://www.nasa.gov/audience/forstudents/postsecondary/features/F_NASA_Great_Observatories_PS.html* (accessed May 15, 2006).

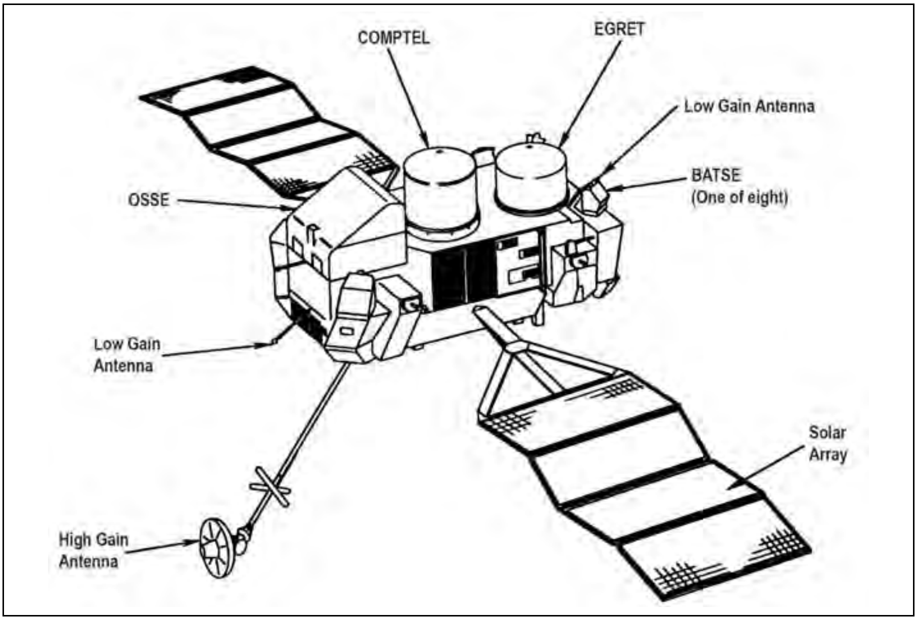

Figure 4–35. Compton Gamma Ray Observatory.

The observatory's scientific agenda included studies of the following energetic celestial phenomena: solar flares, cosmic gamma-ray bursts, pulsars, nova and supernova explosions, accreting black holes of stellar dimensions, quasar emission, and interactions of cosmic rays with the interstellar medium.[119]

The three-axis stabilized spacecraft had a zero momentum biased control system that used reaction wheels. Two solar arrays generated 4,500 watts of power (beginning of life), supplemented by three 50 Ahr nickel cadmium batteries. The hydrazine propulsion system carried 1,900 kilograms (4,198 pounds) of fuel with four 100-pound-force (445-newton) thrusters and eight 5-pound-force attitude control system thrusters. The S-band telecom system provided uplink at 1 kbps and downlink via the TDRS System at 256 kbps to 512 kbps. The S-band telecom system's 1.52-meter (5-foot) high-gain antenna was mounted on a 4.4-meter (14.4-foot) boom.

The CGRO operated successfully for nine years. During this period, the observatory's achievements were unprecedented, as discoveries of phenomena never before seen led scientists to gain new insights and pose more questions. The CGRO's instruments, taking advantage of a "target of opportunity," made the most sensitive, high-energy measurements ever of the Sun, gathering data from two X-class solar flares, the largest and most powerful type of solar flare.[120] The BATSE detected gamma-ray bursts at a higher rate and in more

[119] Rumerman, *NASA Historical Data Book, 1979–1988, Volume V,* pp. 404–406. Also "Universe Missions," *http://science.hq.nasa.gov/missions/universe.html* (accessed May 16, 2006).
[120] John J. Loughlin II, "Gamma Ray Observatory Grabs Target of Opportunity," *Goddard News* 37 (July 1991): 1.

detail than ever before.[121] After less than four months in space, the EGRET detected the most distant and luminous gamma-ray source ever seen, a quasar emitting a large flux of gamma rays, gamma rays with photon energies greater than 100 million electron volts. The luminosity or total energy emitted by the quasar was approximately 10 million times that of the total emission of the Milky Way. The quasar was a variable quasar, meaning that its intensity changed over time. The source should have been visible to two previous gamma ray missions during 1972–1973 and 1975–1982, according to the EGRET PI, but neither previous mission reported detection. Between 1982 and 1991, this quasar went from being undetectable to being one of the few, brightest objects in the gamma-ray sky. [122]

In August 1991, the satellite detected 117 gamma-ray bursts scattered throughout the sky. These were violent bursts coming from a location in the sky where there was no known source of x-rays or gamma rays. The outbursts were thought to originate in binary star systems containing an ordinary star in orbit with a highly compact star, either a neutron star or black hole. The outbursts were believed to be triggered when a large amount of material was suddenly released from a normal star and fell through the intense gravitational field of a compact star to its surface.[123] A few months later, on January 31, 1992, the EGRET detected the largest gamma-ray bursts yet; these "virtually blinded" its instruments. Dubbed the "Super Bowl burst," it was 10 times more energetic than any previous burst, more than 100 times brighter at its peak than the brightest steady source of gamma rays in the Milky Way, and more than 1,000 times brighter than any other known sources outside the Milky Way.[124] Data also indicated the possible occurrence of bursts much deeper in space than many had believed, far beyond the Milky Way galaxy. A two-year BATSE mapping survey showed that the bursts were evenly distributed in space, indicating they may have originated outside our galaxy.[125]

In 1993, the COMPTEL made three major discoveries. The instrument detected two radioactive isotopes, titanium 44 and aluminum 26 emissions. When these isotopes decayed, they left interstellar trails, called gamma-ray lines, which COMPTEL scientists traced to the supernovae that produced the emissions long ago. The third discovery identified the Orion nebula, an area of molecular clouds and star-forming regions, as a source of cosmic rays. Cosmic rays were discovered in 1911, but their source has eluded scientists.[126]

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[121] "NASA Science Instrument Observing Gamma-Ray Bursts," *NASA News* Release 91-81, May 28, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-081.txt* (accessed September 1, 2005).

[122] "NASA Observatory Detects Strongest Gamma Ray Source," *NASA News* Release 91-117, July 25, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-117.txt* (accessed September 1, 2005).

[123] "Compton Observatory Discovers New Energy Source," *Goddard News* 39 (September 1992): 4.

[124] "Findings Burst Gamma Ray Theories," *HQ Bulletin* (May 3, 1993): p. 3. Also, Michael Finneran, "NASA Satellite Shakes Theories on Gamma-Ray Bursts," *Goddard News* 40 (May 1993): 5.

[125] Finneran, "NASA Satellite Shakes Theories on Gamma-Ray Bursts," *Goddard News* 40 (May 1993): 5.

[126] "Gamma-Ray Observatory Produces Three Major Discoveries," *NASA News* Release 93-182, October 12, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-182.txt* (accessed September 1, 2005).

In early 1994, astronomers uncovered new evidence of gamma-ray bursts occurring in the far reaches of the universe. Evidence indicated that the gamma-ray bursts showed relative “time dilation,” an effect created by many of the bursts occurring so far away in the universe that time appeared to run slower in those far regions. Time dilation was a consequence of the general theory of relativity and the expansion of the universe. Thus, time intervals from very distant parts of the universe would be stretched as the gamma-ray bursts made their way across the expanse of space, which itself was expanding.[127]

On July 27, 1994, the BATSE detected an unusually bright x-ray source in the southern constellation Scorpius. Named X-ray Nova Scorpii, or GRO J1655-40, its x-ray emission rivaled those from two other sources, the Crab Nebula and Cygnus X-1. It also raised questions about how x-rays were produced in such objects.[128] The BATSE also detected indications of gamma-ray flashes above thunderstorms at a rate six times that of previous observations.[129]

In early December 1995, astronomers using the BATSE sighted a celestial object with sudden, violent eruptions unlike anything seen before. Since discovery, the “bursting pulsar,” exploded more than 2,000 times in blasts of x-rays, becoming the brightest source of x-ray emissions in the sky. The object did several things at once, both pulsing like the energy surrounding a black hole and bursting explosively like a star. It also oscillated and flickered, emitting x-rays 1 million times the power of the Sun. Scientists expected the strange bursting pulsar to die out within two weeks or, at most, two months.[130]

By the end of 1995, scientists had recorded more than 1,400 gamma-ray bursts, spread evenly across the entire sky. The CGRO also completed a new survey of the highest energy gamma-ray sources, demonstrating that about half were quasars with beams of energy pointed directly toward Earth but leaving the other half unidentified.[131]

On September 24, 1996, the BATSE detected the brightest gamma-ray burst that the CGRO mission had experienced when high-energy gamma radiation in the form of a colossal cosmic gamma-ray burst bombarded the BATSE’s eight detectors. This burst was the most intense that the BATSE had observed.[132] The next month, the BATSE detected four separate gamma-ray bursts in two groups coming in close succession, all from the same part of the

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[127] “Satellite Finds Imprint of Universe on Gamma-Ray Explosions,” *NASA News* Release 94-10, January 15, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-010.txt* (accessed September 1, 2005).

[128] “Compton Gamma-Ray Observatory Finds Bright New X-ray Source,” *NASA News* Release 94-140, August 24, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-010.txt* (accessed September 1, 2005).

[129] “Gamma Ray Flashes in Atmosphere More Common Than Thought,” *NASA News* Release 94-204, December 7, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-204.txt* (accessed September 1, 2005).

[130] “Bursting Pulsar Is ‘One Man Band,’” *HQ Bulletin,* (March 18, 1996): p. 3.

[131] *Aeronautics and Space Report of the President, Fiscal Year 1995 Activities* (Washington, DC: National Aeronautics and Space Administration), p. 18.

[132] “NASA Spacecraft Detects the Brightest Gamma-Ray Burst of Its Mission,” Space Science Features, Marshall Space Flight Center (September 26, 1996), *http://science.nasa.gov/newhome/headlines/ast26sep96_1.htm* (accessed September 1, 2005).

sky, with one burst lasting 23 minutes. This was puzzling because it differed from the typical detection rate of about one gamma-ray burst per day lasting about 10 to 30 seconds and randomly distributed across the sky.[133]

In April 1997, scientists announced the discovery of two unexpected clouds of antimatter in the Milky Way, which scientists called "antimatter annihilation radiation." The discovery, made with the OSSE, pointed to the existence of a hot fountain of gas filled with antimatter electrons rising from a region surrounding the center of the Milky Way. The nature of the furious activity producing the hot antimatter-filled fountain was unclear but could be related to massive star formation taking place near the large black hole at the center of the galaxy.[134]

On December 14, 1997, both the Italian-Dutch BeppoSAX satellite and CGRO detected a massive cosmic gamma-ray burst releasing one hundred times more energy than previously theorized, making it the most powerful explosion observed since the creation of the universe. The burst appeared to have released several hundred times more energy than an exploding star, until then the most energetic known phenomenon in the universe. Finding a large energy release during a brief period of time was unprecedented in astronomy, except for the Big Bang itself. Originating in a faint galaxy, scientists measured the release's distance at about 12 billion light years from Earth. The CGRO provided detailed measurements of the total brightness of the burst, designated GRB 971214, while BeppoSAX provided its precise location, enabling follow-up observations using ground-based telescopes and the Hubble Space Telescope.[135]

In June 1998, the BATSE on the CGRO and the Rossi X-ray Timing Explorer registered a series of bursts coming from a Soft Gamma Repeater (SGR), a neutron star emitting bursts of soft or low-energy gamma rays at irregular intervals. Unlike most one-time gamma-ray bursts, scientists believed SGRs to be just one short phase in the life of a magnetar, a neutron star with an extremely powerful magnetic field. If correct, SGR outbursts were caused by massive starquakes as the magnetic field wrinkled the star's crust—wrinkles only a few millimeters high but releasing more energy than all the earthquakes Earth had ever experienced. The new SGR triggered the BATSE 26 times during June 15–22, including 12 bursts on June 18. Each burst lasted 0.2 seconds, typical for an SGR. Another five bursts from the same area of the sky were recorded on June 17 and June 18, with the last burst peaking at almost 500,000 counts per second, making for a powerful source.[136]

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[133] "Astronomers Detect Never Before Seen Gamma-Ray Multi-Bursts," *NASA News* Release 96-261, December 17, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-261.txt* (accessed September 1, 2005).

[134] "Antimatter Clouds and Fountain Discovered in the Milky Way," *NASA News* Release 97-23, April 28, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-083.txt* (accessed September 1, 2005).

[135] "Most Powerful Explosion Since the Big Bang Challenges Gamma Ray Burst Theories," Goddard Space Flight Center Release 98-052 (HQ 98-75), May 6, 1998, *http://www.gsfc.nasa.gov/news-release/releases/1998/98-052.htm* (accessed August 29, 2005).

[136] "A Whole Lot of Shakin' Going On: Starquakes Lead To Discovery of First New Soft Gamma Repeater in 19 Years," Science@NASA, *http://science.nasa.gov/newhome/headlines/ast09jul98_1.htm* (accessed September 1, 2005).

To keep the CGRO in the correct orbit so it did not reenter Earth's atmosphere, the satellite received scheduled boosts to higher orbits. These boosts were necessary to compensate for orbit decay from the effect of solar activity on the ionosphere, which increased the atmospheric drag on the spacecraft and slowly pushed it toward Earth. The first reboost was accomplished in two phases: one ended in October 1993, and the second spanned November and December 1993. The October boost lifted the observatory's apogee to 280 miles (452 kilometers) from 214 miles (346 kilometers). The November-December boost nudged the spacecraft's perigee to 280 miles, making its orbit around Earth almost perfectly circular. The reboost extended the mission life of the observatory by five years.[137]

A second reboost took place in 1997 over a two-month period ending on June 3, 1997. Before the reboost, which included several rocket burns per week, the CGRO's altitude had slipped to 440 kilometers (273 miles) above Earth. The reboost raised the altitude to 515 kilometers (320 miles). Project scientists stated that this reboost would keep the satellite in orbit until perhaps 2007.[138]

Although the 1997 reboost allowed for possible continuation in orbit until 2007, gyroscope No. 3 began experiencing problems in 1999, and NASA engineers began planning for the observatory's reentry into Earth's atmosphere. NASA chose a controlled deorbit of the spacecraft because of safety concerns. The spacecraft was too large and heavy to burn up on reentry. When it reentered the atmosphere, large pieces most certainly would survive and hit Earth. Some pieces might be as large as 1 ton (907 kilograms) and might hit at 200 miles per hour (320 kilometers per hour). The debris field, or footprint, was estimated at approximately 16 miles wide by 962 miles long (26 kilometers by 1,552 kilometers).[139] NASA also feared that an uncontrolled reentry might occur over populated areas if an additional gyroscope failed. Edward Weiler, Office of Space Science Associate Administrator, stated that NASA estimated there was a one in ten thousand chance a human life could be lost if the spacecraft reentered the atmosphere on its own.[140]

The controlled reentry occurred over a remote region of the Pacific Ocean, after four engine burns between May 30 and June 4, 2000, which gradually lowered its orbit. The CGRO fell to Earth on June 4 after nine years in orbit. Debris landed in an area of ocean approximately 2,400 miles (3,962 kilometers) southeast of Hawaii.[141] See Table 4–49 for further mission details.

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[137] "NASA Succeeds With Gamma-Ray Observatory Reboost," *NASA News* Release 93-224, December 20, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-224.txt* (accessed August 31, 2005).

[138] "Successful Reboost of Compton Gamma Ray Observatory," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/epo/news/reboost.html* (accessed September 1, 2005).

[139] "Goddard Team Prepares To Deorbit CGRO," *Goddard News* (May 26, 2000), *http://www.gsfc.nasa.gov/ftp/gnewsissues/052600/052600.htm* (accessed August 31, 2005).

[140] Keith Cowing "Compton Gamma Ray Observatory Crashes on Earth," SpaceRef.com, *http://www.spaceref.com/news/viewnews.html?id=153* (accessed August 31, 2005).

[141] "Compton Gamma Ray Observatory Safely Returns to Earth," Final Status Report: June 4, 2000, *ftp://ftp.hq.nasa.gov/pub/pao/media/2000/CGRO_status_final_06-04.txt* (accessed August 31, 2005). Also, Cowing "Compton Gamma Ray Observatory Crashes on Earth," SpaceRef.com, *http://www.spaceref.com/news/viewnews.html?id=153* (accessed August 31, 2005).

Advanced X-ray Astrophysics Facility

The AXAF, renamed Chandra in December 1998, was NASA's third Great Observatory. Launched on STS-93 *Columbia* on July 23, 1999, the spacecraft's development took place during a 20-year period. This observatory covers the x-ray portion of the electromagnetic spectrum, observing such objects as black holes, quasars, and high-temperature gases.

Two astrophysicists, Riccardo Giacconi and Harvey Tananbaum, proposed the AXAF to NASA in 1976. The project received funding in 1977, and preliminary work began at Marshall Space Flight Center and the SAO in Cambridge, Massachusetts.[142] At the same time, Marshall Space Flight Center was preparing to launch the first High Energy Astronomy Observatory (HEAO-1) that gave scientists their best views to date of the universe in x-rays, gamma rays, and cosmic radiation. The next spacecraft in the series, HEAO-2, was launched in 1978. (HEAO-2 was also called the Einstein Observatory because it was launched during the centennial year of Albert Einstein's birth.) HEAO-2, the predecessor to AXAF, was the first imaging x-ray telescope and provided the first true images of x-ray-emitting objects.[143]

Design and development of AXAF began in the early 1980s with advanced technology development contracts to Perkin-Elmer and Itek Corporation to develop advanced x-ray mirrors. In 1984, NASA solicited, received, and reviewed, proposals for scientific instrument development.[144] In March 1985, NASA announced the selection of the scientific investigators whose projects would be included on the proposed AXAF. Those selected included instrument PIs to design and fabricate scientific instrumentation for placement in the telescope focal plane, interdisciplinary scientists to provide expertise on x-ray astrophysics and other fields of astronomy, and a telescope scientist to guide telescope fabrication. The investigators, as members of the AXAF science working group, would provide scientific and technical guidance throughout the project and would receive a specified amount of time to use the telescope during its first 30 operational months.[145]

In January 1988, NASA released a proposal to select a prime contractor for the AXAF, envisioned as a long-duration scientific satellite—the third of NASA's projected orbiting Great Observatories. The proposal was for a satellite to be serviced by Space Shuttle or Space Station crews. The AXAF would study high-energy emissions associated with quasars, spinning neutron stars, and black holes, providing valuable information about these phenomena

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[142] “”CXC Biographies: Dr. Harvey Tananbaum, Director, Chandra X-ray Center,” *http://chandra.harvard.edu/press/bios/tananbaum_bio.html* (accessed April 26, 2006).

[143] “History of the Chandra X-Ray Observatory,” *http://www.spacetoday.org/DeepSpace/Telescopes/GreatObservatories/Chandra/ChandraHistory.html* (accessed September 28, 2005).

[144] *Aeronautics and Space Report of the President, 1984 Activities*, (Washington, DC: National Aeronautics and Space Administration, 1985), p. 17.

[145] *Astronautics and Aeronautics, 1985; A Chronology*, (Washington, DC: National Aeronautics and Space Administration Special Publication-4025, 1988), pp. 39–40.

and serving as an important new tool for basic research in plasma physics. The AXAF would collect data on the various forms of "dark matter" in the universe, which might help investigators determine whether the universe was an open or closed loop. At the time, launch was foreseen to occur as early as 1995. The orbiting observatory would be 14 feet (4.3 meters) in diameter, 45 feet (13.7 meters) long, and would weigh 12 tons to 15 tons (10,886 kilograms to 13,608 kilograms). The observatory would be placed into a circular orbit 320 miles above Earth and would operate for about 15 years.[146]

In spring of 1988, Congress authorized the AXAF as a "new start" in NASA's FY 1989 budget, formally moving the program out of the preparatory stage into design and development. During the first year, work focused on developing the high resolution mirror assembly that would focus the x-rays on a complement of scientific instruments.[147] A specially designed x-ray calibration facility was constructed to assure the mirrors met design specifications.[148] In August 1988, NASA selected TRW, Inc. to be the prime contractor for AXAF construction and integration. TRW, Inc. had earlier been the prime contractor for the HEAO spacecraft.[149]

NASA selected the SAO in March 1991 to design, develop, and operate the science support center for the AXAF. The science support center would be the primary telescope focal point for the international science and observer community, The science support center would develop and oversee an observation program for the telescope and manage receipt and distribution of the collected data. The facility would also offer support during development of the telescope and its instruments for testing and verification of ground support systems, calibration of the instruments, and orbital operations relating to science instrument data.[150]

In 1992, in response to pressure to reduce costs, the AXAF was restructured. The restructured mission included two highly-focused smaller missions consisting of a large imaging spacecraft (AXAF-I) and a smaller spectroscopy spacecraft (AXAF-S) in place of the original single, larger observatory.[151] NASA reduced the number of mirrors on AXAF-I from twelve to eight and decided to use only four of the six proposed scientific instruments.[152] The planned orbit was changed from low to high Earth elliptical orbit to preserve the facility's scientific capability.[153] The orbit change meant that the AXAF could not be serviced by the Space Shuttle, and the change

[146] *Astronautics and Aeronautics, 1986–1990; A Chronology*, (Washington, DC: National Aeronautics and Space Administration Special Publication-4027, 1997), p. 147.
[147] "Advanced X-Ray Astrophysics Facility Development," Office of Space Science and Applications Fiscal Year 1991 Estimates, Budget Summary, p. RD 3-13.
[148] "National Aeronautics and Space Administration Fiscal Year 1997 Estimates," p. SI-14.
[149] *Aeronautics and Space Report of the President, 1988 Activities* (Washington, DC: National Aeronautics and Space Administration, 1990), p. 2.
[150] "Smithsonian Astrophysical Observatory Wins AXAF Contract," *NASA News* Release 91-46, March 21, 1991.
[151] *Aeronautics and Space Report of the President, Fiscal Year 1992 Activities* (Washington, DC: National Aeronautics and Space Administration, 1993), p. 12.
[152] The X-Ray Spectrometer (XRS), originally planned for AXAF, became the prime instrument on the fifth Japanese x-ray astronomy satellite, ASTRO-E. Launched in 2000, ASTRO-E failed to reach orbit.
[153] "About the Chandra," *http://chandra.harvard.edu/launch/mission/axaf_mission3.html* (accessed September 28, 2005).

placed the observatory above Earth's radiation belts for most of its orbit. Experts estimated that the mission changes and elimination of maintenance costs and expenses of developing new instruments for later placement into the observatory would reduce development costs about $600 million and operating costs by an additional $1 billion.[154] In 1993, Congress directed the cancellation of the AXAF-S, the second smaller observatory.

Completion of the first and largest of the AXAF's eight mirrors took place in August 1994. Built by Hughes Danbury Optical Systems, this mirror would form part of the high-resolution mirror assembly, the central optical component in the 10-meter (32.8-foot) telescope.[155] The 48-inch (122-centimeter)-diameter mirror was the largest ever made to collect x-rays in space. The mirror's imaging quality for high-energy x-rays was two times better than originally specified, resulting in significant scientific capability improvement.[156]

In January 1995, measuring and polishing of the eight critical x-ray reflecting mirrors, the most precise optics ever developed for imaging x-rays, were completed four months ahead of schedule at Hughes Danbury Optical Systems. Measurements indicated that the shape and smoothness exceeded program goals; they had an average smoothness of 3 angstroms, the width of just three atoms. Critical measurements were made using several techniques and pieces of equipment to eliminate the possibility of a flaw in the measuring equipment. The mirrors were then shipped to Eastman-Kodak for alignment and to the Optical Coating Laboratory, Inc., for iridium coating. The mirrors were returned to Kodak, integrated, and aligned into the High Resolution Mirror Assembly.[157] Assembly was completed between May and October 1996. By the end of March 1997, the mirrors had successfully completed initial testing at Marshall Space Flight Center's X-ray Calibration Facility. The test results showed that the telescope's focus, with a resolution 10 times greater than previous x-ray telescopes, was "very clear, very sharp."[158] After a second phase of successful testing of the observatory's science instruments, the mirrors were shipped in May to TRW, Inc. in California, where the telescope was assembled and tested (see figure 4–36).[159] Assembly was completed in March 1998. In April,

[154] Warren E. Leary, "Satellite Will Offer X-ray View of the Cosmos," *New York Times,* (March 31, 1998: B9, B12, reprinted at *http://www.physics.ohio-state.edu/~wilkins/writing/Assign/topics/xray-telescope.html* (accessed September 28, 2005).

[155] In late 1989, Perkin-Elmer (the company that had manufactured the Hubble primary mirror and which had the AXAF development contract in the early 1980s) sold its optical division to Hughes Danbury Optical System, a subsidiary of Hughes Aircraft. Chaisson, *The Hubble Wars*, p. 150.

[156] "NASA Completes First Mirror for AXAF Observatory," *NASA News* Release: 94-139, August 24, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-139.txt* (accessed September 28, 2005).

[157] "NASA's X-ray Telescope Mirrors Completed Ahead of Schedule," *NASA News* Release 95-10, January 30, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-10.txt* (accessed September 28, 2005).

[158] "Advanced X-Ray Telescope Mirrors Provide Sharpest Focus Ever" Chandra Press Room, Release 97-48, March 20, 1997, *http://chandra.harvard.edu/press/97_releases/press_032097.html* and *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-048.txt* (accessed May 16, 2006).

[159] "Testing Shows X-Ray Telescope Mirrors Give Sharp Focus," *Marshall Star* 37 (March 26, 1997): 2, *http://marshallstar.msfc.nasa.gov/3-26-97.pdf* (accessed October 1, 2005). Also Joy Carter, "Mirrors Depart Center: AXAF Assembly Next," *Marshall Star* 37 (May 7, 1997): 1, *http://marshallstar.msfc.nasa.gov/5-07-97.pdf* (accessed October 1, 2005).

NASA announced a contest to select a new name for the observatory, and in December announced “Chandra” as the new name in honor of the late Indian-American Nobel Laureate Subrahmanyan Chandrasekhar. After delays to carry out additional testing at TRW, Inc. and to correct some problems, the Chandra was shipped to Kennedy Space Center on February 4, 1999.[160] The Chandra was launched on July 23, 1999.

Figure 4–36. Chandra Optical Bench Assembly at TRW.
(Northrop Grumman Space Technology)

Chandra Observatory

The Chandra X-Ray Observatory has three major assemblies: the spacecraft, telescope, and science instrument module (see Figure 4–37). The spacecraft module contains computers, communication antennae, and data recorders to transmit and receive information between the observatory and ground

[160] “Chandra X-Ray Observatory Arrives at KSC for Processing,” *NASA News Release On-Line*, Kennedy Space Center Release no. 10-99, February 4, 1999, *http://www-pao.ksc.nasa.gov/kscpao/release/1999/10-99.htm* (accessed September 28, 2005).

stations. The on-board computers and sensors—with ground-based control center assistance—command and control the observatory and monitor observatory health. The spacecraft module also provides rocket propulsion to move and aim the entire observatory. The module contains an aspect camera that tells the observatory its position and orientation relative to the stars and a Sun sensor that protects the module from excessive light. Two three-panel solar arrays provide the observatory with 2,350 watts of electrical power and charge three nickel-hydrogen batteries that supply backup power.

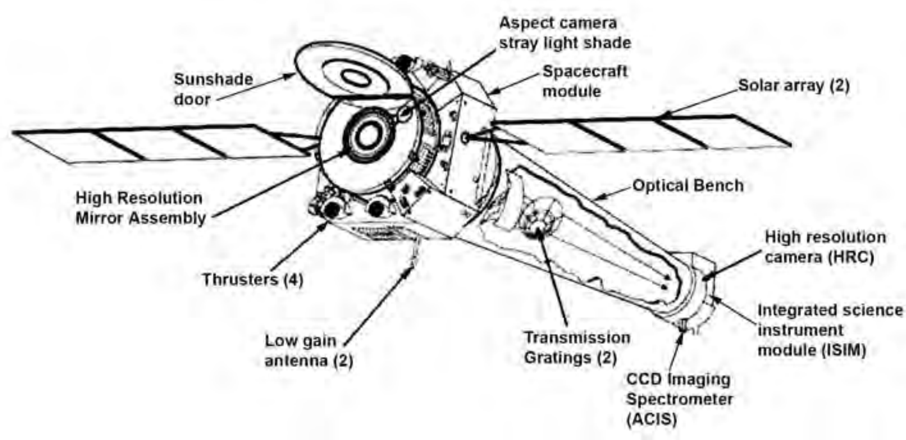

Figure 4–37. Chandra X-Ray Observatory.

The High-Resolution Mirror Assembly is the heart of the telescope system. Since high-energy x-rays would penetrate a normal mirror, special cylindrical mirrors were created. The two sets of four nested mirrors resemble tubes within tubes. Incoming x-rays graze off the highly polished mirror surfaces which focus the x-rays to a tiny spot, about half the width of a human hair, on the focal plane about 30 feet (9 meters) away. The focal plane science instruments, the Advanced Charged Couple Imaging Spectrometer (ACIS) and High Resolution Camera (HRC), capture sharp images formed by the mirrors and provide the following information about incoming x-rays: number, position, energy, and arrival time. The mirrors are the largest of their kind and the smoothest ever created. The largest of the eight mirrors is almost 4 feet (1.2 meters) in diameter and 3 feet (0.9 meter) long. Assembled, the mirror group weighs more than one ton (907 kilograms).

The mirror assembly is encased in the cylindrical telescope portion of the observatory. The entire length of the telescope is covered with reflective multilayer insulation that helps heating elements inside the unit keep a constant internal temperature. By maintaining a precise temperature, the mirrors within the telescope are not subject to expansion and contraction—thus ensuring greater observation accuracy.

The assembled mirrors were tested at Marshall Space Flight Center's X-Ray Calibration Facility. The calibration facility verified that the observatory could differentiate between objects separated by one-half arc second. With its combination of large mirror area, accurate alignment, and efficient x-ray detectors, the Chandra has eight times greater resolution and is 20 to 50 times more sensitive than any previous x-ray telescope.[161]

Two additional science instruments provide detailed information about the x-ray energy, the Low Energy Transmission Grating (LETG) and High Energy Transmission Grating (HETG) spectrometers. These grating arrays can be flipped into the path of the x-rays just behind the mirrors, where they redirect (diffract) the x-rays according to their energy. The HRC or ACIS measure x-ray position to determine the exact energy. The science instruments have complementary capabilities to record and analyze x-ray images of celestial objects and probe their physical conditions with unprecedented accuracy.

The focal plane instruments are mounted on the Science Instrument Module (SIM). The SIM contains mechanisms to move the science instruments in and out of the focal plane, insulation for thermal control, and electronics to control the operation of the science instruments through the spacecraft communication, command, and data management systems.

The science instruments are controlled by commands transmitted from the Operations Control Center in Cambridge, Massachusetts. A preplanned sequence of observations is uplinked to the Chandra and stored in the on-board computer for later execution.

Data collected with Chandra observations is stored on a recorder for later transmission to the ground every 8 hours during regularly scheduled DSN contacts. This data is transmitted to JPL and then to Operations Control at the Chandra X-ray Center (CXC) in Cambridge, Massachusetts, for processing and analysis by scientists.[162] Table 4–50 provides further mission details.

Space Infrared Telescope Facility

The SIRTF (renamed the Spitzer Space Telescope after its 2003 launch) was the fourth and final Great Observatory. It fills in a gap in wavelength coverage not available from the ground—the thermal infrared. The SIRTF was launched into space by a Delta rocket on August 25, 2003.

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[161] "The World's Most Powerful X-ray Telescope," STS-93 Press Kit, updated July 8, 1992, p. 21, *http://jsc.nasa.gov/history/shuttle_pk/pk/Flight_095_STS-093_Press_kit.pdf* (accessed September 28, 2005).

[162] "About Chandra: Science Instruments," *http://chandra.harvard.edu/about/science_instruments.html* (accessed September 28, 2005).

The SIRTF (which originally stood for the Shuttle Infrared Telescope Facility) was first proposed in 1979 in "A Strategy for Space Astronomy and Astrophysics for the 1980s" published by the National Research Council of the National Academy of Sciences. It was envisioned as an astrophysics facility to be developed for the Spacelab. In 1983, NASA issued an announcement of opportunity (AO) to build instruments and conduct observations with a large Shuttle-based telescope. At the time, the first flight was expected to occur around 1990, followed approximately a year later by a second flight.

The SIRTF AO coincided with launch of the international Infrared Astronomy Satellite (IRAS) in January 1983, the first infrared satellite mission. Due largely to its impressive early science returns, NASA amended the AO in September 1983 to include "the possibility of a long duration [free-flyer] SIRTF mission." The flight of a Shuttle-based infrared telescope in 1985 showing that the Shuttle vehicle released considerable contaminating infrared emissions helped NASA decide to proceed with a free-flying observatory. The name of the facility was changed to the Space Infrared Telescope Facility, to reflect its new design.[163]

In 1989, the National Research Council of the National Academy of Sciences commissioned the Astronomy and Astrophysics Survey Committee (AASC), consisting of members from the astronomy and astrophysics communities, to recommend the most significant ground- and space-based initiatives for the 1990s. The committee, which became known as the Bahcall Committee after its chairman, John Bahcall, released its 1991 report, *The Decade of Discovery in Astronomy and Astrophysics,* or the Bahcall Report. The report emphasized the importance of the 1-micron to 1,000-micron infrared and submillimeter portion of the electromagnetic spectrum for studying some of the most critical problems of astrophysics. The report also cited the advances made in infrared detector technology. It also recommended that the SIRTF be "the highest priority for a major new program in space-based astronomy" and the culmination of NASA's Great Observatory program. This telescope, the Executive Summary said, "would be almost a thousand times more sensitive than earth-based telescopes operating in the infrared."[164] The intent was to launch the facility early enough to allow the facility's science to overlap with the science produced by Hubble and AXAF. The report listed four research areas in which the SIRTF was expected to make scientific contributions: 1) formation of planets and stars; 2) the origin of energetic galaxies and quasars; 3) distribution of matter and galaxies; and 4) formation and evolution of galaxies.

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[163] "Early History," Spitzer Space Telescope, *http://www.spitzer.caltech.edu/about/earlyhist.shtml* (accessed April 26, 2006).

[164] National Research Council, Commission on Physical Sciences, Mathematics, and Applications, "Executive Summary" in *The Decade of Discovery in Astronomy and Astrophysics*, (Washington, DC: National Academy Press, 1991), *http://www.nap.edu/execsumm/0309043816.html* (accessed April 26, 2007). (Book available at *http://darwin.nap.edu/books/0309043816/html.*)

Soon after Bahcall Report publication, severe pressures on NASA's budget led to SIRTF, and other mission, redesign. The facility had two significant rescopings within five years, changing from a massive observatory with development costs exceeding $2.2 billion and a planned launch on a Titan launch vehicle to a more modest Delta-launched observatory costing approximately $400 million. Scientists and engineers redesigned the SIRTF with the goal of reducing the cost of every element—the telescope; instruments; spacecraft; ground system; mission operations; and project management. The SIRTF Science Working Group identified a handful of the most compelling problems in modern astrophysics where the SIRTF could make the greatest contributions. The SIRTF's primary scientific areas of focus were the following: protoplanetary and planetary debris disks; brown dwarfs and super planets; ultraluminous galaxies and active galactic nuclei; and the early universe–deep surveys.[165] An important feature of SIRTF redesign was to abandon the idea of placing the observatory into Earth orbit and, instead, insert the facility into an Earth-trailing heliocentric orbit, an orbit where the facility would drift behind Earth while it circles the Sun.[166]

Following the SIRTF's last redesign in 1994, the Committee on Astronomy and Astrophysics, a joint activity of the National Research Council's Space Studies Board and the Board on Physics and Astronomy, established a SIRTF Task Group. NASA asked the group to assess the scientific capabilities of the redesigned facility. The Task Group concluded in its report sent to NASA in April 1994 that the facility's science capabilities remained "unparalleled" in its potential for addressing the areas discussed in the Bahcall Report and still "merits the high-priority ranking it received in the Bahcall Report."[167]

In June 1996, NASA awarded three contracts for facility development. Lockheed-Martin Missiles and Space and Ball Aerospace & Technologies Corporation were chosen to team with JPL to design, develop, test, and integrate the SIRTF. JPL managed the SIRTF project for NASA.[168]

On March 25, 1998, NASA Administrator Goldin authorized the start of work on the SIRTF, signaling the start of the facility design and development phase. The SIRTF was then scheduled for launch in December 2001. The design and development cost cap was $458 million. To add to Lockheed Martin's and Ball Aerospace's responsibility for mission elements, the SAO, Cornell University, and the University of Arizona were

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[165] Office of Space Science, Science Aeronautics and Technology "FY 1998 Estimates, Budget Summary," pp. SAT 1-19–SAT 1-20.

[166] "Innovations: Clever Choice of Orbit," Spitzer Space Telescope, *http://www.spitzer.caltech.edu/about/orbit.shtml* (accessed April 26, 2006).

[167] "Report of the Task Group on SIRTF [Spitzer] & SOFIA," Sent to NASA April 21, 1994, *http://www.spitzer.caltech.edu/about/tgss.shtml* (accessed April 26, 2007).

[168] "Contracts Awarded for Space Infrared Telescope Facility," Jet Propulsion Laboratory, June 24, 1996, *http://www.jpl.nasa.gov/releases/96/sirtfcon.html* (accessed April 26, 2007).

providing the three science instruments. The SIRTF Science Center at the California Institute of Technology would receive and process JPL data and work with the astronomy community.[169]

Ulysses

Ulysses was the first mission to study the environment of space above and below the Sun's poles and the first mission to give scientists a look at the variable effect of the Sun on the space surrounding it.[170] The primary goal of Ulysses was to characterize the heliosphere as a function of solar latitude, specifically the relationship between the Sun and its magnetic field and particle emissions (solar wind and cosmic rays), affording a better understanding of the effect of solar activity on Earth's weather and climate.

Ulysses was based on a proposed project in the late 1950s called "Out of Ecliptic," which was to have been a two-spacecraft operation with one spacecraft furnished by the United States and the second furnished by the ESA. Between 1977 and 1979, the project name was changed to the International Solar Polar Mission (ISPM). In 1979, NASA and the ESA signed a memorandum of understanding for the mission. Delays in Shuttle development and concerns over the effectiveness of the inertial upper stage led the U.S. House Appropriations Committee to recommend in the 1980 Supplemental Appropriations Bill that the mission be terminated. In 1981, budget cuts led NASA to cancel the U.S. spacecraft contribution to the mission, which was restructured to a single ESA spacecraft mission. It was the first time NASA had withdrawn from an international agreement. The cancellation caused such an uproar that the United States agreed to furnish transportation for the ESA spacecraft.[171] In 1984, the mission was renamed the Ulysses project.

In its final configuration, the ESA provided the spacecraft, which was built by Dornier Systems, Germany, and managed the mission operations. NASA provided the Space Shuttle and the inertial upper stage and payload assist module to put Ulysses in its correct out-of-ecliptic orbit. The U.S. Department of Energy supplied the radioisotope thermoelectric generator that powered the spacecraft. Teams from universities and research institutes in Europe and the United States provided the 11 science instruments.

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[169] "NASA Starts Work on New Space Infrared Telescope Facility," Jet Propulsion Laboratory, March 25, 1998, *http://www.jpl.nasa.gov/releases/98/sirtfgo.html* (accessed April 26, 2006).

[170] "Ulysses Factsheet," ESA Space Science, *http://www.esa.int/esaSC/SEMUBG1A6BD_index_0.html* (accessed September 22, 2005).

[171] John Naugle, comments on chapter 4, Space Science, of *NASA Historical Data Book, 1989–1998*. Also "Ulysses Mission Operation Report," Office of Space Science and Applications, Report no. S-448-41-90-01, p. 1. (NASA History Office Electronic Document, Record no. 30797).

Ulysses was scheduled to launch in 1986, but it was another victim of the *Challenger* accident and elimination of the Centaur upper stage. The launch took place in October 1990 using the Shuttle and both an inertial upper stage and a payload assist module.

After launch, a combination of solid-fuel motors propelled Ulysses toward Jupiter. Ulysses arrived at Jupiter on February 8, 1992, to begin the gravity-assist maneuver that bent the spacecraft's flight path downward and away from the ecliptic plane. This put the spacecraft into its unique solar orbit. Ulysses passed over the Sun's south pole in 1994 and the north pole in 1995, and the spacecraft began its second complete orbit of the Sun in 1998.[172] Although scientific observations at Jupiter on the way to the Sun were not a primary objective, scientists used the opportunity to study Jupiter's magnetosphere. The results exceeded all expectations. The spacecraft's path took it to areas where earlier spacecraft (Pioneer 10, Pioneer 11, Voyager 1, and Voyager 2) had not flown, and its instruments produced a wealth of new information relating to the Jovian magnetosphere.

The events of greatest scientific interest occurred when Ulysses was at or higher than 70 degrees latitude at both the Sun's south and north poles. The phenomena being studied were strongly influenced by the 11-year solar cycle.

During Ulysses' primary mission, which covered half of the solar cycle, the spacecraft passed over the Sun's southern pole and then flew northward until it passed over the Sun's northern pole, surveying both polar regions for the first time (see Figure 4–38). On June 26, 1994, Ulysses reached 70° S, where the spacecraft began four months of high-latitude observations of the complex forces in the Sun's corona. Ulysses passed over the solar south pole at a distance of 350 million kilometers (217 million miles) on September 13, 1994, and it passed over the solar north pole at a distance of 140 million kilometers (87 million miles) on July 31, 1995, at its maximum latitude of 80.2° north of the Sun's equator.[173] When the spacecraft reached the summit of its trajectory over the Sun, Ulysses had traveled about 1.86 billion miles (3 billion kilometers).[174] Scientists learned that the Sun has a uniform magnetic field over the poles and lacks the theoretical "cosmic-ray funnel" thought to allow easy access of cosmic rays into the polar regions. Data also revealed that the gas in the heliosphere consists principally of energetic atoms from which one or more electrons has been removed to form ions. These ions become positively charged when they lose their electrons. In addition, three classes of charged particles were identified from their energy and place of origin. Scientists also found that the space between the Sun's equator and poles could be divided into distinct regions, just as Earth could be divided into tropical, temperate, and arctic zones.

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[172] "Ulysses Solar Polar Mission," *http://www.nasa.gov/centers/jpl/missions/ulysses.html* (accessed August 25, 2005).

[173] "Solar and Deep Space Probe Programs and Primary Mission Achievements, Japanese Aerospace Exploration Agency, *http://spaceinfo.jaxa.jp/note/tansa/e/tan9907_satwrld05_e.html* (accessed August 15, 2005).

[174] "Ulysses Climbs to Highest Latitude over Sun's Northern Pole," July 1995, *http://ulysses.jpl.nasa.gov/pdfs/highestnlatjul95.pdf* (accessed April 28, 2006).

The primary mission ended on September 29, 1995, when the spacecraft completed the northern polar pass. Ulysses then began traveling back to Jupiter's orbit, the farthest point from the Sun, reaching the planet on April 17, 1998. Ulysses began its second solar orbit and, as it started looping back toward the Sun, revisited the Sun's south pole in 2000 and north pole in 2001.[175] Aboard Ulysses. SWICS measurements reported in May 1996 found that helium-3, a lighter isotope of the element, had increased a "surprisingly small" amount since universe formation, allowing a more precise estimate of the amount of dark matter in the universe. Scientists believed that as much as 90 percent of the universe consisted of dark matter.[176] During March and April of 1997, scientists had the opportunity to use the Ulysses spacecraft's unique, high-latitude orbit to gain understanding of changes in comet Hale-Bopp as it neared the lower latitudes of the Sun while spewing its outer layers of gas and dust. The Ulysses Comet Watch group, a collaboration between JPL and the University of Colorado, provided worldwide observations of the returning comet as it descended from the polar regions of the Sun. The Ulysses group watched for changes in the comet's narrower, paler plasma tail, which consisted of ionized gas emitted by the comet and picked up by the magnetic field being swept along by the solar wind.[177] According to observations, the plasma tail of the comet was found to be surprisingly structureless at high latitude, and a tail disconnection was observed on May 7–May 8, 1997.[178]

The capture of a gamma-ray flare from a magnetic star was a highlight of 1998. On August 27, 1998, Ulysses and other spacecraft with high-energy radiation detectors in space observed a gamma-ray burst located in the constellation Aquila (20,000 light years away). Only Ulysses measured the magnitude of the event, which was twice that of any other recorded burst. The star, SGR1900+14, was a "magnetar" (for magnetic star), a class of objects with the strongest magnetic fields known in the universe. SGR1900+14 was thought to have a magnetic field about a thousand trillion times stronger than Earth's magnetic field and about one thousand times stronger than any found elsewhere in the universe.[179] This secondary phase lasted until December 2001. Table 4–51 lists mission milestones.

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[175] Diane Ainsworth, "Ulysses Completes First Full Orbit Around the Sun," *Universe*, Jet Propulsion Laboratory, 28 (May 1, 1998): 1 (NASA History Office Folder 33866). Also Diane Ainsworth, "Ulysses Finds Surprises During First Solar Orbit," *Universe*, Jet Propulsion Laboratory, 26 (January 12, 1996): 5; "Ulysses Factsheet," ESA, *http://www.esa.int/esaSC/SEMUBG1A6BD_index_0.html* (accessed September 22, 2005).

[176] "Ulysses Measurements Give New Clues to Dark Matter," Jet Propulsion Laboratory, May 16, 1996, *http://ulysses.jpl.nasa.gov/pdfs/heliummay96.pdf* (accessed April 28, 2006).

[177] "Ulysses Scientists Begin Capturing Unique View of Hale-Bopp," Jet Propulsion Laboratory, March 1997, *http://ulysses.jpl.nasa.gov/news/comet_studies.html* (accessed April 28, 2006).

[178] "Ulysses Scientific Results: Fall 1997," *http://ulysses.jpl.nasa.gov/pdfs/results-97.pdf* (accessed April 28, 2006).

[179] "Ulysses Captures Gamma-Ray Flare from Shattered Star," Jet Propulsion Laboratory, October 1, 1998, *http://ulysses.jpl.nasa.gov/pdfs/ulygamburstoct98.pdf* and "Ulysses Captures Gamma-Ray Flare from Magnetic Star," *http://ulysses.jpl.nasa.gov/pdfs/ulss98-12.pdf* (accessed April 28, 2006).

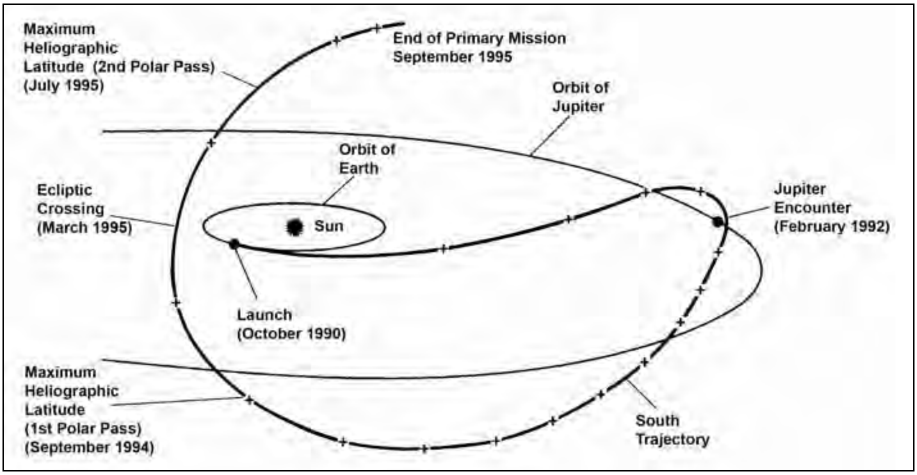

Figure 4–38. Ulysses Primary Mission.

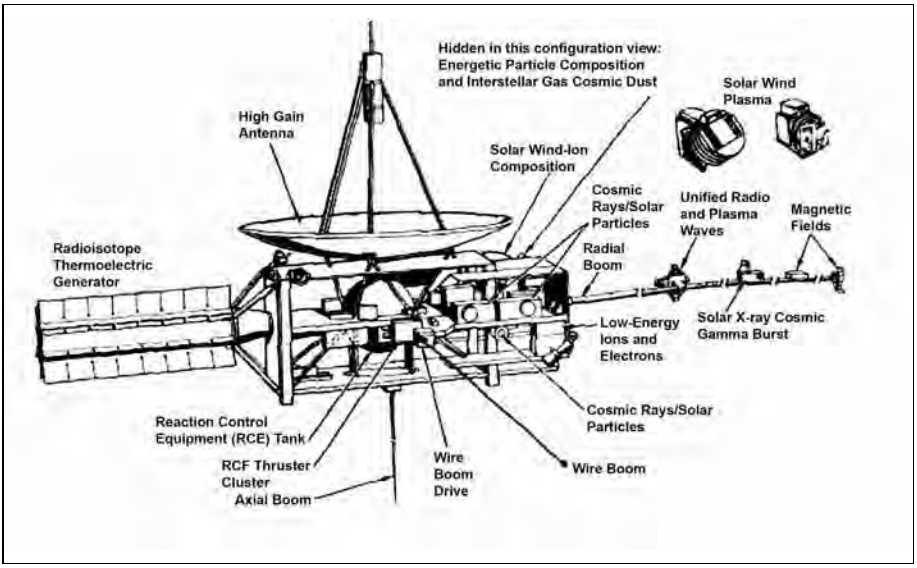

Figure 4–39. Ulysses Configuration.

The spacecraft's systems and scientific instruments were contained within a main spacecraft bus (see Figure 4–39). Ulysses maintained communication with Earth via a parabolic high-gain antenna. After release from *Discovery*'s cargo bay, the spacecraft deployed a radial boom carrying several experiment sensors as well as a dipole wire boom and an axial boom, which served as antennae for a radio-wave/plasma-wave experiment.

The spacecraft's main computer was the on-board data handling system, responsible for processing commands received from the ground as well as managing and passing on all data from each Ulysses science instrument. Each of the system's two tape recorders could store 45.8 million bits of data—representing 16 hours to 64 hours of data-taking, depending on how often data was sampled.

The attitude control system was responsible for determining the spacecraft's attitude in space, as well as firing thrusters to control the attitude and spin rate. This system included a redundant computer, Sun sensors, and the reaction control system with eight thrusters and the hydrazine fuel system. The load of monopropellant hydrazine fuel was stored in a single diaphragm tank mounted on the spacecraft's spin axis.

The spacecraft's telecommunications system included two S-band receivers; two 5-watt S-band transmitters; two 20-watt X-band transmitters; a high-gain antenna; and two smaller low-gain antennae.

Ulysses was powered by an RTG similar to RTGs flown on previous solar system exploration missions. RTGs are required for these deep-space missions because solar arrays large enough to generate sufficient power at long distances from the Sun would be too large and heavy to be launched by available launch vehicles. In the RTG, heat produced by the natural decay of plutonium-238 is converted into electricity by thermocouples.[180]

Ulysses' scientific payload consisted of nine instruments (see Table 4–52). To add, the spacecraft radio was used to conduct a pair of experiments and communicate with Earth.

Advanced Satellite for Cosmology and Astrophysics (Astro-D)

The ASCA (originally Astro-D) was a Japanese-led program involving the United States as a participating partner. Astro-D was renamed ASCA after launch. The Japanese characters for ASCA literally mean "flying bird"; it was also the name of an ancient era of Japan when the country was modernized and culture flourished. In return for its scientific instrument contributions, the United States received 15 percent of the observing time and shared an additional 25 percent observing time for collaborative U.S.-Japan scientific investigations.[181]

The ASCA was Japan's fourth cosmic x-ray astronomy mission and the second for which the United States provided part of the scientific payload. The Japanese Institute of Space and Astronautical Science (ISAS) provided overall program management, the launch vehicle, the spacecraft, and two gas scintillation imaging system detectors. NASA provided four tested, thin-foil, grazing-incidence telescope mirrors and two x-ray CCD solid state detectors. NASA also provided telemetry tracking support using DSN ground stations.

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[180] "STS-41 Press Kit," p. 13.

[181] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, cover memo (NASA History Office Folder 5670).

The ASCA was the first "high energy imaging and spectroscopy" mission to cover a wide energy range exceeding 10 keV and the first to combine imaging capability with a broad passband, good spectral resolution, and a large effective area.[182] The mission also was the first satellite to use CCDs for x-ray astronomy. The primary scientific purpose of the ASCA was the x-ray spectroscopy of astrophysical plasmas—especially the analysis of discrete features such as emission lines and absorption edges.[183]

The ASCA was launched on February 20, 1993. After approximately eight months of on-orbit calibration and performance verification, and due to the proprietary data rights to which the mission developers were entitled, the mission changed to a general/guest observer status for the remainder of the mission. In this phase, the proprietary data was archived with the remainder of the data, and the observing program opened to astronomers based at Japanese and U.S. institutions as well as those located in ESA member states.[184]

The ASCA carried four large-area identical XRTs. At the focus of two of the telescopes were Gas Imaging Spectrometers (GISs). At the focus of the other two XRTs were Solid-state Imaging Spectrometers (SISs). The sensitivity of the ASCA's instruments allowed the first detailed, broadband spectra of distant quasars to be derived. In addition, the ASCA's suite of instruments provided the best opportunity to date for identifying the sources whose combined emission made up the cosmic x-ray background.[185] Data from the x-ray detectors were processed by the on-board data processing unit and telemetered in real-time and stored in the on-board data recorder.

The spacecraft was three-axis stabilized, and its pointing accuracy was approximately 30 arc seconds, with stability better than 10 arc seconds. The attitude control system consisted of a four-gyroscope (plus one back-up gyroscope) inertial reference system; four reaction wheels; two star trackers; three magnetic torquers for unloading angular momentum; and the control electronics. The spacecraft orientation was limited to direct the solar paddles within 30 degrees from the Sun. This orientation limited the observable sky to a belt within which the Sun angle was between 60 degrees and 120 degrees. The spacecraft was given a bias angular momentum that always was directed to the Sun if an abnormality in the attitude control occurred. This bias angular momentum could secure enough power when the spacecraft went automatically into a safe-hold mode (spinning around the Sun vector).

The ISAS managed ASCA operations, which were conducted mainly by Japanese scientists and graduate students from various groups. Among other duties, several scientists were in charge of scheduling observations,

[182] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, p. 6 (NASA History Office Folder 5670).

[183] "The ASCA Mission (1993–present)," (NASA History Office Folder 5670).

[184] "The Advanced Satellite for Cosmology and Astrophysics (ASCA)," *http://heasarc.nasa.gov/docs/asca/asca2.html* (accessed August 28, 2005).

[185] "The Advanced Satellite for Cosmology and Astrophysics (ASCA)," *http://legacy.gsfc.nasa.gov/docs/asca/asca2.html* (accessed August 29, 2005).

programming, and executing commands; tracking and quick look; monitoring the health of the spacecraft and instruments; and first-order processing of the data. During the satellite's 15 daily orbits, direct contact was made five times each day from the ISAS Kagoshima Station and five to eight times each day from NASA's DSN stations at Goldstone, California; Madrid, Spain; and Canberra, Australia. Each satellite contact lasted about 10 minutes.[186] Table 4–53 provides further mission details.

BeppoSAX

BeppoSAX was an x-ray astronomy satellite named "Beppo" in honor of Italian physicist Giuseppe Occhialini, a pioneer in gamma ray and cosmic ray astronomy.[187] Launched from Cape Canaveral, Florida, in April 1996 on the 100th Atlas-Centaur launch, it was a project of the Italian Space Agency with participation by the Netherlands Agency for Aerospace Programs. It was the first x-ray mission with a scientific payload covering more than three decades of energy—from 0.1 keV to 300 keV—with a relatively large effective area, medium energy resolution, and imaging capabilities in the range from 0.1 keV to 10 keV.

A consortium of institutes in Italy and the Netherlands and the ESA's Space Science Department supported development of the spacecraft. The Max Planck Institut für extraterrestrische Physik (Max Planck Institute for Extraterrestrial Physics) also collaborated for x-ray mirror testing and calibration of the concentrator/spectrometer system. The BeppoSAX U.S. Coordination Facility was established at NASA's High Energy Astrophysics Science Archive Research Center in February 1997. The facility's aim was to provide a BeppoSAX archive in the United States. The facility worked closely with the BeppoSAX Science Data Center in Rome, Italy. In addition, the facility provided basic support to the U.S. astronomical community for proposal preparation and use of satellite data.

With more precision than ever before achieved, BeppoSAX could determine the position of gamma-ray bursts at x-ray wavelengths and relay that information to astronomers. Astronomers could then investigate these short-lived bursts using powerful, ground-based optical telescopes and the orbiting Hubble Space Telescope. BeppoSAX, working in tandem with the CGRO and RXTE, offered the possibility of expanding the number of gamma-ray burst detections.[188] See Table 4–54 for further mission details.

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[186] "Mission Overview," ASCA Guest Observer Facility, *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mission_overview1.html* (accessed August 29, 2005).

[187] "Beppo" is a nickname for Giuseppe. Giuseppe Occhialini was a member of at least two teams in which the team leader received a Nobel Prize. He also was instrumental in forming the European Space Research Organization, predecessor to the ESA.

[188] "Gamma-Ray Bursts Solved," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/epo/news/opcounter.html* (accessed September 1, 2005).

New Millennium Program

The New Millennium Program was an aggressive technology development and demonstration program designed to bring about a revolution in the design, development, and implementation of science spacecraft and instruments. The program was a partnership between NASA's OSS and the Office of Space Access and Technology (OSAT) working closely with the science community. The program encompassed spacecraft components and subsystems; science instruments; and streamlined design, development, and qualification methodologies. The OSS[189] funded the program, and JPL managed program implementation.[190]

The New Millennium Program was established in response to the need for low-mass, affordable spacecraft and instruments, as well as the need lower development, launch service, and mission operations costs due to shrinking budgets. The program's idea was to try out new technologies on inexpensive spacecraft in preparation for more complex future missions. Established in 1995, the program formed partnerships among NASA's space science and Earth science organizations and organizations in government, private industry, academia, and the nonprofit sector, enabling the expertise and know-how of scientists, engineers, and managers to be pooled and used as a resource to meet program goals.[191] The primary program objectives were to increase the performance capabilities of spacecraft and instruments while simultaneously reducing total costs of future science missions, thereby increasing the science mission flight rate. Key areas addressed included reducing spacecraft and instrument launch volume and weight, which allowed smaller launch vehicles to be used, and increasing overall spacecraft autonomy and performance to reduce operations costs and increase science return.

Although the objective of the New Millennium Program technology validation missions was to enable future science missions, the New Millennium Program missions were not science-driven. The missions were technology-driven with the principal requirements coming from the needs of the advanced technologies forming the payload. The missions were high risk because they incorporated unproven technologies without, in most cases, functionally equivalent backups. The New Millennium Program tested and validated new technologies in a series of deep space and Earth-orbiting missions. One New Millennium Program mission flew during the decade ending in 1998, Deep Space 1. The launch vehicle also carried a secondary payload, the SEDSAT-1. See Table 4–55 for further mission details.

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[189] "New Millennium Program," Science, Aeronautics, and Technology Fiscal Year 1997 Estimates Budget Summary, p. SAT 1.1-40.

[190] "New Millennium Spacecraft," NASA Budget Fiscal Year 1996 Estimate, Science, Aeronautics, and Technology, Office of Space Science, Planetary Exploration, *http://www.hq.nasa.gov/office/budget/fy96/table.html* (accessed August 1, 2005).

[191] "New Millennium Program," *http://nmp.jpl.nasa.gov/PROGRAM/program-index.html* (accessed August 1, 2005).

Deep Space 1

Deep Space 1, a technology demonstrator funded by NASA's OSS, was the first launch of NASA's New Millennium Program and the program's first deep-space mission. Deep Space 1 was one of NASA's first deep-space launches where technology, rather than science, was the key focus.

Technologies tested on this mission included the following: a xenon ion engine; a solar concentrator array; autonomous navigation plus two other autonomy experiments; a small transponder; a Ka-band solid state power amplifier; and experiments in low-power electronics, power switching, and multifunctional structures (in which electronics, cabling, and thermal control were integrated into a load bearing element).[192]

Deep Space 1 probe construction began in 1995 after NASA chose JPL to design and build a spacecraft to flight-test cutting-edge technology systems that NASA wanted to test for future space missions. The 1,072-pound (486-kilogram) probe was designed and built in three years. Originally scheduled to launch in July 1998, late delivery of the spacecraft's power electronics system and an ambitious flight software development schedule (which together left insufficient time to test the spacecraft thoroughly for a July launch) delayed the launch until October 24. The new launch trajectory included a flyby of near-Earth asteroid 1992 KD.[193]

In space, all 12 technologies worked so well that NASA extended the probe's mission to fly toward a comet in July 1999. After validating all the technology, the primary Deep Space 1 mission successfully concluded in September 1999. The Deep Space 1 mission was the first mission to use the Delta II 7326 Med-Lite launch vehicle.[194]

Although there were 12 advanced technologies on Deep Space 1, the rest of the spacecraft was composed of current, less costly components that had been tested and used on other missions. This approach allowed the New Millennium Program to focus on proving that the program's advanced technologies worked in space, not on building complete spacecraft like those to fly on future missions. The octagonal, aluminum spacecraft structure was based on the three Miniature Seeker Technology Integration (MSTI) spacecraft built by Spectrum Astro, Inc. for the Ballistic Missile Defense Organization. Most of the components were mounted on the exterior of the bus, simplifying accessibility for replacement during integration and test.[195] Batteries and two solar panel wings attached to the sides of the frame powered the spacecraft. The solar

[192] "Deep Space 1," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-061A* (accessed August 18, 2005).
[193] "New Deep Space 1 Trajectory Includes Asteroid Flyby," Jet Propulsion Laboratory Release, June 5, 1998, *http://stardust.jpl.nasa.gov/news/news22.html* (accessed August 17, 2005).
[194] "NASA's First New Millennium Mission: Deep Space 1," *www.spacetoday.org/SolSys/Comets/DeepSpace1.html* (accessed August 17, 2005).
[195] "Deep Space 1–General Interest: Spacecraft," *http://nmp.jpl.nasa.gov/ds1/gen/spacecraft.html* (accessed August 17, 2005).

panel, Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET II), was one of the technologies tested. The array used 720 lenses to focus sunlight onto 3,600 solar cells, each converting the light into electricity to power the ion propulsion system and the rest of the spacecraft. The solar array consisted of four 160-centimter by 113-centimeter (63-inch by 45-inch) panels. The array furnished 2,500 watts of power at 100 volts at the beginning of the mission; it furnished less power as the spacecraft moved farther from the Sun and the solar cells aged.[196] Communications were via a high-gain antenna, three low-gain antennae, and a Ka-band antenna, all mounted atop the spacecraft except for one low-gain antenna mounted on the bottom.

A xenon ion engine mounted in the propulsion unit on the bottom of the frame provided propulsion (see Figure 4–40). The 30-centimeter-diameter engine consisted of an ionization chamber into which xenon gas was injected. Electrons were emitted by a cathode traverse discharge tube and collided with the xenon gas, stripping off electrons and creating positive ions. The ions were accelerated through a 1,280-volt grid at 31.5 kilometers per second (19.6 miles per second) and ejected from the spacecraft as an ion beam, producing 0.09 newton of thrust at maximum power (2,300 watts) and 0.02 newton at the minimum operational power of 500 watts. The excess electrons were collected and injected into the ion beam to neutralize the electric charge. Approximately 17 kilograms (37 pounds) of the original 81.5 kilograms (180 pounds) of xenon were consumed during the primary mission.[197]

Students for the Exploration and Development of Space Satellite

The SEDSAT-1 was the secondary payload on the June 24, 1998, Delta 2 launch of Deep Space 1. Students at the University of Alabama, Huntsville, designed the microsatellite, which was placed into a 547-kilomter by 1,079-kilometer (340-mile by 670-mile) orbit inclined at 31.5 degrees. The spacecraft carried cameras to make images available over the World Wide Web and two radio amateur packet communications payloads. The on-orbit goals were the following:

- Provide multispectral remote sensing to the broadest possible community. The cameras were to collect in narrow wavebands chosen to coordinate with ground-based observations across the United States. Unlike other remote sensing systems, the data would be broadly accessible because it would be entirely in the public domain, and its communication system would be integrated into the World Wide Web.

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[196] "Solar Concentrator Arrays," Deep Space 1: Advanced Technologies, *http://nmp.jpl.nasa.gov/ds1/tech/scarlet.html* (accessed October 10, 2005).
[197] "Deep Space 1," NSSDC Master Catalog: Spacecraft *http://nssdc.nasa.gov/database/MasterCatalog?sc=1998-061A* (accessed August 18, 2005).

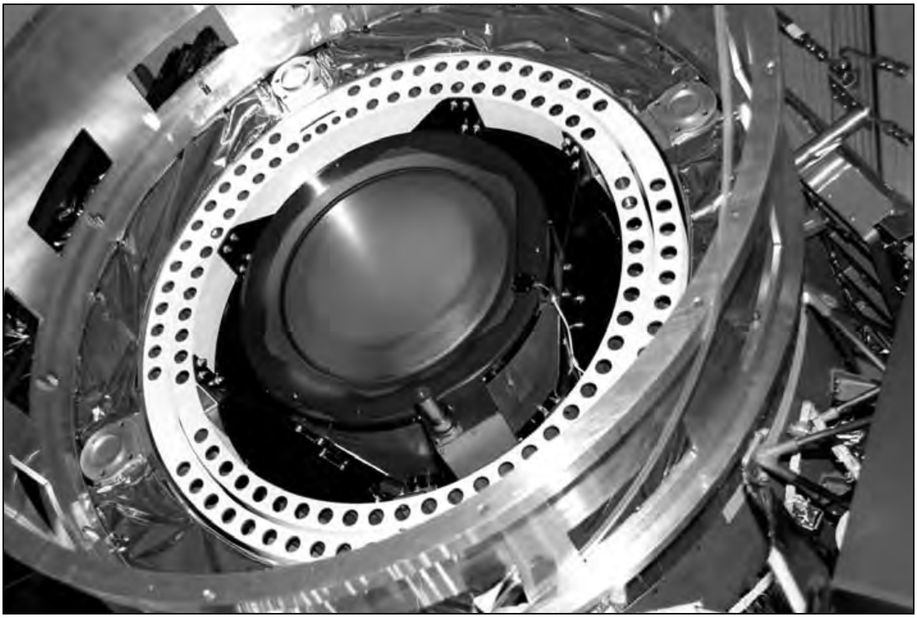

Figure 4–40. Deep Space 1 is lifted from its work platform, giving a close-up view of the experimental solar-powered ion propulsion engine. The ion propulsion engine was the first non-chemical propulsion to be used as the primary means of propelling a spacecraft. (NASA Photo No. KSC-98PC-1192)

- Serve as a development platform for advanced microsatellite position determination and control algorithms. The satellite was to demonstrate a unique attitude determination system and new technology in active microsatellite control.
- Provide the amateur radio community with digital packet store-and-forward and analog repeater systems.
- Generate new data on the space performance of nickel-metal hydride batteries and advanced electronic components.
- Provide additional opportunities for space studies because of its on-board GPS, extensive reprogrammability, and other flexible instruments. The students developed an experiment to demonstrate mobile IP (Internet Protocol) on the SEDSAT that was to allow the SEDSAT to appear as an active node on the Internet.[198]

The satellite was launched with a known negative power configuration and suffered a failed uplink capability on October 27, 1988, which compromised full success. As a result, the spacecraft operated for more than two years transmitting only engineering health telemetry until the batteries were fully discharged. The reboot logic included a “non-transmit” period,

[198] “Sedsat Project Information,” *http://www.seds.org/sedsat/info* (accessed October 10, 2005).

allowing it to charge the batteries before it began transmitting again in a new cycle.[199] The SEDSAT was operational only in transmit mode at least until September 2003.[200]

High Energy Transient Experiment/Satelite de Aplicaciones Cientificas-B

The Argentinean SAC-B and the HETE were launched together on a Pegasus XL launch vehicle on November 4, 1996 from NASA's facility at Wallops Island, Virginia. Goddard Space Flight Center provided one instrument on the SAC-B, the Hard X-Ray Spectrometer. Although the Pegasus achieved a nominal orbit, it did not eject the two spacecraft from the rocket as planned. Telemetry indicated a power failure on the transient power bus of the Pegasus third stage, causing three crucial pyrotechnics to fail to ignite. Thus, the system flew with the SAC-B, the HETE, and the Pegasus third stage connected together as a single 650-kilogram (1,433-lb) object. The HETE remained enclosed in the dual payload attachment fitting.

The SAC-B deployed its solar panels successfully and operated for about 10 hours. On-board software was modified to permit operation without a separation indication, and the attitude control system (ACS) was placed in safe-hold mode in an attempt to gain control and point the solar panels toward the Sun. However, the ACS was not designed to control such a massive tumbling object. With the Pegasus third stage shadowing at least part of the solar array, there was insufficient power to charge the batteries, even during the daylight part of the orbit. The SAC-B battery power continued to decrease, and subsequent passes over Wallops Island, Virginia, did not produce any signal from the satellite.

At the same time, on the morning of November 5, operators of a 23-meter (75-foot) very high frequency antenna at Wallops Island received a transmission while monitoring a frequency used by the HETE's emergency beacon. Subsequent passes over Los Alamos National Laboratory and Wallops Island also picked up a similar, though much weaker, signal. Unable to deploy solar panels to charge its batteries, the HETE expired several days after launch.[201] Because of the importance of gamma-ray burst science, NASA agreed to a second attempt using spare flight hardware from the HETE-1. In July 1997, the NASA funded the HETE-2, and construction began in mid-1997 at MIT.[202] HETE-2 was successfully launched on October 9, 2000.

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[199] "Sedsat," The Satellite Encyclopedia, *http://www.tbs-satellite.com/tse/online/sat_sedsat.html* (accessed October 10, 2005). Also Chris Lewicki, e-mail to author, October 12, 2005.

[200] Dennis Wingo, e-mail to author, October 12, 2005.

[201] "SAC-B," Quicklook, *http://msl.jpl.nasa.gov/QuickLooks/sacbQL.html*. Also "HETE," Quicklook," *http://msl.jpl.nasa.gov/QuickLooks/heteQL.html* (accessed August 11, 2005).

[202] "HETE-2 Spacecraft To Study Gamma Ray Bursts Fully Operational On-Orbit," Press Release AeroAstro, *http://www.aeroastro.com/releases/2000/pr_10_09_00.php* (accessed August 19, 2005).

The HETE-1 was to have been an international mission led by MIT. Its prime objective was to carry out the first multi-wavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments. A unique feature of the mission was its capability to localize bursts with several arc-second accuracy in near real-time aboard the spacecraft. These positions would be transmitted to the ground and picked up by a global network of primary and secondary ground stations, enabling sensitive follow-up studies. The HETE was Sun-pointing with four solar panels connected to the bottom of the spacecraft bus. Magnetic torque coils and a momentum wheel were to control spacecraft attitude.

The SAC-B was a small satellite built by the Argentinean National Commission of Space Activities. The SAC-B was designed to advance the study of solar physics and astrophysics through the examination of solar flares, gamma-ray bursts, diffuse x-ray cosmic background, and energetic neutral atoms. The satellite also was designed to test and characterize the performance of new equipment and technologies that might be used in future operational or scientific missions. The SAC-B was three-axis-stabilized, using two momentum wheels in a "V" configuration for roll and yaw control. Pitch axis control and momentum unloading were accomplished using magnetic torque coils. Coarse and fine Sun sensors, combined with magnetometer readings were to provide spacecraft attitude knowledge. See Table 4–56 for further details.

International Solar-Terrestrial Physics Program

The ISTP program was an international, multi-spacecraft, collaborative science mission comprising a complement of satellites, ground-based observations, and theoretical investigations studying the Sun and Earth system in a global context. Goddard Space Flight Center managed the ISTP program, and NASA, the ESA, and Japan contributed spacecraft. Australia; Austria; Belgium; Canada; Finland; France; Germany; Greece; Ireland; Italy; Japan; the Netherlands; Norway; Sweden; Switzerland; the United Kingdom; the United States; and the former Soviet Union participated in spacecraft development and scientific investigations.[203]

The ISTP program consisted of five spaceflight missions: two cooperative ESA/NASA missions, the SOHO and Cluster; two NASA missions, Wind and Polar; and Japan's Geotail spacecraft. NASA's contributions to Geotail, the SOHO, and Cluster were referred to as the Collaborative Solar-Terrestrial Research (COSTR) Program.[204] The scientific objectives of the ISTP program were the following:

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[203] "ISTP Unites Scientists for Study of Sun-Earth System," *NASA Facts On-Line*, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/istp.htm* (accessed September 2, 2005).

[204] "ISTP Unites Scientists for Study of Sun-Earth System."

- Determine the structure and dynamics in the solar interior and their role in driving solar activity.
- Identify the processes responsible for heating the solar corona and its acceleration outward as the solar wind.
- Determine the flow of mass, momentum, and energy through geospace.
- Gain a better understanding of the turbulent plasma phenomena mediating the flow of energy through geospace.
- Implement a systematic approach to the development of the first global solar-terrestrial model, leading to a better understanding of the chain of cause-effect relationships that begins with solar activity and ends with the deposition of energy in the upper atmosphere.[205]

The GGS initiative, a subset of the ISTP program, focused on the global flow of energy from the solar wind through the three regions of geospace: the magnetosphere, ionosphere, and atmosphere. NASA contributed the Wind and Polar spacecraft to the GGS initiative, and Japan contributed Geotail. Complementary theoretical and ground-based investigations and data sets obtained from spacecraft operated by NOAA and the Los Alamos National Laboratory, also participants in the GGS program, were combined with space-based data.[206] Together, the GGS and COSTR programs were known as the ISTP program.[207]

Participants in the GGS program collaborated to obtain coordinated, simultaneous investigations of the Sun-Earth space environment over an extended time and combined their measurements to operate as a laboratory in space. The program provided the first coordinated geospace measurements of key plasma source and storage regions, performed multispectral global auroral imaging, and provided a multipoint study of Earth's magnetic response to the solar wind. The GGS program enhanced understanding of how energy and matter from the Sun influenced Earth's geospace and atmosphere and contributed to assessments of the relationship of the Sun to Earth's climate.[208] GGS program spacecraft were positioned in different regions of the magnetosphere and routinely followed events in space from their birth on the Sun, through the interplanetary medium, and then in terms of their role in creating geomagnetic storms and substorms in the near-Earth environment.

Each GGS program spacecraft was launched by NASA on Delta II rockets. Each carried a liquid propulsion system to maneuver the spacecraft to its final mission orbit and permit attitude control and stationkeeping during the mission lifetime. The two U.S. spacecraft together used 19 instruments to simultaneously measure the interaction of the solar wind with Earth's magnetic field.

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[205] "ISTP Project Overview," *http://www-istp.gsfc.nasa.gov/istp/misc/istp_project.html* (accessed April 25, 2006).
[206] The ESA's Cluster spacecraft were destroyed at launch.
[207] "Mission Operation Report, International Solar-Terrestrial Physics Program (ISTP), Geotail," Report no. S-418-92-01 (NASA History Office Electronic Document 30777).
[208] "Sciences, Aeronautics and Technology Fiscal Year 1995 Estimates," Office of Space Science, Physics & Astronomy, pp. SAT 1.1-10–SAT 1.1-11.

The GGS program science objectives were the following:

- Trace the flow of matter and energy through the geospace system from the solar wind to ultimate deposition into the atmosphere.
- Understand how the regions of geospace interact.
- Investigate the physical processes controlling the origin; entry; transport; storage; energization; and loss of plasma—high-energy, ionized gases—near Earth.
- Contribute to other Sun-Earth studies by observing solar particles and fields near Earth's orbit.[209]

The NASA portions of the GGS program, Wind and Polar, almost were canceled. In 1993, Administrator Goldin established the Program Commitment Agreement, an agreement between the NASA Administrator and the Associate Administrator to execute program requirements within particular constraints, including "specific technical and schedule commitments at a stated cost."[210] If estimated mission cost at completion exceeded the stated cost in the Program Commitment Agreement by more than 15 percent, or when any other baseline requirement was violated, it triggered an additional review by the Program Management Council. The Council was directed specifically to recommend "cancellation or continuation of programs and projects." Wind and Polar, being developed by Martin Marietta, were both experiencing development problems and cost overruns. At a review before the Program Management Council, to contain costs, the GGS project manager proposed moving ahead with Wind while delaying Polar. The Council accepted this approach. Ultimately, both Wind and Polar were completed and launched; together, they remained under the 15 percent overrun limit.[211]

Geotail

Geotail was a joint project of the ISAS of Japan and NASA that investigated the geomagnetic tail region of the magnetosphere. Geotail measured global energy flow and transformation in the magnetotail to increase understanding of fundamental magnetospheric processes, including the physics of the magnetopause, the plasma sheet, and reconnection and neutral line formations.

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[209] "ISTP Unites Scientists for Study of Sun-Earth System."
[210] NASA Handbook 7120.5, "Management of Major System Programs and Projects Handbook," November 8, 1993, (cancelled).
[211] Green and Dewhurst, "Space Physics," in Logsdon, ed., p. 171.

The ISAS designed and developed the satellite, and it carried two ISAS, two NASA, and three joint ISAS/NASA instruments. The launch, on a Delta II ELV, was the first under NASA's Medium ELV launch service contract with McDonnell Douglas Corporation.

Geotail was an element of the ISTP program. In the early phase of the program, simultaneous measurements in the key regions of geospace from Geotail and the two U.S. satellites of the GGS program, Wind and Polar, along with equatorial measurements, were used to characterize global energy transfer.

The Geotail memorandum of understanding between the ISAS and NASA was signed in December 1989 after the exchange of notes between Japan and the United States in September 1989. Geotail, along with Wind and Polar and supporting equatorial measurements, provided simultaneous data to enable study of the solar wind input to the magnetosphere and key elements of the magnetospheric response comprising geomagnetic tail energy storage, ring current energy storage, and ionospheric energy input. The SOHO (launched in 1995), an ESA/NASA cooperative mission, complemented these measurements.[212]

Geotail was a spin-stabilized spacecraft using mechanically despun antennae with a design lifetime of about four years. The nominal spin rate of the spacecraft was about 20 revolutions per minute around a spin axis maintained between 85 degrees and 89 degrees to the ecliptic plane. Real-time telemetry data transmitted in the X-band was received at the Usuda Deep Space Center in Japan. There were two tape recorders on board, each with a capacity of 450 megabits, allowing continuous data coverage. The NASA DSN collected the data in playback mode. Figure 4–41 shows the Geotail spacecraft configuration.

Mission objectives required spacecraft measurements in two orbits: a nightside double lunar swingby orbit out to distances of 220 Earth radii (1,401,620 kilometers) and a near-Earth, mid-magnetosphere orbit at about 8 Earth radii by 30 Earth radii (51,024 kilometers by 191,340 kilometers). During the initial two-year phase, the nightside orbit apogee used the Moon's gravity in a series of double-lunar-swingby maneuvers that resulted in the spacecraft spending most of its time in the distant magnetotail, where the magnetotail was stretched out as a result of the impact of the solar wind encountering Earth. The orbital period in this orbit varied from one month to four months.

Then, starting in November 1994, a series of maneuvers brought the spacecraft into its near-Earth orbit. The transition orbit lasted about three months with the apogee varying from 50 Earth radii to 30 Earth radii (318,900 kilometers to 181,340 kilometers). In February 1995, phase two began as the apogee was reduced to 30 Earth radii (181,340 kilometers) to study the near-Earth substorm

[212] "Mission Operation Report, International Solar-Terrestrial Physics Program (ISTP), Geotail," Report no. S-418-92-01 (NASA History Office Electronic Document 30777).

processes, including neutral line formation.[213] This phase was dedicated to the study of near-Earth magnetospheric processes, including neutral line formation. In June 1997, the perigee was slightly lowered to 9 Earth radii from 9.5 Earth radii (57,402 kilometers to 60,591 kilometers) to increase the probability that the spacecraft would fly inside the dayside magnetopause. The near-tail orbit of 9 Earth radii by 30 Earth radii (57,402 kilometers by 181,340 kilometers) (with an inclination of -7 degrees to the ecliptic plane) allowed extensive study of the magnetosheath, the bow shock, and the upstream region as well.[214] See Table 4–57 for further details.

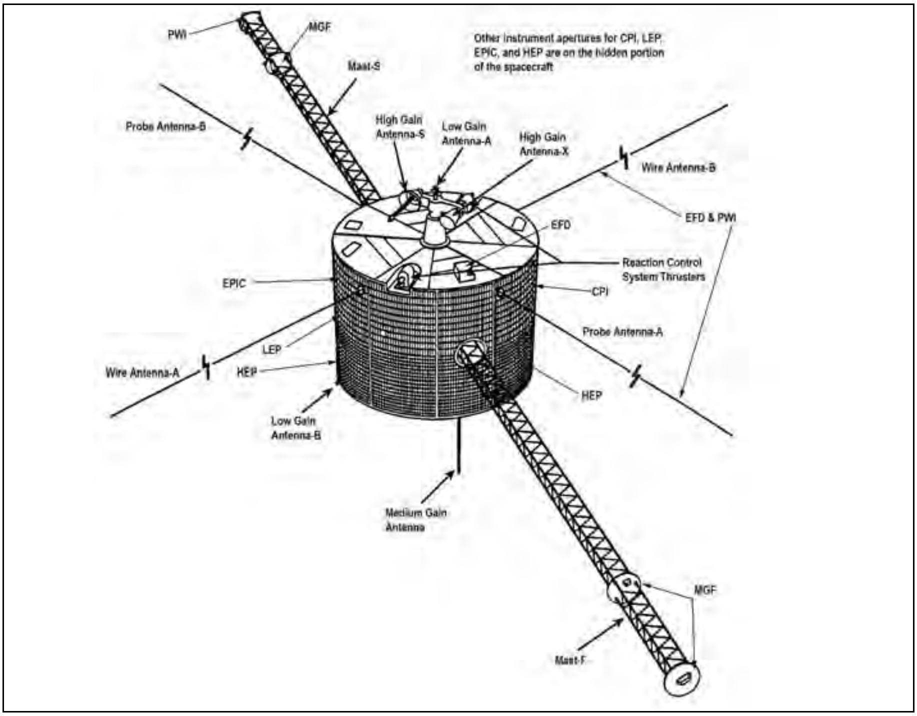

Figure 4–41. Geotail Spacecraft Configuration.

Wind

Wind was the first of two NASA spacecraft in the GGS initiative. Wind, together with Geotail, Polar, SOHO, and Cluster projects, constituted the cooperative ISTP program. The main purpose of the Wind spacecraft was to measure the incoming solar wind, magnetic fields, and particles, although the spacecraft also observed Earth's foreshock region early in its mission.

[213] "Geotail: Project Overview," *http://pwg.gsfc.nasa.gov/istp/geotail/geotail.html* (accessed September 2, 2005). Also "Geotail," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-044A* (accessed September 2, 2005).
[214] Herbert J. Kramer, "Geotail," *http://directory.eoportal.org/pres_GEOTAIL.html* (accessed September 2, 2005).

The Wind spacecraft had on-board propulsion and a design lifetime of three to five years. The cylindrical spacecraft had body-mounted solar cells to generate power, long wire spin-plane antennae, inertial booms, and spin-plane appendages to support sensors. Experiment booms were deployed along both Z axes. The spin rate was 20 revolutions per minute around an axis within 1 degree of normal to the ecliptic. Data was stored using on-board tape recorders and relayed to NASA's DSN at either 5.5 kbps or 11.1 kbps. Wind had eight science instruments, including one from France and one from the Soviet Union. It was the first time that a Soviet instrument had flown on an American spacecraft. The instrument, known as KONUS, was a gamma-ray burst experiment first proposed by the Soviet Union in 1989. The KONUS cooperative agreement was carried out under the auspices of the U.S.-U.S.S.R. joint working group on Space Astronomy and Astrophysics.[215] Figure 4–42 shows a diagram of the spacecraft.

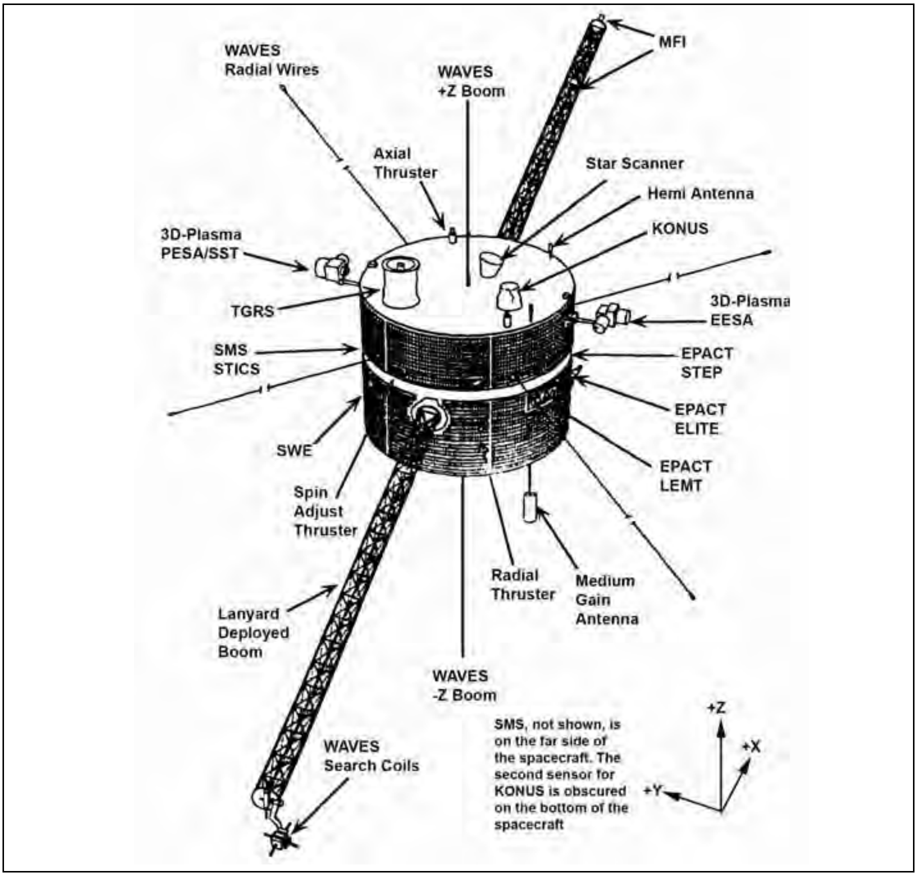

Figure 4–42. Wind Spacecraft.

[215] "Soviet Scientists and ISTP Partners Visit Goddard," *Goddard News* 36, no. 4 (April 1990): 8. (NASA History Office Folder 5910).

Some of the instruments aboard Wind measured properties of the solar wind plasma, including the speed of the plasma's flow, the flow's direction, and the distribution of electron and ion energies. The instruments also measured the proportions of various ions in the solar wind: protons and alpha-particles were most abundant, but the stream also included the more rare isotopes of "heavy" hydrogen and "light" helium, as well as carbon, oxygen, and other elements. The variation of these proportions shed light on processes in the Sun's corona, where the solar wind originated.

Radio wave receivers monitored emissions from the Sun and from space plasmas, and a magnetometer sampled the IMF up to 44 times a second. Because the IMF was very weak (about 1/10,000 of Earth's surface field), the magnetic fields produced by electric currents on the spacecraft were strong enough to disturb its observation, and the magnetometer was therefore placed at the end of a long boom, away from the interference. Wind also carried two gamma-ray detectors to observe and time gamma-ray bursts from distant space, probably beyond our galaxy.[216] See Table 4–58 for further information.

For the first nine months of the mission, Wind was placed in a double lunar swingby orbit near the ecliptic plane, with apogee from 80 Earth radii to 250 Earth radii (382,600 kilometers to 1,594,500 kilometers) and perigee of between 5 Earth radii and 10 Earth radii (31,890 kilometers and 63,780 kilometers). In this orbit, lunar gravity assists kept Wind's apogee over the day hemisphere of Earth, and magnetospheric observations were made. Wind was then inserted into a small halo orbit, about the sunward Sun-Earth gravitational equilibrium point (L1 Lagrangian point), varying from 235 Earth radii to 265 Earth radii (1,498,830 kilometers to 1,690,170 kilometers).[217] In this orbit, Wind continuously measured the incoming solar wind, magnetic fields, and particles while providing a warning of approximately 1 hour to the other ISTP spacecraft of changes in the solar wind.[218] After several months at this location, Wind made two passes by the Moon, and in October 1998, began a six-month series of "petal" orbits that took the spacecraft out of the ecliptic phase. These orbits brought Wind as close as 10 Earth radii (about 63,780 kilometers) and as far as 80 Earth radii (510,240 kilometers) from Earth. The orbit took Wind at an angle of 60 degrees from the ecliptic plane, allowing the spacecraft to sample regions of interplanetary space and the magnetosphere that had not been studied before.[219]

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[216] "WIND," *http://www.phy6.org/Education/wwind.html* (accessed October 25, 2005).

[217] The Earth-Sun L1 point is 1 percent of the way to the Sun, four times the distance from Earth to the moon, or about one million miles away from Earth. The solar wind reaches L1 about 1 hour before it reaches Earth, making it a good place to observe changes in solar activity before it affects Earth. From the L1 Home Page, *http://triana.gsfc.nasa.gov/instruments/lagrange.htm* (accessed August 8, 2005).

[218] "Wind," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-071A* (accessed September 27, 2005).

[219] "ISTP Science News," April 1998, *http://pwg.gsfc.nasa.gov/istp/news/9804* (accessed September 27, 2005).

Polar

The Polar satellite was the second of two NASA spacecraft in the GGS program. It was launched in early 1996 after delays caused by cost overruns; suspected faulty components; a failure of the launch vehicle's solid rocket motor separation system on an earlier Delta launch that delayed launches until resolution of the problem; and the precedence of other missions. When finally launched, the Polar satellite set a new record for back-to-back launches of the Delta II, coming just seven days after launch of the NEAR spacecraft.[220]

The primary objective of the Polar mission was to study aurora light and other electromagnetic radiation emissions and characterize the solar particles present within the magnetosphere over Earth's polar regions. The Polar satellite was launched into a large elliptical orbit that looped over the poles for a three-year mission. The Polar satellite made its observations as its orbit precessed with time, observed the equatorial inner magnetosphere, and progressed toward an extended Southern Hemisphere campaign. Polar gave scientists new perspectives on how the constant bombardment from radiation and particles from the Sun affected Earth's space environment, data that eventually could help scientists forecast "space weather."[221]

Within the fleet of spacecraft studying the Sun-Earth connection, Polar was responsible for multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere.

Polar was a spin-stabilized, cylindrical-shaped spacecraft flying in a highly eccentric polar orbit to survey the ionosphere and upper atmosphere. The reinforced structure carried the scientific instruments, support subsystems, and body-mounted solar array panels. Openings in the solar array provided viewing ports required for radial viewing instruments. A despun platform provided an inertially stable mounting surface for four instruments, the Visible Imaging System (VIS), Ultraviolet Imager (UVI), Polar Ionospheric X-ray Imaging Experiment (PIXIE), and Comprehensive Energetic Particle Pitch Angle Distribution/Source-Loss Cone Energetic Particle Spectrometer (CEPPAD/SEPS). These instruments provided multispectral images of the aurora and measurements of high-energy ion composition.

The Despun Platform Mechanism (DPM) performed orientation and control of the despun platform. The DPM was a high-precision electromechanical device maintaining continuous near-inertial orientation of the platform while the main body of the spacecraft rotated at 10 revolutions per minute. Honeywell Satellite Systems Operations designed and built the DPM.

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[220] Joel W. Powell, "Geospace Observed: Secrets of Aurora Probed by Polar Satellite," *Spaceflight* 38 (November 1996): 370–372.

[221] "Polar Launch Completes Global Geospace Science Program Missions," Goddard News Release 96-008, February 7, 1996, *http://www.gsfc.nasa.gov/news-release/releases/1996/96-008.txt* (accessed August 10, 2005).

In 1997, Polar started viewing the Hale-Bopp comet. Hale-Bopp crossed the orbital plane of Polar on April 1, 1997, and was within the FOV of the imagers, the VIS, UVI, and PIXIE, from March 27 to April 2. They imaged the comet during its closest approach to the Sun (its perihelion) in a wide wavelength range covering the visible through x-ray bandwidths, something no other imaging system could do. Polar's specialized cameras had sensitivities in different wavelengths: the VIS observed the comet with one far UV and 10 visible filters. At the same time, the UVI imaged with four filters sensitive in different bands of the far UV; the PIXIE obtained an upper limit on the x-ray flux from the comet.[222] Figure 4–43 shows the position of Polar's instruments. Table 4–59 provides further mission details.

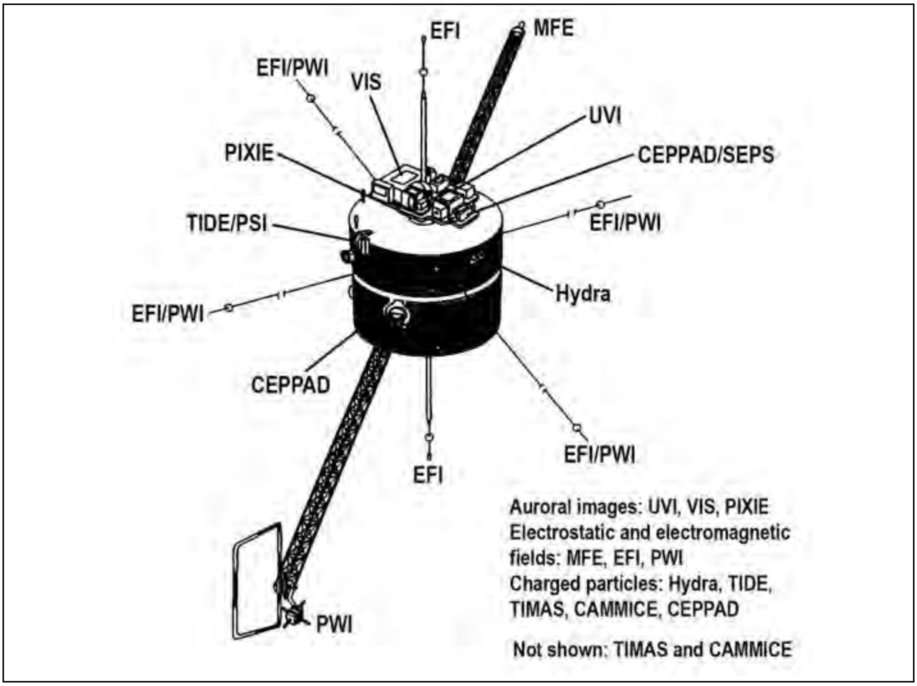

Figure 4–43. Location of Polar Instruments.

Solar and Heliospheric Observatory

The SOHO was an international cooperative mission between the ESA and NASA and part of the ISTP program. The ESA and NASA signed the memorandum of understanding for the SOHO in December 1989. The observatory consisted of a three-axis stabilized ESA spacecraft with shared

[222] "Comet Hale-Bopp's into the Polar Satellite Field-of-View," *http://pwg.gsfc.nasa.gov/istp/events/halebopp/incoming/press/press.html* (accessed August 10, 2005).

NASA and ESA solar physics telescopes and plasma physics fields and particles instrumentation. The two agencies shared tracking and data acquisition. NASA conducted mission operations.

The SOHO was launched December 2, 1995 on an Atlas IIAS ELV. The SOHO observed the Sun 24 hours a day and without interruption from its orbit around the L1 libration point, which it reached on February 14, 1996. The spacecraft returned its first image on December 19, 1995, and it was declared operational by April 16, 1996.[223]

The main scientific purpose of the SOHO was to study the Sun's internal structure by observing velocity oscillations and radiance variations and to examine the physical processes forming and heating the Sun's corona and giving rise to the solar wind. The SOHO used imaging and spectroscopic diagnosis of the plasma in the Sun's outer regions coupled with in situ measurements of the solar wind. It was also the most prolific comet-finder ever.

The three-axis stabilized Sun-pointing spacecraft had two modules. The service module formed the lower portion of the spacecraft. The service module provided power, thermal control, telecommunications, and pointing for the entire spacecraft, as well as support for the solar panels. The payload module sat above the service module and housed the 12 scientific instruments developed and furnished by 12 international consortia involving 29 institutes from 15 countries. U.S. scientists led three consortia; European scientists led nine consortia. More than 1,500 scientists in countries around the world were either directly involved in the SOHO's instruments or used SOHO data in their research programs. NASA's DSN tracked the spacecraft beyond Earth's orbit.

The SOHO successfully completed its primary mission in April 1998. Major science highlights to that time included the following:

- Detection of plasma rivers beneath the surface of the Sun.
- Discovery of a magnetic "carpet" on the solar surface seeming to account for a substantial part of the energy needed to cause the very high temperature of the Sun's corona.
- The first detection of flare-induced solar quakes.
- Discovery of more than 50 sungrazing comets.
- The most detailed view to date of the solar atmosphere.
- Spectacular images of coronal mass ejections, which were used to improve the ability to forecast space weather.[224]

Figure 4–44 shows a series of SOHO images taken on February 11, 1996.

[223] Asif Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, Monographs in Aerospace History no. 24 (Washington, DC: National Aeronautics and Space Administration, 2002), pp. 159–160.

[224] "SOHO Spacecraft Observations Interrupted," *NASA News* Release 98-112, June 26, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-112.txt* (accessed August 8, 2005).

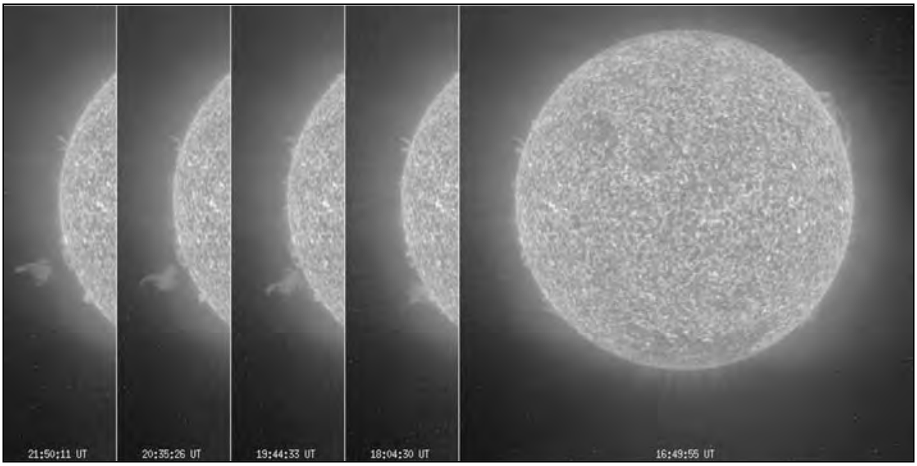

Figure 4–44. SOHO took this sequence of images with the Extreme Ultraviolet Imaging Telescope. Visible on the lower left is an "eruptive prominence," or blob, of 60,000°F (33,315°C) gas measuring more than 80,000 miles (128,747 km) long. When SOHO took the image on February 11, 1996, the blob was traveling at more than 15,000 miles per hour (24,140 km per hour). Eruptions such as these occur when a significant amount of cool dense plasma or ionized gas escapes from low-level magnetic fields in the Sun's atmosphere. When they occur, they sometimes disrupt power and communications. (NASA Photo No. GSFC 091)

In December 1997, a key event in solar physics occurred when SOHO scientists discovered "jet streams" or "rivers" of hot, electrically charged plasma flowing beneath the surface of the Sun. These new findings helped scientists understand the 11-year sunspot cycle and associated increases in solar activity that disrupted Earth's power and communications systems.[225]

Ground controllers lost contact with the SOHO during maintenance operations on June 24, 1998. The SOHO went into emergency Sun reacquisition mode, which occurs when an anomaly causes the spacecraft to lose its orientation toward the Sun. The spacecraft fired its attitude control thrusters under the guidance of an on-board Sun sensor in an effort to point itself toward the Sun again. A month later, on July 27, ground-based radio telescopes detected and found the spacecraft near its original position in space, turning slowly at a rate of roughly one revolution per minute. On August 3, the SOHO answered signals sent to it through the DSN station at Canberra, Australia. Coming intermittently in the form of bursts of signal lasting from 2 to 10 seconds with no data, the signals showed that the spacecraft was still capable of receiving and responding to ground commands. On August 8, the first telemetry from the SOHO indicated that its service module was "very cold." Over the next two days, the spacecraft sent temperature and electrical data to ground controllers, signaling low, high, and

[225] "Chronology of Defining Events in NASA History," *http://history.nasa.gov/Defining-chron.htm* (accessed August 8, 2005).

normal temperatures from its scientific instruments. Further, the hydrazine fuel used by its thrusters was partially frozen. Thawing the fuel took nearly three weeks, which was followed by warming the pipes that carried the fuel to the thrusters. By September 3, the propulsion system had been fully thawed, and sunlight was hitting the solar panels at a slant angle of nearly 60 degrees. The batteries were recharged and had a full charge by September 8.[226]

On September 16, the SOHO obeyed commands to stop spinning and turned its face and solar panels fully toward the Sun for the first time since June 24, when it spun out of control and lost contact. By the second week in October, scientists released high-quality. new pictures of the Sun taken from the SOHO. On October 14, the project announced that 9 of the 12 instruments had been successfully reactivated. Before the end of the month, the remaining instruments were successfully reactivated.[227]

The spacecraft had a second brief crisis on December 21, 1998, when it went into emergency Sun reacquisition mode because the last of its three gyroscopes failed. To stop the rapid depletion of fuel caused by continually firing on-board jets to keep the spacecraft's sensors pointed toward the Sun, engineers designed software to enable the spacecraft to resume science operations without gyroscopes. Beginning on February 2, 1999, the spacecraft was reprogrammed to ignore faulty information from the gyroscopes and use new software sent by ground controllers. This was the first time that a spacecraft equipped with gyroscopes continued working without them.[228] Table 4–60 provides further mission details.

Solar-A/Yohkoh

Solar-A was a cooperative mission of Japan, the United States, and the United Kingdom. The mission's prime purpose was to study high-energy phenomena in solar flares during the period of maximum solar activity. The mission was a successor to Hinotori, an earlier Japanese spacecraft flown at the previous solar activity maximum in 1981. One of the four instruments on Yohkoh, the Soft X-ray Telescope (SXT), was the product of international collaboration between the United States and Japan. Solar-A was renamed Yohkoh after successfully achieving orbit. Yohkoh means "sun-ray" or "sunbeam" in Japanese.

Yohkoh was a three-axis stabilized satellite carrying four instruments: two imagers and two spectrometers. The imaging instruments, the SXT and the Hard X-ray Telescope (HXT), had almost full Sun fields of view to avoid missing any flares on the visible disk of the Sun; they were in sunlight for 65

[226] "SOHO Is Pointing at the Sun Again," ESA Press Release no. 33-1998, September 17, 1998, *http://www.esa.int/esaCP/Pr_33_1998_p_EN.html* (accessed August 8, 2005).
[227] F.C. Vandenbussche, "SOHO's Recovery–An Unprecedented Success Story," from *ESA Bulletin* 97, (March 1999): 39 *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31893* (accessed July 7, 2006).
[228] "SOHO Gets Back to Work: Historic First in Space," ESA Press Release no. 05-99, February 3, 1999, *http://www.esa.int/esaCP/Pr_5_1999_p_EN.html* (accessed August 8, 2005).

minutes to 75 minutes of each 90-minute orbit period. The SXT acquired its first image of the Sun on September 30, 1991. The HXT acquired its first image data on October 3, 1991. The sensitivity of HXT was approximately 100 times that of its predecessor instrument on the Solar Maximum Mission spacecraft, and approximately 10 times the sensitivity of the x-ray imager aboard the Hinotori spacecraft.[229] Production and data analysis for the SXT was a collaboration between Japanese scientists at the National Astronomical Observatory of Japan and U.S. solar physicists at the Lockheed Palo Alto Research Laboratory. The spectrometers were the Bragg Crystal Spectrometer (BCS) (developed by the National Astronomical Observatory of Japan in collaboration with the United Kingdom Science and Engineering Research Council, the U.S. National Institute of Standards and Technology, and the U.S. Naval Research Laboratory) and the Wide Band Spectrometer (WBS) (developed by Japan's Institute of Space and Astronautical Science).[230]

The spacecraft structure consisted of a main body and six solar panels. A combination of passive and active methods provided spacecraft thermal control. Multilayer thermal blankets and thermal radiators were used for passive thermal control. Heaters with thermostats controlled the temperature of the batteries, the star tracker, and the SXT.

The spacecraft flew in a slightly elliptical low-Earth orbit. During five to six of its orbits each day, Yohkoh passed through the radiation belts of the South Atlantic Anomaly where the BCS, HXT, and most channels on the WBS (all of which used high voltages) had to be turned off to avoid damage to the instruments and satellite.

Observations from the instruments were stored in the Spacecraft Bubble Data Recorder (BDR). Approximately 50 megabytes of data were accumulated each day and stored in the 10-megabyte on-board tape recorder. To optimize the recorder, the BDR could operate at several bit-rates—high, medium, and low. Switching between the bit-rates was controlled both automatically and by on-board deferred commands. This switching was necessary because the high bit rate held only 42 minutes of data. Some overwriting of data was permitted.

The satellite operated in several spacecraft and subsystem modes. The two modes of principal interest were the Quiet Mode and Flare Mode. Switching between these two particular modes was controlled by a flare flag generated by the WBS. Yohkoh's operating mode determined which instruments could collect the data and how much they could collect. Generally, more HXT data was taken during the Flare Mode than during the Quiet Mode.

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[229] "Hard X-Ray Telescope," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-062A&ex=1* (accessed September 26, 2005).

[230] "Solar-A Mission Operation Report," Report no. S-416-91-01, (NASA History Office Folder 14684).

During each orbit, Yohkoh passed over the Kagoshima Space Center in Japan. Commanding of the satellite could be performed at that time. The rest of the time the satellite was controlled by on-board deferred command storage. In addition, Kennedy Space Center received current data from the BDR. At other locations in the orbit, the data was sent to ground stations in NASA's DSN. Figure 4–45 shows the solar cycle as a mosaic of Yohkoh images gathered between 1991 and 1999. Table 4–61 provides further mission details.

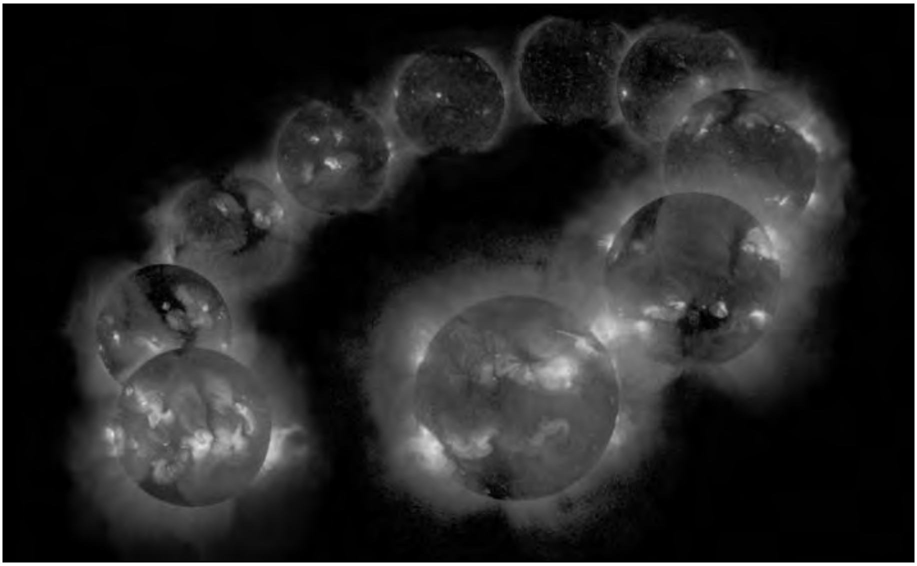

Figure 4–45. This mosaic of Yohkoh images shows the changing appearance of the solar corona during a solar activity cycle. Beginning in late 1991, these x-ray images depict the million-degree plasma of the Sun's atmosphere as it evolved from high activity (many hot active regions in the left-hand image), to very low activity (1995–1996, upper right-hand images), and back to high activity (1999, front image near center). Because only very hot plasmas emit x-rays, the much cooler surface of the Sun appears as a dark sphere underneath the radiating corona.[231]

Ongoing Physics and Astronomy Missions

Two physics and astronomy missions launched before 1989 continued to operate into the 1990s.

[231] The solar x-ray images are from the Yohkoh mission of ISAS, Japan. The x-ray telescope was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS.

Interplanetary Monitoring Platform (IMP)-8

The IMP-8 satellite, also called Explorer 50, was the last in a family of 10 IMPs. The IMP-8 was launched on October 26, 1973, into a nearly circular orbit about Earth at a radius of about 35 Earth radii (223,230 kilometers).[232] It spent 60 percent or more of each 12-day orbit in the solar wind and the rest of its time in the magnetosheath and magnetosphere. The IMP-8 was a spin-stabilized spacecraft, with its spin vector nearly perpendicular to the ecliptic plane, and a spin rate of 24 revolutions per minute.[233] Telemetry coverage was 90 percent in the early years, but only 60 to 70 percent through most of the 1980s and early 1990s. Coverage returned to the 90 percent range in the mid to late 1990s.

The IMP-8 was a drum-shaped spacecraft, 135.6 centimeters (53.4 inches) across and 157.4 centimeters (62 inches) high, instrumented for interplanetary and magnetotail studies of cosmic rays, energetic solar particles, plasma, and electric and magnetic fields.[234]

Experiments on the spacecraft were the following: 1) Magnetic Field Experiment (magnetometer); 2) Solar Plasma Faraday Cup; 3) Solid-State Detectors; 4) Measurement of Low-Energy Protons and Electrons; 5) Energetic Electrons and Protons (also called the Energetic Particle Experiment); 6) Electrons and Hydrogen and Helium Isotopes; 7) Cosmic Ray Nuclear Composition; 8) Solar and Cosmic-Ray Particles; 9) Charged Particle Measurements Experiment; 10), Solar Plasma Electrostatic Analyzer; 11) Electrostatic Fields; and 12) Electrostatic Waves and Radio Noise.

The IMP's magnetometer failed on June 10, 2000. The Charged Particle Measurements Experiment and the Energetic Particle Experiment operated successfully for 28 years and generated high-quality data leading to new discoveries and resulting in hundreds of publications. Both instruments continued to perform without problems until NASA terminated IMP-8 operations as an independent mission at the end of October 2001.[235] Telemetry acquisition resumed after about three months at the Canberra, Australia, ground station only (30 to 50 percent coverage) as an adjunct to the Voyager and Ulysses missions. As of August 2005, the IMP-8 continued in this mode.[236]

[232] The NSSDC Master Catalog Database says that IMP-8's initial orbit "was more elliptical than intended, with apogee and perigee distances of about 45 and 25 Earth radii" and "its eccentricity decreased after launch." *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

[233] "IMP-8 Charged Particle Measurement Experiment (CPME) and Energetic Particle Experiment (EPE)," *http://sd-www.jhuapl.edu/IMP/imp_index.html* (accessed October 20, 2005).

[234] "IMP-J," NSSDC Master Catalog Display: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

[235] "IMP-8 Charged Particle Measurement Experiment (CPME) and Energetic Particle Experiment (EPE)," *http://sd-www.jhuapl.edu/IMP/imp_index.html* (accessed October 20, 2005).

[236] "IMP-J," NSSDC Master Catalog Display: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

The IMP-8 was an important adjunct to the ISTP program. The IMP-8 provided in-ecliptic, one Astronomical Unit (AU) baseline data for the deep-space Voyager and Ulysses missions, and it accumulated a long time-series database useful in understanding long-term solar processes.[237]

International Ultraviolet Explorer

The International Ultraviolet Explorer (IUE) was launched into geosynchronous orbit at the end of NASA's second decade on January 26, 1978.[238] Totally dedicated to UV astronomy, the satellite operated for more than 18 years, long after its three-year to five-year expected lifetime. The spacecraft made the last of its astrophysical observations on September 27, 1996. The IUE remained operational until its hydrazine was deliberately vented and batteries were drained. The IUE transmitter turned off on September 30, 1996, after it received its final command to "shut down."[239]

The IUE was one of the most productive astronomical telescopes ever. Its 18 years and 8 months of operations returned 104,470 high-resolution and low-resolution spectra of 9,600 astronomical sources from all classes of celestial objects in the 1,150-angstrom to 3,350-angstrom UV band. These were transformed into 111,000 spectral files collected together and accessible worldwide through the ESA's IUE Newly Extracted Spectra (INES) system. The Laboratory for Space Astrophysics and Theoretical Physics in Spain operated the IUE INES for the astronomical community in close collaboration with the Canadian Astronomical Data Centre in Victoria, British Columbia. NASA maintains an IUE archival site, under the Multimission Archive at the Space Telescope Science Institute in Baltimore, Maryland.[240] Figure 4–46 shows IUE satellite-recorded spectra.

The IUE was a three-way collaborative project among NASA, the ESA, and the British Science and Engineering Research Council (later named the Particle Physics and Astronomy Research Council). The IUE operated in a real-time mode similar to ground-based observatories and was the only geosynchronous astronomy satellite capable of continuous observation 24 hours daily. More available observing hours per day and per year allowed researchers to explore and test ideas that may not have been possible with more restricted observing time.[241] Until October 1995, the IUE operated

[237] "IMP-8 Project Information," *http://nssdc.gsfc.nasa.gov/space/imp-8.html* (accessed October 20, 2005).

[238] Details of the IUE project can be found in Rumerman, *NASA Historical Data Book, Volume V, 1979–1998* (Washington, DC: National Aeronautics and Space Administration Special Publication-4012, 1999), pp. 399–401.

[239] Joseph King and Michael Van Steenberg, "IUE Final Archive Creation and Future Management: IUE, NSSDC, and STScI Roles," *NSSDC News* 14 (June 1998), *http://nssdc.gsfc.nasa.gov/nssdc_news/june98/01_j_king_0698.html* (accessed September 30, 2005).

[240] "IUE Science Results," ESA, *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31290* (accessed September 30, 2005).

[241] Y. Kondo, "Space Astronomy and IUE," in *Ultraviolet Astrophysics Beyond the IUE; Final Archive*, Proceedings of the Conference held in Sevilla, Spain, November 11–14, 1997 (The Netherlands: European Space Agency Special Publication-413, ESA Publications Division, 1998).

continuously, controlled 16 hours daily from Goddard Space Flight Center and 8 hours daily from the ESA facility at Villafranca, Spain. After October 1995, the operational scheme changed so that science operations were fully controlled from Villafranca, with 16 hours daily devoted to scientific operations and 8 hours daily in the low-quality part of the orbit used for spacecraft housekeeping.[242] About two-thirds of the observing time was allocated through NASA's competitive guest observer program with the remainder allocated through the ESA's equivalent program.[243]

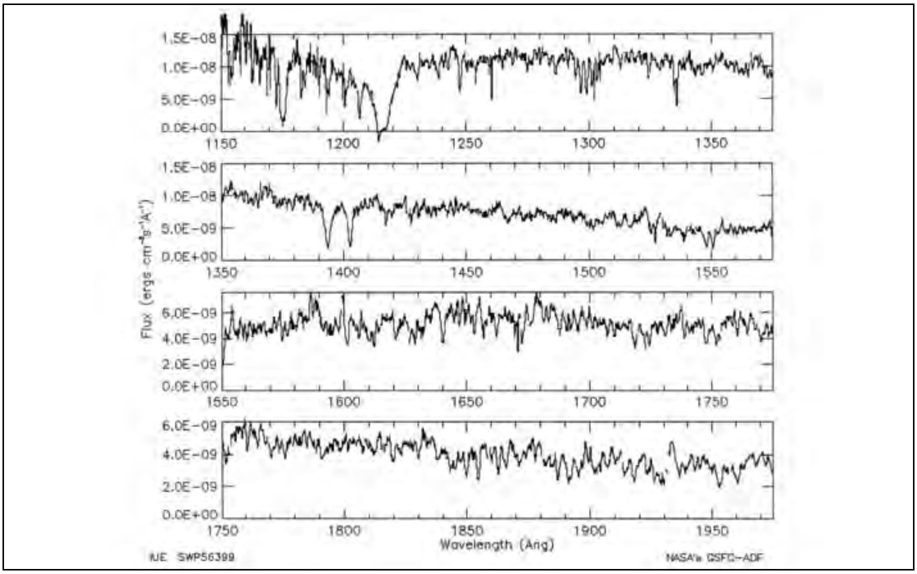

Figure 4–46. The IUE satellite recorded spectra in the UV wavelength region. The spectra (light flux versus wavelength) contain many absorption lines, or dips of flux at certain wavelengths. The strengths of these lines contain information about an astronomical object's chemical composition, the physical conditions such as temperature and pressure on the surface, and the component of any motion (the radial velocity) on the surface directed toward the external observer. (Credit: MAST/D. Massi)

During its lifetime, the IUE served more than 2,000 guest observers from around the world, including astronomers from North and South America; Europe; China; India; Russia; Africa; and Australia. Approximately 3,500 scientific articles in peer-reviewed journals were written based on IUE observations, more than any other satellite observatory to that time.[244] More than 1,000 European observing programs were conducted from the ESA's "IUE

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[242] "INES, IUE Newly Extracted Spectra," *http://ines.vilspa.esa.es/ines/Ines_PCentre/iue.htm* (accessed July 18, 2006).

[243] King and Van Steenberg, "IUE Final Archive Creation and Future Management: IUE, NSSDC, and STScI Roles," *NSSDC News* 14 (June 1998), *http://nssdc.gsfc.nasa.gov/nssdc_news/june98/01_j_king_0698.html* (accessed September 30, 2005).

[244] Jim Sahli, "IUE 'Lights Out,'" *Goddard News* 43 (November 1996): 5 (NASA History Office Folder 6079).

Observatory" at the Villafranca Satellite Tracking Station in Spain. The IUE was the first satellite designed as a common facility to be used by the world community of observers, the first scientific satellite to allow visiting astronomers to make real-time observations of UV spectra, and the first astronomical and satellite facility to deliver fully reduced data within 48 hours to the worldwide science community. The IUE also led to creation of the first worldwide astronomical reduced-data archive delivering 44,000 spectra per year (5 spectra per hour) to astronomers in 31 countries.[245] NASA maintains an IUE archival site, under the Multimission Archive at the Space Telescope Science Institute in Baltimore, Maryland. The project has received numerous recognitions during its lifetime, including the U.S. Presidential Award for Design Excellence, awarded to the IUE in 1988 during its 10th anniversary year.[246]

The spacecraft's only serious problems stemmed from the failures of five of the six gyroscopes in its ACS, occurring in 1979, 1982, 1982, 1985, 1991, and 1996. When the fourth gyroscope failed in 1985, the IUE continued operations owing to an innovative reworking of its ACS that substituted the fine Sun sensor. Even when the fifth gyroscope was lost in 1995, the IUE could still be stabilized in three axes (with only a single gyroscope) by adding star tracker measures.

During its lifetime, the IUE greatly surpassed its original science goals. Despite the value of the Hubble Space Telescope, which was launched in 1990, the IUE retained its importance because it covered the entire spectral region in ways not possible with the Hubble Space Telescope's high-resolution spectrographs in low-Earth orbit. The combination of the IUE and the Hubble Space Telescope provided a very efficient complementary function for astronomers.[247] The IUE's major scientific discoveries, taken from the INES Principal Centre, were the following:

- First detection of the existence of an aurora in Jupiter
- First detection of sulfur in a comet
- First quantitative determination of H_2O (water) loss in a comet (some 10 tons per second)
- First evidence for strong magnetic fields in chemically peculiar stars
- First orbital radial velocity curve for a WR (Wolf-Rayet) star allowing its mass determination
- First detection of hot dwarf companions to Cepheid variables
- First observational evidence for semi-periodic mass loss in high mass stars
- First discovery of high-velocity winds in stars other than the Sun

245 "INES, IUE Newly Extracted Spectra," *http://ines.vilspa.esa.es/ines/Ines_PCentre/iue.html* (accessed September 7, 2005).

246 Kondo, "Space Astronomy and IUE," in *Ultraviolet Astrophysics Beyond the IUE; Final Archive*.

247 "IUE Science Results," ESA, *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31290* (accessed September 30, 2005).

- First identification of the progenitor of any supernova in history (Supernova 1987A)
- Discovery of starspots on late type stars through Doppler mapping techniques
- Discovery of large-scale motions in the transition regions of low-gravity stars
- Discovery of high temperature effect in stars in the early stages of formation
- Discovery of high-velocity winds in cataclysmic variables
- Discovery of the effect of chemical abundance on the mass loss rate of stars
- First determination of a temperature and density gradient in a stellar corona outside the Sun
- First detection of gas streams within and outflowing from close binary stars
- The determination that no nova ejects material with solar abundance
- Discovery of the "O-Ne-Mg" (oxygen-neon-magnesium) novae, where the excess of these elements can be directly traced to the chemical composition of the most massive white dwarfs
- Discovery of a ring around Supernova 1987A, a leftover from previous evolutionary stages
- First direct detection of galactic halos
- First observations of extragalactic symbiotic stars
- First uninterrupted light curves of stars for more than 24 hours continuously
- First detection of photons at wavelengths less than 50 nanometers from any astronomical source apart from the Sun
- First direct determination of the size of the active regions in the nuclei of Seyfert galaxies (mini-quasars)
- First detection of a transparent sightline to a quasar at high redshift, allowing the first abundance determination of the intergalactic medium in the early universe

Suborbital Program

NASA's suborbital program used balloons, aircraft, and sounding rockets to conduct versatile, relatively low-cost research of Earth's ionosphere and magnetosphere; space plasma physics; stellar astronomy; solar astronomy; and high-energy astrophysics. Activities were conducted on both a national and international cooperative basis. The physics and astronomy program funded suborbital missions.

Sounding rockets carried scientific instruments into space along parabolic trajectories, providing nearly vertical traversals along their upleg and downleg while appearing to "hover" near their apogee location. The overall time in space was typically only 5 minutes to 20 minutes, for a well-placed scientific experiment, and the short time and low vehicle speeds were completely adequate (and sometimes ideal) to carry out a successful scientific experiment. Some important regions of space were too low to be sampled by satellites, so sounding rockets provided the only platforms that could carry out direct *in situ* measurements in these regions.

The sounding rocket program served as a less costly testbed for new scientific techniques, scientific instrumentation, and spacecraft technology eventually flown on numerous satellite missions. For example, COBE; CGRO; EUVE; FAST; ASTRO-2; UARS; SOHO; TRACE; and numerous other NASA satellite missions were enabled by technology and techniques developed in the suborbital program. The low cost of sounding rocket access to space fostered the following innovation: instruments and/or technologies which were not sufficiently developed to warrant the investment of satellite-program scale funding were often "prototyped" with initial space testing on sounding rockets.

Sounding rockets offered the following advantages:

- Quick, low-cost access to high altitudes where optical observations of astronomical, solar, and planetary sources could be made of radiation at wavelengths absorbed by Earth's lower atmosphere.
- Direct access to Earth's mesosphere and lower thermosphere (40 kilometers to 120 kilometers) (25 miles to 75 miles).
- Low cost.
- Rapid response times.
- Ability to fly relatively large payload (>500 kilograms) (1,102 pounds) masses on inexpensive vehicles.
- Provision of several minutes of ideal, "vibration-free" microgravity.
- Ability to use Earth's limb as an occulting disk to observe astronomical sources close to the Sun.
- Ability to gather *in situ* data in specific geophysical targets such as the aurora; the cusp; the equatorial electrojet; noctilucent clouds; and thunderstorms.
- Access to remote geophysical sites and southern hemisphere astronomical objects.
- Dwell times of several minutes at apogee.
- Slow vehicle speed with respect to the ambient medium (and much slower than that of orbiting satellites).
- Collection of vertical profiles of geophysical parameters.
- Ability to fly simultaneous rockets along different trajectories (e.g., with different apogees, flight azimuths).
- Ability to fly numerous free-flying sub-payloads from a single launch vehicle.
- Ability to recover and refly instruments.

NASA used 13 launch vehicles in the NASA Sounding Rocket Program. All NASA sounding rocket launch vehicles used solid propellant propulsion systems. Extensive use was made of 20-year-old to 30-year-old military surplus motors in 10 of the systems. All vehicles were unguided except those using the S-l9 Boost Guidance System. During flight, all launch vehicles were given a spinning motion to reduce potential dispersion of the flight trajectory due to vehicle misalignments.[248]

Figure 4–47 shows the four-stage Black Brant, one of NASA's commonly used sounding rocket models. At 66 feet (20 meters) tall, this rocket could carry scientific payloads weighing up to 1,213 pounds (550 kilograms) to altitudes of 800 miles (1,287 kilometers).

Figure 4–47. The four-stage Black Brant shown here blasting off from a launch pad at the Wallops Island Flight Facility in rural Virginia is at 66 feet (20 meters), the tallest of NASA's 13 sounding rockets. (NASA Photo No. WI-88-589-4)

[248] *Sounding Rocket Program Handbook*, Document 810-HB-SRP, July 2001, p. 28, *http://www.wff.nasa.gov/code810/docs/SRHB.pdf* (accessed October 25, 2005).

NASA used helium-filled balloons to conduct a variety of scientific studies. Wallops Flight Facility on the eastern shore of Virginia launched an average of 25 scientific balloons each year. Balloons were also launched routinely from the National Scientific Balloon Facility in Palestine, Texas, and the Scientific Balloon Flight Facility in Fort Sumner, New Mexico.

NASA balloons were constructed of thin, 0.002-centimeter (0.8-mil), polyethylene film, about the same thickness as ordinary sandwich wrap. The balloon system included the balloon, parachute, and payload containing the instruments to conduct the experiment, as well as the command and control electronics for the balloon.

Scientific balloons could carry a payload weighing as much as 8,000 pounds (3,630 kilograms), about the weight of three small cars. They could fly to an altitude of 26 miles (42 kilometers), with flights lasting an average of 12 to 24 hours. Some special-purpose, long-duration balloon flights lasted more than two weeks.

The development of an Ultra-Long Duration Balloon (ULDB) expanded the capabilities of the balloon program. The ULDB project developed advanced materials, a superpressure balloon design, and a standard gondola that included power and telemetry/command. The ULDB project also sought to extend flight duration. These advances could be applied to other commercial, DOD, and NASA science balloon missions. Figure 4–48 shows a balloon ready for launch at the National Scientific Balloon Facility in Palestine, Texas.

Table 4–62 lists NASA sounding rocket flights between 1989 and 1998; Table 4–63 lists NASA balloon flights during the same period.

Planetary/Solar System Exploration

NASA's Planetary and Solar System Exploration program encompassed the scientific exploration of the solar system, including the planets and their satellites, comets and asteroids, and the interplanetary medium. The objectives of planetary and solar system exploration missions were the following: 1) determine the nature of planets, comets, and asteroids as a means for understanding the origin and evolution of the solar system; 2) understand Earth better through comparative studies with the other planets; 3) understand how the appearance of life in the solar system related to the chemical history of the solar system; and 4) provide a scientific basis for future use of resources available in near-Earth space.

Magellan

Magellan was the first deep space mission launched by the United States in almost 11 years, and it also was the first launched by the Space Shuttle. Originally scheduled for 1988, NASA remanifested Magellan after the *Challenger* accident and elimination of the Centaur upper stage. The launch took place on May 4, 1989, on STS-30 with an inertial upper stage boosting the spacecraft into a Venus transfer orbit. It arrived at Venus on August 10, 1990, and was inserted into a near-polar elliptical orbit around the planet. Figure 4–49 shows the Earth-to-Venus trajectory.

Figure 4–48. Balloon Ready for Launch at the National Scientific Balloon Facility in Palestine, Texas.

The primary objectives of the Magellan mission were to map the surface of Venus with a synthetic aperture radar (SAR) and to determine the topographic relief of the planet. The Magellan mission scientific objectives were to study land forms and tectonics, impact processes, erosion, deposition, and chemical processes, as well as model the interior of Venus. At the completion of radar mapping, 98 percent of the surface was imaged at resolutions better than 100 meters (328 feet), and many areas were imaged multiple times.

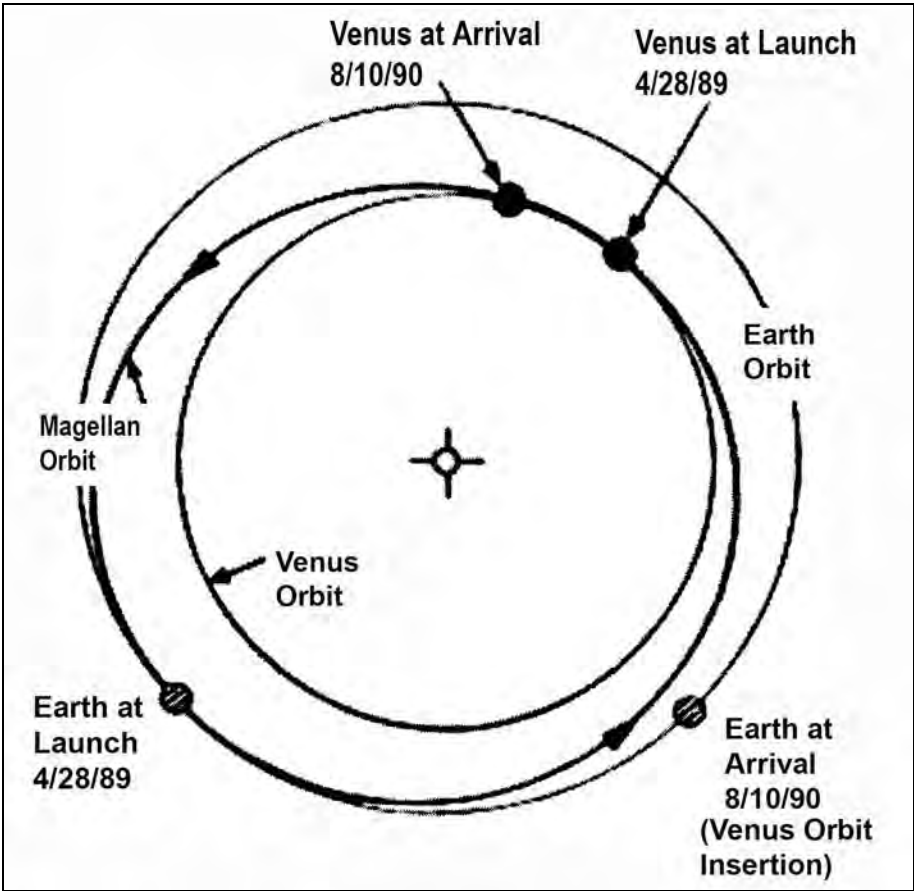

Figure 4–49. Magellan Earth-to-Venus Trajectory.

A radar system was used for Venus mapping because it could penetrate the thick clouds covering the planet while optical photography could not. Magellan's SAR created high-resolution images by using computer processing on Earth to simulate a large antenna on the spacecraft. The on-board radar system operated as though it had a huge antenna, hundreds of meters long. Its actual diameter was 12 feet (3.7 meters) in diameter.[249] (Real aperture radar can be used to make images, but their resolution is poor.)

Magellan's initial orbit was highly elliptical, taking it as close as 294 kilometers (182 miles) from Venus and as far away as 8,543 kilometers (5,296 miles). The orbit flew over Venus's north and south poles. Magellan completed one orbit every 3 hours, 15 minutes. During the part of its orbit closest to Venus, Magellan's radar mapper imaged a swath of the planet's surface ranging from 17 kilometers to 28 kilometers (10 miles to 17 miles) wide. At the end of each

[249] "Space Shuttle Mission STS-30" Press Kit, April 1989, *http://science.ksc.nasa.gov/shuttle/missions/sts-30/sts-30-press-kit.txt* (accessed September 15, 2005).

orbit, the spacecraft radioed back to Earth a map of a long ribbon-like strip of the planet's surface captured during that orbit. Venus rotated once every 243 Earth days (about eight months). Each of these periods was called a "cycle." During each cycle, Magellan collected several strips of radar image data while the planet rotated under the spacecraft, eventually covering the entire globe by the end of the 243-day orbital cycle.[250] Figure 4–50 shows Magellan's Venus orbital operations.

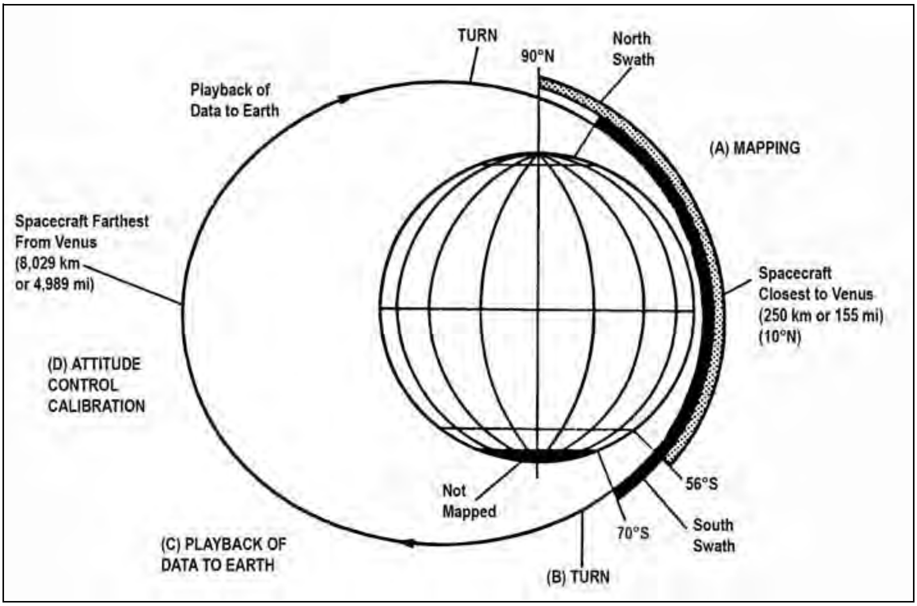

Figure 4–50. Magellan Venus Orbital Operations.

By the end of its first eight-month orbital cycle between September 1990 and May 1991, Magellan had returned to Earth detailed images of 84 percent of Venus's surface. The spacecraft then conducted radar mapping on two more eight-month cycles from May 1991 to January 1992 and from January 1992 to September 1992. This allowed Magellan to capture detailed maps of 98 percent of the planet's surface. The follow-on cycles also allowed scientists to look for any changes in the surface from one year to the next. In addition, because the "look angle" of the radar was slightly different from one cycle to the next, scientists could construct three-dimensional views of Venus's surface.

During Magellan's fourth eight-month orbital cycle at Venus, from September 1992 to May 1993, the spacecraft collected data on the planet's gravity field. During this cycle, Magellan did not use its radar mapper but instead transmitted a constant radio signal to Earth. If it passed over an area of Venus with higher than normal gravity, the spacecraft would slightly speed up in its orbit. This caused the frequency of Magellan's radio signal to change

[250] "Magellan Summary Sheet," *http://www2.jpl.nasa.gov/magellan/fact1.html* (accessed August 16, 2005).

very slightly due to the Doppler effect. Due to the ability of radio receivers in the NASA/JPL DSN to measure frequencies with very high accuracy, scientists could build a detailed gravity map of Venus.

At the end of Magellan's fourth orbital cycle in May 1993, flight controllers lowered the spacecraft's orbit using a then-untried technique called aerobraking. This maneuver sent Magellan dipping into Venus's atmosphere once every orbit; the atmospheric drag on the spacecraft slowed it and lowered its orbit. When the aerobraking was completed on August 3, 1993, Magellan's orbit reached 180 kilometers (112 miles) from Venus at its nearest point and 541 kilometers (336 miles) at its most distant point. Magellan also circled Venus more quickly, completing an orbit every 94 minutes. This new, more circularized orbit allowed Magellan to collect better gravity data in the higher northern and southern latitudes near Venus's poles.

After the end of the fifth orbital cycle in April 1994, Magellan began a sixth and final orbital cycle, collecting more gravity data and conducting radar and radio science experiments. By the end of the mission in October 1994, Magellan had captured high-resolution gravity data for an estimated 95 percent of the planet's surface.[251]

In September 1994, Magellan's orbit was lowered once more in another test called a "windmill experiment." In this test, the spacecraft's solar panels were turned to a configuration resembling the blades of a windmill, and Magellan's orbit lowered into the thin outer reaches of Venus's dense atmosphere. Flight controllers then measured the amount of torque control required to maintain Magellan's orientation and keep it from spinning. This experiment gave scientists data on the behavior of molecules in Venus's upper atmosphere, and it gave engineers new information useful in designing spacecraft.[252] The mission ended on October 12, 1994 when the spacecraft was commanded to drop lower into the fringes of the Venusian atmosphere during an aerodynamic experiment and, as expected, burned up. Table 4–64 lists major mission events.

The spacecraft consisted of the structure and thermal control, power, attitude control, propulsion, command data and data storage, and telecommunications subsystems. The structure included the high-gain antenna, forward equipment module, spacecraft bus including solar array, and orbit-insertion stage. The high-gain antenna was used as the antenna for the SAR as well as the primary antenna for the telecommunications system to return data to Earth. The parabolic dish was made of strong, lightweight graphite epoxy sheets mounted on an aluminum honeycomb for rigidity. The parabolic dish was a spare from the Voyager project.

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[251] Douglas G. Griffith, Magellan Project Manager (retired), e-mail received September 19, 2005.

[252] "Magellan Mission to Venus," NASA Facts, Jet Propulsion Laboratory, July 1996, updated February 2002, *http://www.jpl.nasa.gov/news/fact_sheets/mgn.pdf* (accessed September 16, 2005).

Magellan's cone-shaped medium-gain antenna received commands and sent engineering data during the 15-month cruise from Earth. A low-gain antenna provided the ground team with an alternative means of commanding the spacecraft in case an emergency prevented use of normal data rates. The altimeter antenna was mounted to one side of the high-gain antenna and pointed vertically down at the surface of Venus during the radar data acquisitions. The forward equipment module contained the radar electronics, the reaction wheels controlling the spacecraft's attitude, and other subsystem components.

The bus was a 10-sided structure. The bus housed the remainder of the subsystem components, including the solar panel array, star scanner, medium-gain antenna, rocket engine modules, command data and data storage subsystem, monopropellant tank, and nitrogen tank for propellant pressurization.

The orbit insertion stage contained a Star 48 solid rocket motor to place the spacecraft into orbit around Venus. Once in orbit, the motor casing was jettisoned. The rocket motor weighed 4,721 pounds (2,141 kilograms), of which 4,430 pounds (2,009 kilograms) were fuel. It had 15,232 pounds (67,755 newtons) of thrust. A combination of louvers, thermal blankets, passive coatings, and heat-dissipating elements controlled the spacecraft's temperature. Normal operating temperature for the spacecraft components ranged between 25°F (-4°C) and 104°F (40°C).

Two solar panels powered the spacecraft and experiments. The array could produce 1,200 watts of power. Two nickel cadmium batteries provided power when the spacecraft was shadowed by the planet, and the batteries allowed normal spacecraft operations independent of solar illumination. The solar arrays charged the batteries.

Electric motors drove the three reaction wheels, which controlled the spacecraft's attitude in relation to the planet and stored momentum while they were spinning. At a point in each orbit near apoapsis, the rocket motors were used to counteract the torque on the spacecraft as the reaction wheels were despun to eliminate excess momentum. There was one reaction wheel for each of the spacecraft's axes—yaw, pitch, and roll. The spacecraft also had 24 thrusters for trajectory correction and attitude control. Figure 4–51 shows a drawing of the spacecraft.

Magellan showed Venus as an Earth-sized planet with no evidence of Earth-like plate tectonics. The landscape was dominated by volcanic features, faults, and impact craters.[253] At least 85 percent of the surface was covered with volcanic flows, the remainder by highly deformed mountain belts. Huge areas of the surface showed evidence of multiple periods of lava flooding with flows lying on top of previous ones. Even with the high surface temperature (475°C) (887°F) and high atmospheric pressure (92 bars), the complete lack of water made erosion a negligibly slow process, and surface features could persist for hundreds of millions of years. Some surface modification in the

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[253] "Venus," *http://www1.jsc.nasa.gov/er/seh/venus.html* (accessed May 9, 2006).

form of wind streaks was observed. More than 80 percent of Venus lay within 1 kilometer of the mean radius of 6,051.84 kilometers (3,766.7 miles). The mean surface age was estimated to be about 500 million years. A major unanswered question was whether the entire surface had been covered in a series of large events 500 million years ago or if it had been covered slowly over time. The gravity field of Venus was highly correlated with the surface topography, which indicated that the mechanism of topographic support was unlike Earth's, and the topography might be controlled by processes deep in the interior. Details of the global tectonics on Venus remained unresolved.[254] Figure 4–52 shows a section of a Magellan radar image.[255] Figure 4–53 shows a three-dimensional representation of brightness variations in a radar image of Golubkina crater. Table 4–65 provides further mission details.

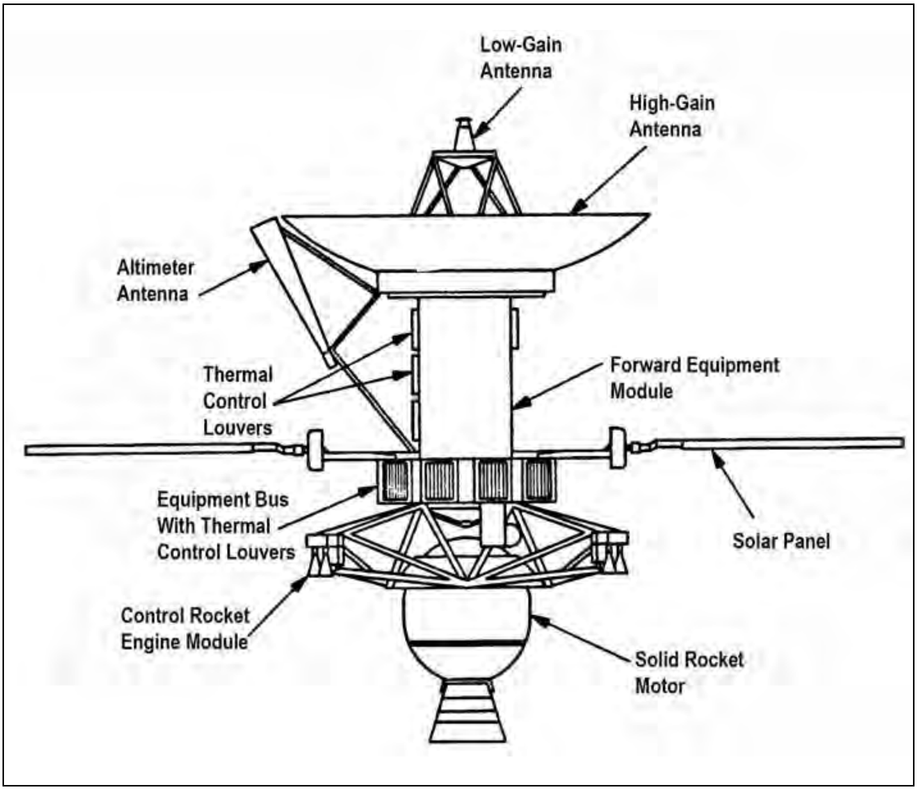

Figure 4–51. Magellan Spacecraft.

[254] "Magellan Mission to Venus," *http://nssdc.gsfc.nasa.gov/planetary/magellan.html* (accessed September 16, 2005).
[255] "Magellan Mission to Venus." Also "Magellan Summary Sheet," *http://www2.jpl.nasa.gov/magellan/fact1.html* (accessed August 16, 2005).

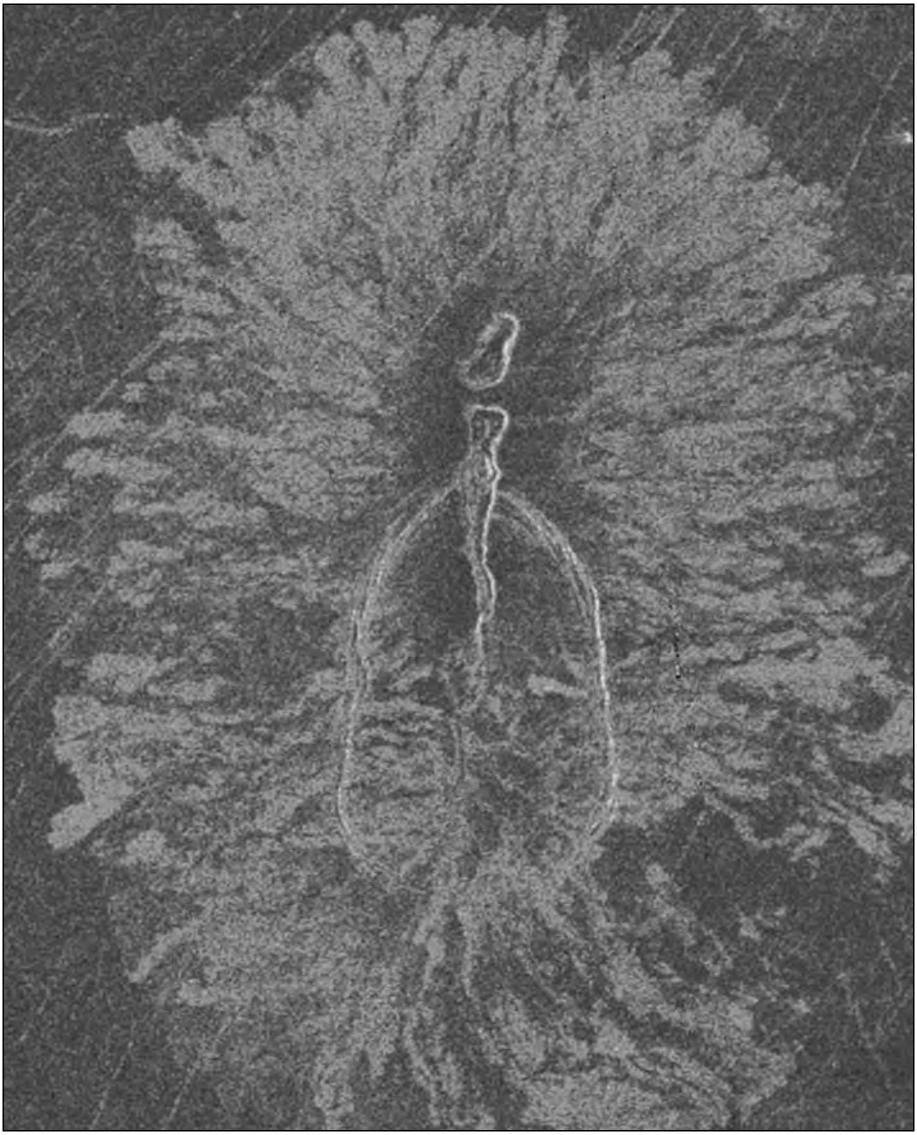

Figure 4–52. Shown is a section of a Magellan radar image of a 40-kilometer by 60-kilometer (25-mile by 37-mile) "petal" type Venusian volcano in eastern Aphrodite Terra. (NSSDC Image Catalog)

Galileo

The Galileo mission, one of NASA's most ambitious deep space exploration projects, used remote sensing by an orbiter and *in situ* measurements by an atmospheric probe to make a comprehensive, long-term study of Jupiter's atmosphere, magnetic field, and moons. Named for the Italian Renaissance scientist Galileo Galilei, who discovered Jupiter's major moons in 1610, the mission was the first to use an instrumented probe to make direct measurements in Jupiter's atmosphere and the first to conduct long-term observations of the planet and its magnetosphere and satellites from orbit around Jupiter. The Galileo mission was also the first to encounter an asteroid and photograph an asteroid's moon.

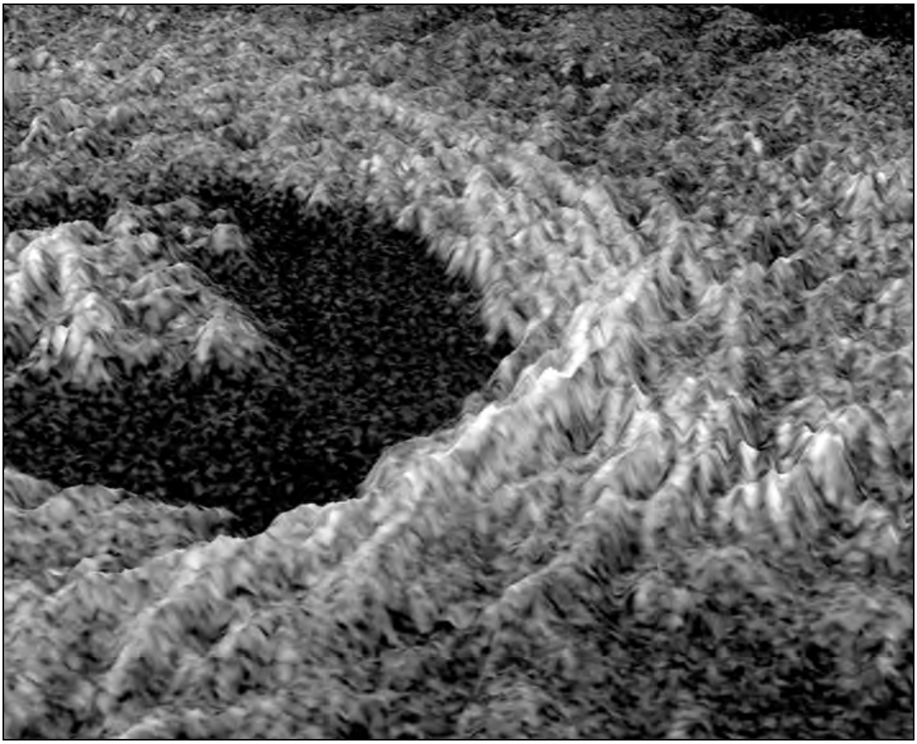

Figure 4–53. This three-dimensional representation of brightness variations in a radar image of Golubkina crater on Venus enhances the structural features of the crater. Golubkina is characterized by terraced inner walls and a central peak typical of large impact craters on Earth, the Moon, and Mars. The terraced inner walls form at late stages in the formation of an impact crater, due to collapse of the initial cavity formed by the meteorite impact. The central peak forms due to rebound of the inner crater floor. (NASA-JPL Photo No. PIA00209)

JPL designed and developed the orbiter spacecraft and operated the mission. Ames Research Center developed the atmospheric probe with Hughes Aircraft Company as prime contractor. The German government was a partner in the mission, providing the spacecraft propulsion subsystem and two science experiments. Scientists from six nations participated in the mission. Galileo communicated with its controllers and scientists through NASA's DSN tracking stations in California, Spain, and Australia.[256]

[256] "Galileo Overview," *http://www2.jpl.nasa.gov/galileo/overview.html* (accessed September 12, 2005).

The 2,223-kilogram (2.5-ton) Galileo orbiter spacecraft carried 10 scientific instruments; the 339-kilogram (750-pound) probe carried another seven. In addition, the spacecraft radio link to Earth and the probe-to-orbiter radio link served as instruments for other scientific investigations.

Galileo consisted of three segments: the atmospheric probe, a non-spinning (or "despun") section of the orbiter, and the spinning main section of the orbiter. This innovative "dual spin" design allowed part of the orbiter to rotate constantly at 3 revolutions per minute and part of the spacecraft to remain fixed. The orbiter could easily accommodate magnetospheric experiments (which need to take measurements while rapidly sweeping about) while providing stability and a fixed orientation for cameras and other sensors. While the spacecraft flew throught various environments, the spinning section included the fields and particles instruments that sensed and measured the environments directly. The spinning section also held with the main antenna, the power supply, the propulsion module, most of the computers, and control electronics. The despun section carried instruments and other remote sensors whose operation depended on a steady pointing capability. Figure 4–54 shows the spacecraft.

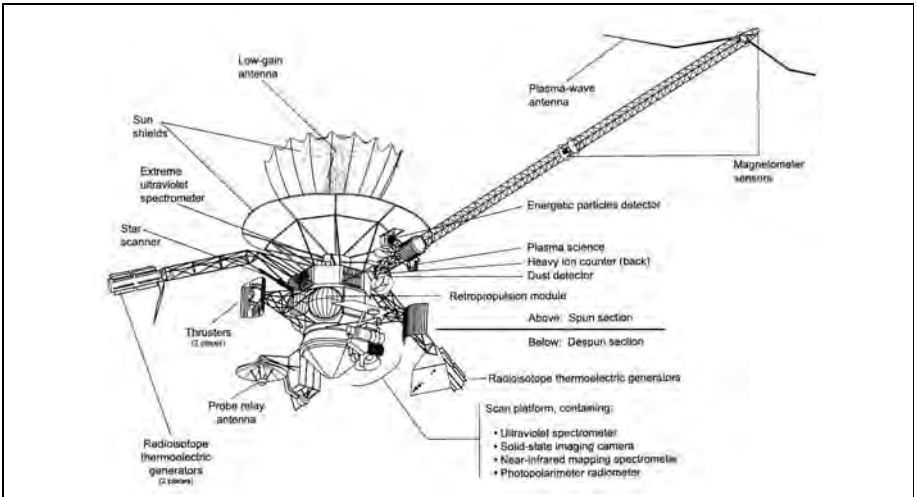

Figure 4–54. Galileo Spacecraft.

Mission Events

Galileo was originally designed for a direct flight to Jupiter of about three and one-half years using a three-stage inertial upper stage booster. When that booster was canceled, plans changed to an early 1985 launch on a Shuttle/Centaur upper stage combination. That was delayed first to 1986 and then to 1989 because of the *Challenger* accident and cancellation of the Centaur upper stage for use with the Shuttle. A two-stage inertial upper stage replaced the Centaur, but its lesser capabilities precluded a direct trajectory toward Jupiter. When the Galileo spacecraft was launched on October 18, 1989, on STS-34, the two-stage inertial upper stage boosted it into an unusual Venus-Earth-Earth Gravity Assist (VEEGA) trajectory that would provide the spacecraft with the energy needed to reach Jupiter. In a gravity assist, the spacecraft flies close enough to a planet to be propelled by its gravity, in essence, "stealing" some angular momentum during a flyby of a planet in motion and "removing" momentum from that planet.[257]

The roundabout path required a flight time of a little more than six years. The spacecraft flew past Venus at an altitude of 16,000 kilometers (nearly 10,000 miles) on February 10, 1990. It swung past Earth at an altitude of 960 kilometers (597 miles) on December 8, 1990. That flyby increased Galileo's speed enough to send it on a two-year elliptical orbit around the Sun. The spacecraft made a second Earth swingby exactly two years later on December 8, 1992, at an altitude of 303 kilometers (188 miles) and then headed toward Jupiter. Table 4–66 lists major mission events. Figure 4–55 shows Galileo's trajectory to Jupiter and major events.

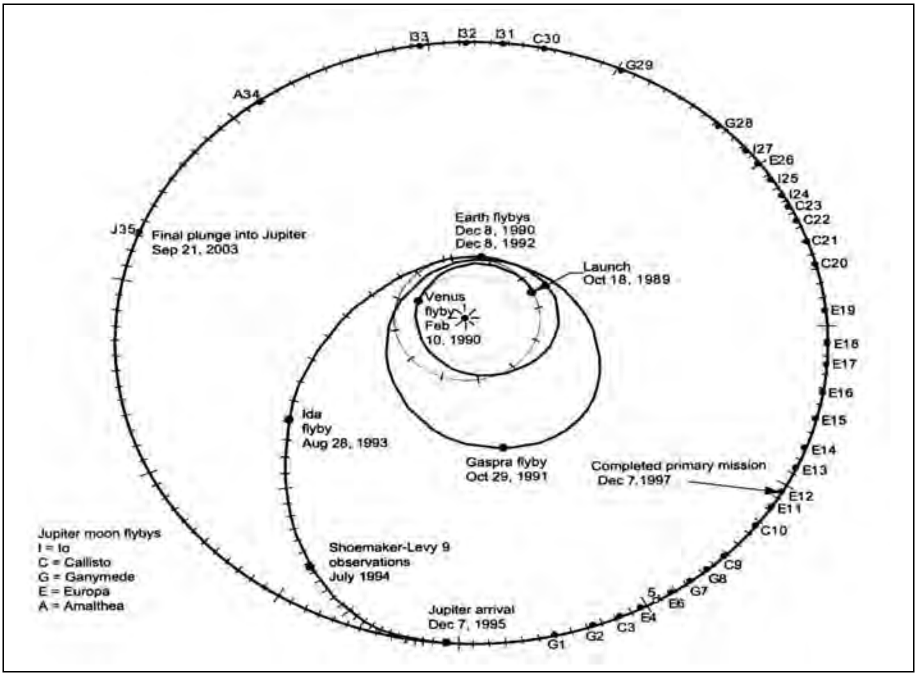

Figure 4–55. Galileo Trajectory.

257 Rather than comparing its motion to a slingshot, when a spacecraft uses a gravity assist, the spacecraft comes up and steals some angular momentum during a single flyby of a planet in motion, removing momentum from that planet. A gravity assist is much more like a ping-pong ball hitting the revolving blade of a ceiling fan, taking energy from the fan blade, and bouncing off at a speed greater than it had coming in. "Cassini-Huygens: Mission–Gravity Assists/Flybys, A Quick Gravity Assist Primer," *http://saturn1.jpl.nasa.gov/mission/gravity-assist-primer2.cfm* (accessed September 20, 2005).

The flight path provided opportunities for scientific observations. Scientists obtained the first views of midlevel clouds on Venus and confirmed the presence of lightning on that planet. Scientists also made many Earth observations, mapped the surface of Earth's Moon, and observed its north polar regions.[258]

Because of the trajectory around the Sun, Galileo was exposed to a hotter environment than originally planned. To protect it from the Sun's heat, project engineers devised a set of sunshades and pointed the top of the spacecraft toward the Sun, with the umbrella-like high-gain antenna remaining furled until well after the first Earth flyby in December 1990. Flight controllers communicated with the spacecraft through a pair of low-gain antennae, which sent and received data at a much lower rate.

On April 11, 1991, after Galileo traveled far enough from the heat of the Sun to reduce its exposure to extreme temperatures, the spacecraft executed stored computer commands designed to unfurl the large high-gain antenna. But telemetry received minutes later showed that the motors had stalled, and the antenna had only partially opened. After analyzing Galileo's telemetry and testing on the ground with an identical spare antenna, a team of more than 100 technical experts from JPL and private industry concluded that the problem was most likely due to the sticking of a few antenna ribs. This sticking was caused by friction between their standoff pins and sockets resulting from the loss of lubricant between the parts. The loss of lubricant had been caused by vibrations that the antenna had experienced during several cross-country truck trips between Florida and JPL in California during launch delays.

All attempts to free the stuck hardware failed, including heating and cooling the apparatus by turning it toward and away from the Sun, "hammering" the antenna deployment motors, and spinning the spacecraft at its fastest rotation rate. After efforts lasting more than four years, the project concluded that there was no significant prospect of the antenna being deployed. At the same time, from 1993 to 1996, extensive new flight and ground software was being developed and ground stations of NASA's DSN enhanced to use the spacecraft's low-gain antennae to accomplish the mission. In March 1996, project engineers radioed new software to the spacecraft, inaugurating advanced data compression techniques designed specifically for use with the low-gain antenna. The new software provided programs to "shrink" the voluminous science data that the Galileo orbiter collected and stored on its tape recorder. Software changes, coupled with hardware and software adaptations at ground receiving stations, increased the data rate from Jupiter by as much as 10 times, to 160 bits per second.[259]

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[258] "Galileo End of Mission Press Kit," September 2003, *http://www.jpl.nasa.gov/news/press_kits/galileo-end.pdf* (accessed September 13, 2005).

[259] "Galileo Jupiter Arrival Press Kit," December 1995, *http://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf* (accessed September 12, 2005).

Galileo's two planned visits to the asteroid belt on its way to Jupiter provided opportunities for close observation of these bodies. On October 29, 1991, the spacecraft passed the asteroid Gaspra, flying within 1,601 kilometers (1,000 miles) of its center at a relative speed of about 8 kilometers per second (18,000 miles per hour). The spacecraft obtained the world's first close-up asteroid images, revealing a cratered, complex, irregular body about 20 kilometers by 12 kilometers by 11 kilometers (12.4 miles by 7.4 miles by 6.8 miles) with a thin covering of dust and rubble. Figure 4–56 shows the Gaspra asteroid.

Figure 4–56. This picture of asteroid 951 Gaspra is a mosaic of two images taken by Galileo from 5,300 kilometers (3,300 miles) away some 10 minutes before its closest approach on October 29, 1991. The Sun is shining from the right. A striking feature of Gaspra's surface is the abundance of small craters. More than 600 craters 100 meters to 500 meters (330 feet to 1,650 feet) in diameter are visible. Gaspra's very irregular shape suggests that the asteroid was split from a larger body by nearly catastrophic collisions. (NASA-JPL Photo No. PIA00119)

At the end of August 1993, Galileo flew by a second asteroid, Ida, and discovered the first confirmed asteroid moon. The tiny moon, named Dactyl, had a diameter of only about 1.5 kilometers (less than a mile). Ida was about 55 kilometers (34 miles) long and 24 kilometers (15 miles) wide. Observations indicated that both Ida and Gaspra had magnetic fields. Ida was older than Gaspra, and its surface also was cratered. Figure 4–57 shows Ida and its moon, Dactyl.

In July 1994, Galileo was the only observer in position to obtain images of the far side of Jupiter when more than 20 fragments of comet Shoemaker-Levy plunged into Jupiter's night-side atmosphere during a six-day period. Figure 4–58 shows four images of the comet taken by Galileo.

Arrival at Jupiter

At launch, the spacecraft consisted of an orbiter and a probe. These two elements journeyed together toward Jupiter until July 13, 1995, when the probe was released on a trajectory guiding it into Jupiter's atmosphere. The probe had no engine or thrusters, thus its flight path was established by pointing the Galileo orbiter before the probe's release. Two weeks after the probe was released from the spacecraft on July 27, the orbiter performed the first sustained firing of its main rocket engine while readjusting its flight path toward Jupiter and performing a flyby of Jupiter's volcanic moon Io.[260] On November 26, the orbiter entered Jupiter's environment, crossing over the boundary from interplanetary space into its magnetosphere.[261]

On December 7, 1995, Galileo flew past two of Jupiter's major moons, Europa and Io. Galileo passed Europa at an altitude of about 33,000 kilometers (20,000 miles) and Io at an altitude of about 900 kilometers (600 miles). The same day, Galileo's probe penetrated the top of Jupiter's atmosphere traveling 170,000 kilometers per hour (106,000 miles per hour) while withstanding temperatures twice as hot as the Sun's surface. The probe slowed by aerodynamic braking for about 2 minutes before deploying its parachute and dropping a heat shield. While the orbiter flew 215,000 kilometers (134,000 miles) overhead, the probe floated about 200 kilometers (125 miles) down through the clouds, transmitting data to the orbiter on sunlight and heat flux; pressure; temperature; winds; lightning; and atmospheric composition. The probe sent data from a depth with pressure 23 times that of Earth's average pressure, more than twice the mission requirement. After 58 minutes, the probe succumbed to high temperatures and stopped transmitting.[262] Figure 4–59 illustrates the probe's mission events.

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[260] "Galileo End of Mission Press Kit." Also "Orbiter Deflection Maneuver Status July 27," *http://www2.jpl.nasa.gov/galileo/odm.html* (accessed September 13, 2005).

[261] "Galileo Crosses Boundary into Jupiter's Environment," Jet Propulsion Laboratory Status Report, (December 1, 1995), *http://www2.jpl.nasa.gov/galileo/status951201.html* (accessed September 12, 2005).

[262] "The Galileo Spacecraft," *http://www2.jpl.nasa.gov/galileo/spacecraft.html* (accessed September 12, 2005). Also "Galileo Probe Mission Science Summary," May 10, 1996, *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/Science_summary.html* (accessed September 13, 2005).

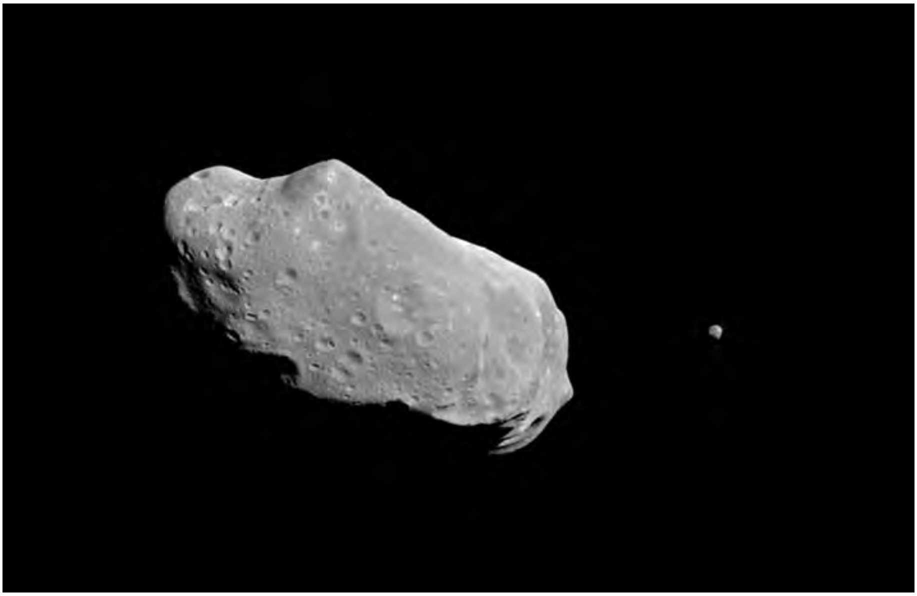

Figure 4–57. This is the first full picture showing both asteroid 243 Ida and its newly discovered moon transmitted to Earth from the Galileo spacecraft—the first conclusive evidence that natural satellites of asteroids exist. Ida, the large object, is about 55 kilometers (34 miles) long. Ida's natural satellite is the small object to the right. This portrait was taken by Galileo's CCD camera on August 28, 1993, about 14 minutes before the spacecraft's closest approach to the asteroid, from a range of 10,870 kilometers (6,755 miles). (NASA-JPL Photo No. PIA00136)

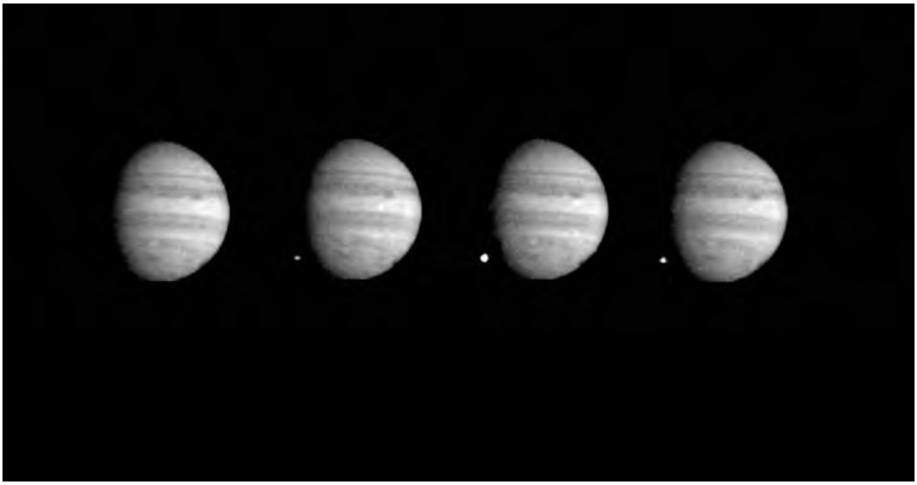

Figure 4–58. These four images of Jupiter and the luminous night-side impact of fragment W of comet Shoemaker-Levy 9 were taken by the Galileo spacecraft on July 22, 1994. The spacecraft was 238 million kilometers (148 million miles) from Jupiter at the time, and 621 million kilometers from Earth. The spacecraft was about 40 degrees from Earth's line of sight to Jupiter, permitting this direct view. (NASA-JPL Photo No. PIA00139)

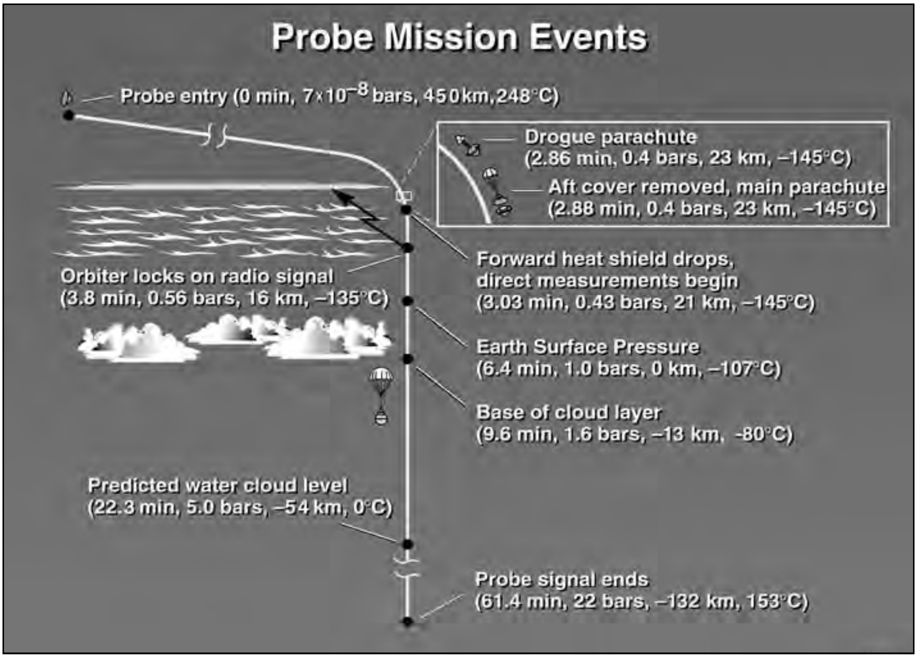

Figure 4–59. Galileo Probe Mission to Jupiter. (Minutes refer to the amount of time that had passed since the probe entered Jupiter's atmosphere.)[263]

Probe Science Findings

During its 58 minutes in the Jovian atmosphere, Galileo's probe made several important scientific discoveries. Some of these were very surprising, possibly because the probe entered Jupiter near the edge of a so-called infrared "hot spot." These hot spots were believed to represent regions of diminished clouds on Jupiter to the extent of being among the clearest and driest spots on the planet.

- The Energetic Particle Instrument (EPI) discovered a new, intense radiation belt between Jupiter's ring and the uppermost atmospheric layers while measuring the radiation in the previously unexplored inner regions of Jupiter's magnetosphere. The radiation in this belt measured approximately 10 times as strong as Earth's Van Allen radiation belts and included high-energy helium ions of unknown origin.
- Initial results from Atmosphere Structure Instrument (ASI) measurements of the temperature, pressure, and density structure of Jupiter's atmosphere from the uppermost regions down through an atmospheric pressure of about 24 bars found upper atmospheric densities and temperatures significantly higher than expected.[264] An additional source of heating

[263] Richard Young, Ames Research Center (e-mail dated September 16, 2005).
[264] An atmospheric pressure of 24 bars is 24 times the atmospheric pressure at sea level on Earth, equal to the pressure at a depth of 230 m (750 ft) in the ocean.

beyond sunlight appeared necessary to account for that result. At deeper levels, the temperatures and pressures were close to expectations. The vertical variation of temperature in the 6-bar to 15-bar pressure range (about 100 kilometers to 150 kilometers below visible clouds) indicated that the deep atmosphere was drier than expected and also was convective. These results suggested the need to reconsider accepted ideas about the abundance and distribution of water on Jupiter.

- The Nephelometer (NEP) instrument, which searched for cloud particles next to the probe, found far less than expected. It did not find thick, dense clouds, and visibility in the atmosphere was much greater than expected in the immediate vicinity of the probe entry site.
- The Net Flux Radiometer (NFR) detected a dense cloud at a far distance away from the probe entry site. Large variations in the brightness of the sky in different directions were noticed until an abrupt drop in the variation below the 0.6-bar pressure level; this indiacted that a cloud layer was most likely the previously postulated ammonia cloud layer, a layer believed to be Jupiter's uppermost cloud layer. The cloud seen by this instrument was not seen by the NEP, leading investigators to conclude the clouds were patchy and the probe went through a relatively clear area.
- Initial results from the Doppler Wind experiment indicated that the winds below the clouds blew at 700 kilometers per hour (435 miles per hour) and were roughly independent of depth. Winds at the cloud tops monitored by the Hubble Space Telescope were of similar strength. These results suggested that winds on Jupiter were probably not produced by heating due to sunlight or condensation of water vapor, two heat sources powering winds on Earth. Rather, a likely mechanism for powering Jovian winds appeared to be heat escaping from the planet's deep interior.
- The Lightning and Radio Emission Detector (LRD) searched for optical flashes and radio waves emitted by lightning discharges. The LRD did not observe optical lightning flashes in the vicinity of the probe but observed many discharges at radio frequencies. The form of the radio signals indicated that the discharges were roughly one Earth diameter away, and the lightning bolts were much stronger than those in Earth's atmosphere. Radio wave intensity suggested that lightning activity was 3 to 10 times less common than on Earth; the intensity also suggested that lightning on Jupiter was very different than on Earth.
- Initial results obtained with the Neutral Mass Spectrometer (NMS) and Helium Abundance Detector (HAD) found several key elements in nearly solar proportions in Jupiter's atmosphere, providing fundamental clues to Jupiter's formation and evolution. The NMS indicated that the atmosphere had much less oxygen—mainly found as water vapor in Jupiter's atmosphere—than the Sun's atmosphere, implying a surprisingly dry atmosphere. The amount of carbon—mainly found as methane gas—was highly enriched with respect to the Sun, while sulfur (in the form of

hydrogen sulfide gas) occurred at greater than solar values. The abundance of neon was highly depleted. Little evidence of organic molecules was found. The HAD very accurately measured the abundance of helium in Jupiter's atmosphere and found the relative abundance of helium approached the level in the Sun's atmosphere.[265]

Galileo's Tour

On December 7, 1995, an hour after receiving the last transmission from the probe 200,000 kilometers (130,000 miles) above the planet, the Galileo spacecraft fired its main engine to brake into orbit around Jupiter, beginning its 23-month, 11-orbit tour of Jupiter's magnetosphere and moons, including 10 close satellite encounters (see Figure 4–60).

The first orbit lasted about seven months. Galileo fired its thrusters at its farthest point in the orbit to keep it the needed distance from Jupiter on later orbits. This adjustment helped reduce the likelihood of damage to spacecraft sensors and computer chips from Jupiter's intense radiation environment. During this orbit, new software was installed, giving the spacecraft additional data processing capabilities needed because of its reliance on its low gain antenna.[266]

During its primary mission orbital tour lasting two years, Galileo made four flybys of Jupiter's moon Ganymede, three of Callisto, and three of Europa. These encounters came about 100 to 1,000 times closer than those performed by NASA's Voyager 1 and 2 spacecraft in 1979. Galileo's instruments scanned and scrutinized the surface and features of each moon. After about a week of intensive observations, when its tape recorder was full of data, the spacecraft spent the period until the next orbital encounter playing back and transmitting the information to Earth.[267] During its two-year primary mission orbital tour, Galileo's orbiter returned 2.4 gigabits of data; the probe returned 3.5 megabits obtained during its 1 hour of operations. In spite of a failed high-gain antenna and some problems with the tape recorder, Galileo accomplished more than 70 percent of its original prime mission science objectives.[268]

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[265] "Galileo Probe Mission Science Summary," May 10, 1996, *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/Science_summary.html* (accessed September 13, 2005).
[266] "Galileo End of Mission Press Kit."
[267] "Galileo End of Mission Press Kit."
[268] "The Galileo Mission at Jupiter–Fact Sheet," (no date), *http://www2.jpl.nasa.gov/galileo/Page_1_GEM_Fact_Sheet.pdf* (accessed September 14, 2005).

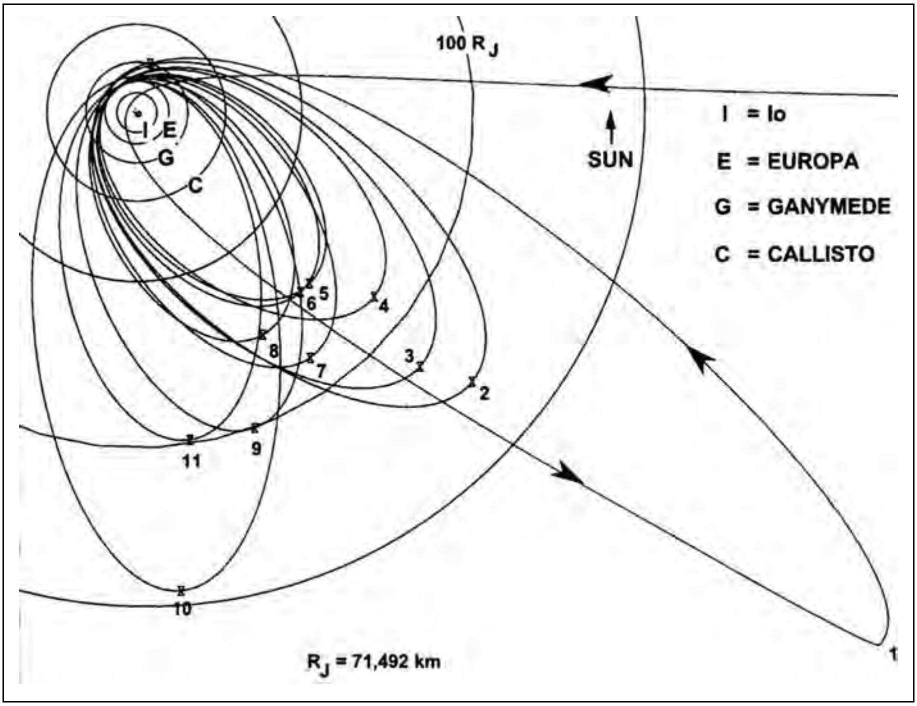

Figure 4–60. This diagram shows the series of 11 flower-shaped orbits on Galileo's primary mission. After the first encounter, the orbits were much shorter, and the time for each ranged from one to two and one-half months

Orbital Tour Science

Galileo's primary mission included a number of key science findings.[269] Some of these findings included the following:

- *Jupiter's Storms and Rings*. Data from the probe's plunge into the top cloud layers of Jupiter and from the orbiter's search for water indicated that Jupiter's billowing thunderstorms were many times larger than those on Earth. These storms resulted from the vertical circulation of water in the top layers, leaving some large areas (such as the probe entry site) where air descended and became dry like the Sahara desert and other areas where water rose to form the thunderstorms. Galileo also found that Jupiter's rings were made of small dust grains that impacts of meteoroids blasted off the surface of Jupiter's four innermost satellites (Adrastea, Metis, Amalthea, and Thebe).
- *Hot, Active Volcanoes on Io*. Voyager 1 first discovered Io's volcanoes in 1979. The volcanoes resulted from 100-meter (328-foot) tides in its

[269] "Discovery Highlights," Solar System Exploration, Galileo Legacy Site, *http://galileo.jpl.nasa.gov/discovery.cfm* (accessed September 13, 2005). Also "The Galileo Mission at Jupiter–Fact Sheet," *http://www2.jpl.nasa.gov/galileo/Page_1_GEM_Fact_Sheet.pdf*.

solid surface. Galileo found evidence of very hot volcanic activity on Io and observed dramatic changes compared to observations during Voyager and even during the period of Galileo's observations. By taking Io's temperature with Galileo's instruments, scientists learned that some of Io's volcanoes were hotter (1,800°C [3,240°F]) than Earth's. From this, scientists surmised that lava made of a silicate material rich in magnesium erupted from below Io's surface. Galileo also spotted changes more than 100,000 square miles (~260,000 square kilometers) in size on Io's surface that occurred within the past five months due to coating by volcanic debris as well as longer-term changes since the Voyager flybys.

- *A Possible Ocean on Europa*. Possessing more water than the total amount found on Earth, Europa appeared to have had, in recent geologic history, a salty ocean underneath its icy cracked and frozen surface, as revealed in images from Galileo with resolutions as small as 26 meters (85 feet). Ice "rafts" up to 15 kilometers (9.3 miles) across appeared to have broken and drifted apart; a frozen "puddle" smoothed over older cracks; warmer material bubbled up from below to blister the surface; evaporative-type salts were exposed; and a lack of craters showed the surface to be relatively young. Heat to melt the ice below could have come from Europa's exposure to tidal friction from the gravity of Jupiter—less severe but as significant as the similar effect on Io.
- *Ganymede's Magnetic Field*. The magnetic field discovered on Ganymede was the first found on a moon. Scientists suggested that enough heat from internal tidal friction, perhaps arising from a slightly different orbit in its past, caused the separation of material inside Ganymede and the "stirring" of a molten core of iron or iron sulfide, generating Ganymede's magnetic field. Ganymede's magnetic field was found to be larger than the magnetic field on the planet Mercury.
- *Evidence for an Ocean Hidden Beneath Callisto's Surface*. Galileo discovered evidence supporting the existence of a subsurface ocean on Callisto. The ocean would have had to be deep enough inside the moon that it did not affect the moon's heavily cratered surface. Instead, the ocean might be "showing itself" indirectly through the magnetic field it generated. An electric flow in a salty ocean might be generated by Jupiter's strong magnetic field passing through it. Galileo also discovered an atmosphere of hydrogen and carbon dioxide on Callisto.[270]

Extended Europa Mission

The GEM was a two-year, 14-orbit, low-cost extension of Galileo's exploration of the Jovian system beginning in December 1997. The longest part of this campaign, consisting of eight orbits around Europa, lasted through

[270] "Galileo Mission Continues To Soar," The Planetary Society, *http://www.planetary.org/html/news/articlearchive/headlines/1997/headln-121997.html* (accessed September 13, 2005).

May 4, 1999. The GEM objectives were to study and characterize Europa's crust; atmosphere; and possible ocean, past or present, beneath Europa's icy surface using imaging, gravity, and space physics data.[271] Galileo made its closest approach to Europa on December 16, 1997 at 201 kilometers (125 miles). Mission data was compared with previous images for surface changes that might have occurred, and the surface was scanned for signs of spewing active ice volcanoes and other direct evidence. Because a flowing, salty subsurface ocean could generate a magnetic field, scientists tried to determine if the magnetic signals nearest Europa were generated from within. By measuring the pull of Europa's gravity, the thickness of the ice shelf could be better determined.

Four Callisto encounters between May 5 and October 10, 1999, rapidly lowered the spacecraft's orbit to Io for the third part of the extended mission. Called the Jupiter water/Io torus study, its 10 orbits around Io focused on detailed storm and wind patterns in Jupiter's atmosphere, including thunderstorms, and mapped the distribution of water. Galileo mapped the density of the Io torus, a donut-shaped cloud of charged particles that rings Io's orbit, and used the gravitational pull of Callisto to halve the orbit's perijove (closest distance to Jupiter) to prepare for encountering Io. Scientists also looked at Callisto's magnetic field signatures to search for further evidence of an ocean.[272]

The Io campaign from October 11, 1999, through December 31, 1999, consisted of two orbits around Io.[273] The campaign obtained high-resolution images and a compositional map of Io. The campaign also sampled a volcanic plume, flying 500 kilometers (310 miles) over the active volcano Pillan Patera. Table 4–67 lists all of Galileo's encounters, both the primary and the extended mission through 1999. See Table 4–68 for additional mission details.

The Discovery Program

In 1989, NASA's Solar System Exploration Division initiated a series of workshops to define a new strategy for exploration through the year 2000. The panels included a Small Mission Program Group chartered to devise a rationale for missions that would be low cost and allow focused scientific questions to be addressed in a relatively short time. The group recommended the use of small spacecraft to implement limited-scope missions. This was different from NASA's usual way of conducting very large missions carrying many instruments. These large missions usually took many years to organize and often cost more than one billion dollars.

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[271] "Galileo Europa Mission (GEM) Fact Sheet," (no date), *http://www2.jpl.nasa.gov/galileo/gem/fact.html* (accessed August 18, 2005).

[272] "The Galileo Europa Mission–Exploring Through 1999," The Galileo Mission at Jupiter–Fact Sheet, *http://www2.jpl.nasa.gov/galileo/Page_2_GEM_Fact_Sheet.pdf* (accessed September 14, 2005).

[273] "The Galileo Europa Mission–Exploring Through 1999," The Galileo Mission at Jupiter–Fact Sheet.

Although the proposal was initially greeted with skepticism, largely because of the example set by the low-cost Planetary Observer program and the Mars Observer mission, which "grossly overran" its budget and schedule, they agreed to use the successful Explorers Program as a model.[274] The group gave this new program the name "Discovery." A Science Working Group was established and in 1990; the group reviewed a number of concepts that could be implemented as less costly missions. In May 1991, after examining specific missions and the feasibility of the Discovery approach, Wesley Huntress, Director of the Solar System Exploration Division, decided to include the Discovery Program as an element in the division's 1991 Strategic Plan. The NEAR was planned as the first Discovery mission.[275]

Meanwhile, in the fall of 1991, the Senate Appropriations Committee directed NASA in the FY 1992 appropriations bill to prepare a plan "to stimulate and develop small planetary or other space science projects, emphasizing those which could be accomplished by the academic or research communities." NASA described the Discovery initiative[276] in the requested report submitted to Congress in April 1992.

The Discovery Program was a good fit with NASA Administrator Goldin's "faster, better, cheaper" approach to space science missions. Discovery missions aimed to incorporate state-of-the-art technologies into smaller projects with faster turnaround to foster the continuing conduct of science at significantly lower cost.

Discovery missions had a $150 million ceiling for development; operations costs could not exceed $35 million; and mission development from start through launch plus 30 days could take no more than 36 months. Spacecraft had to fit on an ELV no larger than a Delta II. Anyone could submit proposals—academia, industry, and the government—and the formation of teams was encouraged.[277] NASA did not specify development details of Discovery missions. Rather, each science team had maximum flexibility to pursue innovative and cost-effective approaches to meet mission goals. The Discovery Program "bought" the mission from the Principal Investigator who was accountable for the scientific success of the mission. This manage-

[274] "A Look Back at the Beginning: How the Discovery Program and the NEAR Mission Came To Be," *Discovery Dispatch*, 2 (January 2001): 1–2, *http://discovery.nasa.gov/news/newsletters/newsletter_archive/2001/January2001.pdf* or *http://discoverynewfrontiers.msfc.nasa.gov/lib/presentations/docs/HistoricalDiscoveryProgramInformation.doc* (accessed October 25, 2005).
[275] "A Look Back at the Beginning: How the Discovery Program and the NEAR Mission Came To Be," *Discovery Dispatch*, 2 (January 2001): 1–2.
[276] "National Aeronautics and Space Administration, Small Planetary Mission Plan, Report to Congress, April 1992," in Logsdon, ed. *Exploring the Unknown, Vol. V.*, pp. 461–468.
[277] Costs given in FY 1992 dollars. Howard E. McCurdy, *Faster Better Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore, MD: The Johns Hopkins University Press, 2001), pp. 55–56. In FY 1999 dollars, ceilings were listed as $190 million for design and development through launch and total mission cost at $299 million, including preliminary analysis, definition, launch services, and mission operations, *The Near Earth Asteroid Rendezvous: A Guide to the Mission, the Spacecraft, and the People* (1999), p. 20 (NASA History Office Folder 17070).

ment approach ensured performance-based missions emphasizing delivery of scientific data. The programmatic goals of Discovery missions were to do the following:[278]

- Create a new way of doing business between a government agency and the private sector.
- Demonstrate that the philosophy of "faster, better, cheaper" could successfully yield a rapid development, very inexpensive planetary science mission with significant responsibility vested with the Principle Investigator.
- Create an innovative education and outreach program that stimulates public interest in planetary exploration.

NEAR and Mars Pathfinder were the first projects selected under the program. Work on the two began in 1993. The Lunar Prospector, the third mission and first selected competitively, began in 1995. Stardust was the fourth Discovery mission, launched in 1999. The Comet Nucleus Tour (CONTOUR) and Genesis missions were selected in 1997. Table 4–69 lists NASA-approved Discovery missions selected through 1998.

Near Earth Asteroid Rendezvous

The primary goal of the NEAR mission was to rendezvous with the asteroid 433 Eros (an S-class asteroid) approximately 355 million kilometers (220 million miles) from Earth and gather data on its composition and physical properties (mineralogy, morphology, internal mass distribution, and magnetic field). The NEAR was the first mission to put a spacecraft in orbit around an asteroid and the first to orbit a body whose mass and exact size were unknown until arrival. Since Discovery missions were limited to launch vehicles no larger than a Delta II, the NEAR mission used a "long, looping path" to the asteroid belt and back toward Earth and depended on a gravity assist from Earth to reach Eros. The spacecraft's retrograde orbit, moving opposite the asteroid's rotation, enabled its stable orbit.[279]

Work on the project began in 1993. The Johns Hopkins University Applied Physics Laboratory (APL) was responsible for mission operations, which were conducted through a dedicated NEAR Mission Operations System Ground Segment at the APL. JPL was responsible for navigation. Science operations were conducted from the Science Data Center at the APL. All data from the spacecraft were forwarded to the Science Data Center for processing, distribution, and archiving.

[278] "Lunar Prospector: End of Mission and Overview," Press Kit, July 1999, *http://lunar.arc.nasa.gov/resources/LPBckgrn.pdf* (accessed October 25, 2005).
[279] Scott L. Murchie et al, "NEAR So Far: Approaching Asteroid Eros," *The Planetary Report* (November/December 1998): 4-8.

The journey to Eros took four years. A year after its launch, on February 18, 1997, the NEAR spacecraft established a record for the greatest distance from the Sun for a solar-powered spacecraft when it reached 327 million kilometers (203 million miles). On June 27, 1997, the NEAR spacecraft performed a 25-minute flyby of the asteroid 253 Mathilde, flying 1,212 kilometers (753 miles) above the asteroid and photographing 60 percent of the asteroid's surface. This was the first look at a C asteroid. The collected information indicated that craters covered the 4.5-billion-year-old asteroid and that it was less dense than previously believed.

A midcourse correction on July 3, 1997, sent the NEAR spacecraft past Earth on January 23, 1998 for a gravity assist on its way to Eros; the spacecraft flew about 540 kilometers (335 miles) above Ahvaz in southwestern Iran. Viewers on the ground in France, the southern United States, and Hawaii reported seeing the spacecraft as it approached. On April 1, 1998, the NEAR spacecraft set a record as the most distant manufactured object detected by optical means when an amateur astronomer in New South Wales, Australia, spotted the spacecraft at a distance of 33.65 million kilometers (20.91 million miles) from Earth.

A series of engine burns in December were required for the spacecraft to catch up with and orbit around the faster-moving asteroid. However, on December 20, 1998, the first rendezvous burn was aborted and contact with the spacecraft was lost for 27 hours.[280] The aborted engine burn resulted in a postponement of the NEAR spacecraft's orbit of Eros, which had been scheduled for January 10, 1999. Instead, the NEAR spacecraft was put on a backup trajectory allowing a different flyby than originally planned. As part of this new plan, the spacecraft flew past Eros on December 23, 1998, at a range of 3,827 kilometers (2,378 miles) (distance measured from the center of mass), observing about 60 percent of the asteroid. During its flyby, the NEAR spacecraft discovered that Eros was smaller than expected, and it had two medium-sized craters, a long surface ridge, and a density similar to the density of Earth's crust.[281] Following the flyby, the NEAR spacecraft conducted a successful 24-minute, large bipropellant engine burn on January 3, 1999, to increase the spacecraft's speed for rendezvous with Eros, rescheduled for February 2000. A small hydrazine engine burn on January 20 "fine-tuned" the spacecraft's trajectory and increased its speed by 14 meters per second (31 miles per hour). Periodic trajectory burns throughout the year set the NEAR spacecraft on course to begin orbiting the asteroid on February 14, 2000. The spacecraft landed on Eros on February 12, 2001.[282] In March 2000, the spacecraft was

[280] It was determined that the abort had been caused when the brief engine burn exceeded certain safety limits associated with the on-board system autonomously controlling the spacecraft. Reprogramming of the values was done, readying the spacecraft for a January 3, 1999 main engine burn.

[281] Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, pp. 161–162.

[282] "NEAR Spacecraft To Fly by Asteroid Eros on December 23; Rendezvous with Eros in 2000," The Johns Hopkins University Applied Physics Lab News Archive, December 22, 1998, *http://near.jhuapl.edu/news/flash/98dec22_3.html*, "NEAR Spacecraft Makes Planned Flyby of Asteroid Eros," December 23, 1998, *http://near.jhuapl.edu/news/flash/98dec23_1.html*, "NEAR Spacecraft Set for Jan. 3 Main Engine Burn," December 30, 1998, *http://near.jhuapl.edu/news/flash/98dec30_1.html*, and Helen Worth, "NEAR Team Recovers Mission After Faulty Engine Burn," January 29, 1999, *http://near.jhuapl.edu/news/articles/99jan29_1/* (all accessed August 8, 2005).

renamed NEAR Shoemaker to honor Dr. Eugene M. Shoemaker, the geologist who influenced decades of research on the role of asteroids and comets in shaping the planets. Dr. Shoemaker co-discovered comet Shoemaker-Levy 9; the comet crashed into Jupiter in 1994.

The NEAR spacecraft comprised two independent structures: the propulsion system and the spacecraft. The APL designed and fabricated the spacecraft structure. Aerojet, the propulsion system vendor, built the propulsion system structure. These systems were coupled at the aft deck. The spacecraft structure was composed of the spacecraft adapter, two decks, and eight side panels.[283]

The three major components—instruments, solar panels, and high-gain antenna—were fixed and body-mounted. The system was designed to be highly fault-tolerant. Fully redundant subsystems included the complete telecommunication system (except the high-gain and medium-gain antennae), the solid-state recorders, command and telemetry processors, data buses, attitude interface unit and flight computers for guidance and control, and power subsystem electronics. The use of redundant components provided additional fault tolerance. The NEAR spacecraft had 2 inertial measurement units (1 operational and 1 backup), 5 sun sensors, and 11 small thrusters.

The NEAR spacecraft design was mechanically simple and geared toward a short development and test time. The solar panels, the high gain antenna (HGA), and the instruments were all fixed. The 1.5-meter (4.9-foot) antenna and four solar panels were mounted on the outside of the forward deck. The solar panels were folded down along the spacecraft sides during launch and were deployed shortly after separation from the launch vehicle. Most electronics were mounted on the forward and aft decks. The science instruments, except for the magnetometer, were hard-mounted on the outside of the aft deck with co-aligned fields-of-view. The magnetometer was mounted on the HGA feed. The interior of the spacecraft contained the propulsion module.[284]

The NEAR spacecraft was the first probe to rely on solar cells for power during operations beyond the Mars orbit—a technical innovation in spacecraft design. It had a design lifetime of four years and the capability to operate at distances of 203 million miles (327 million kilometers) from the Sun. Other technical innovations included the following:

- The first spaceflight of a laser incorporating an inflight calibration system.
- The first spaceflight using a near-infrared system with a radiometric calibration target and an indium-gallium-arsenide focal plane array that did not require cooling with liquid nitrogen.
- The first spaceflight of a silicon solid-state detector viewing the Sun and measuring the solar input x-ray spectrum at high resolution.

[283] A. G. Santo, S. C. Lee, and R. E. Gold, "NEAR Spacecraft and Instrumentation," pp. 1–2, *http://near.jhuapl.edu/PDF/SC_Inst.pdf* (accessed August 10, 2005).
[284] A. G. Santo, S. C. Lee, and R. E. Gold, "NEAR Spacecraft and Instrumentation," p. 1.

- The first spaceflight of a bismuth germanate anti-coincidence shielded gamma-ray detector.[285]

Table 4–70 provides further NEAR mission details.

Lunar Prospector

The Lunar Prospector was launched from Cape Canaveral, Florida, on January 6, 1998, on top of a solid-fueled Athena II launch vehicle on a one-year mission to map the entire lunar surface. The spacecraft successfully collected data about the chemical composition of the lunar surface, the gravity and magnetic fields, and the resources of the Moon. It was the first launch of the Athena II ELV, the third mission to launch in NASA's Discovery Program, and the first competitively selected Discovery mission. The mission successfully demonstrated NASA's "faster, better, cheaper" concept and was one of the most cost-effective planetary missions ever flown, costing approximately $63 million.[286]

After traveling 105 hours, the spacecraft entered orbit around the Moon on January 11, 1998, following a series of orbit burns. It reached its mapping orbit on January 13 and settled into its final orbit within a few more days. (See figure 4–61 for the mission profile). On December 19, 1998, the spacecraft was placed into an orbit with an average altitude of 40 kilometers (25 miles). This transition orbit was between the nominal mapping orbit (with altitude of 100 kilometers) (62 miles) and the extended mission orbit (with altitude of 25 kilometers to 30 kilometers) (16 miles to 18 miles), where the gravity model was verified. On January 28, 1999, the spacecraft was successfully maneuvered into its extended mission orbit. Two burn sequences placed the spacecraft in a 15-kilometer by 45-kilometer (9-mile by 28-mile) altitude orbit to maintain an average altitude above the surface of 30 kilometers (18 miles). It was the lowest altitude mapping of another world.

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[285] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," The Johns Hopkins University Applied Physics Laboratory, December 1999, p. 15, *http://near.jhuapl.edu/media/99-1030B_NEARMarch.pdf* (accessed August 8, 2005).

[286] Howard McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program,* p. 5. Also "Lunar Prospector, End of Mission & Overview," Press Kit, July 1999, pp. 5, 7–8, *http://lunar.arc.nasa.gov/resources/LPBckgrn.pdf* (accessed August 2, 2005).

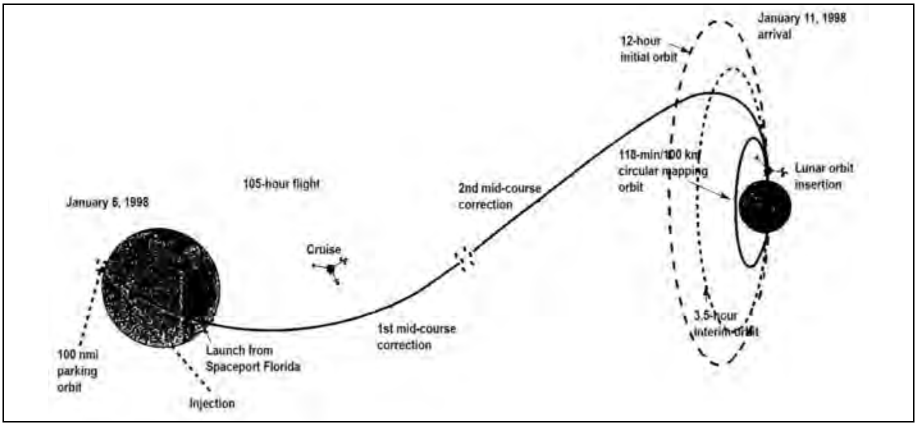

Figure 4–61. Lunar Prospector Mission Profile.

On March 5, 1998, the Prospector science team announced the discovery of a "definitive signal" for water ice at both the lunar poles, the first such discovery. A conservative analysis of the available data indicated that a significant quantity of water ice, possibly as much as 300 million metric tons (661,387 pounds), was mixed into the lunar soil at each pole, with 15 percent more at the north pole than at the south pole. The presence of water ice at both lunar poles was strongly indicated by data from the spacecraft's neutron spectrometer instrument. That quantity was dispersed over an area of 3,600 square miles to 18,000 square miles (9,324 square kilometers to 46,620 square kilometers) across the northern pole and an additional area of 1,800 square miles to 7,200 square miles (4,662 square kilometers to 18,648 square kilometers) across the southern polar region.[287] Scientists also detected strong, localized magnetic fields; delineated new mass concentrations on the surface; and mapped the global distribution of major rock types, key resources, and trace elements. There were strong suggestions that the Moon had a small, iron-rich core.[288]

On July 31, 1999, the Lunar Prospector was targeted to impact in a permanently shadowed area of a crater near the lunar south pole. It was hoped that the impact would liberate water vapor from the suspected ice deposits in the crater and that the plume would be detectable from Earth; however, no plume was observed. The lack of physical evidence left open the question of whether ancient comet impacts delivered ice that remained buried in permanently shadowed regions of the Moon, as suggested by the large

[287] "Lunar Prospector Finds Evidence of Lunar Ice," *HQ Bulletin* (March 23, 1998): 3 (History Office Folder 5728).
[288] "NASA's Lunar Prospector Sends Back a Wealth of Scientific Data," *HQ Bulletin* (September 14, 1998): 1 (History Office Folder 16834).

amounts of hydrogen measured indirectly by the spacecraft during its main mapping mission.[289] Figure 4–62 depicts the Lunar Prospector before it impacted the Moon's surface.

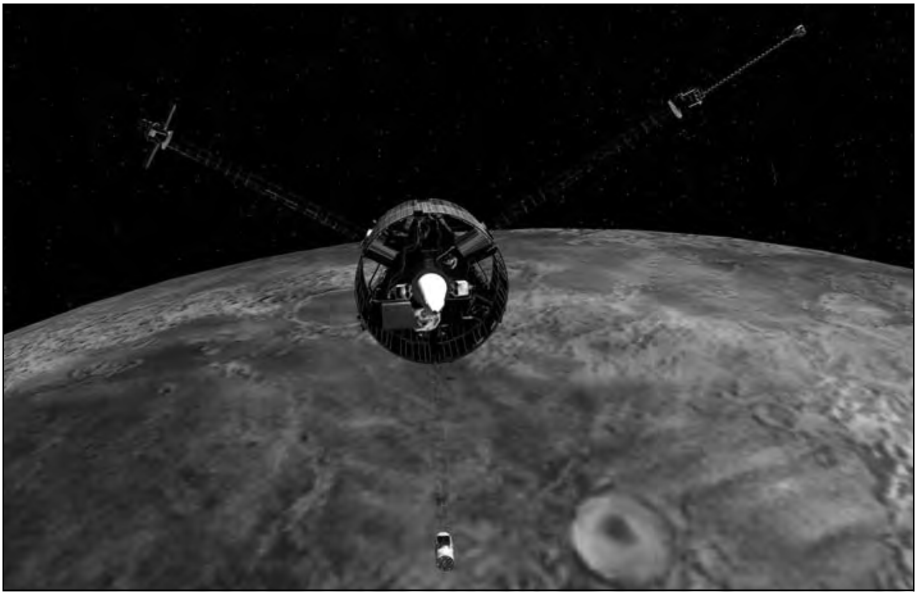

Figure 4–62. This image is an artist's conception of the front of the Lunar Prospector spacecraft just before it impacts the Moon. It was released July 29, 1999, two days before the actual impact. (Ames Research Center Home Page)

The Lunar Prospector was a graphite-epoxy drum with three radial instrument booms, spin-stabilized and controlled by six hydrazine monopropellant 22-newton thrusters. Communications were through two S-band transponders and a slotted, phased-array medium-gain antenna and omnidirectional low-gain antenna. There was no on-board computer; ground command was through a 3.6-kbps telemetry link commanding a single on-board command and data handling unit. Data was downlinked directly and also stored on a solid-state recorder and downlinked after 53 minutes to ensure all data collected during communications blackout periods was received. See Table 4–71 for further details.

Clementine

NASA and the Ballistic Missile Defense Organization, formerly the Strategic Defense Initiative Organization (SDIAO), jointly sponsored the Clementine project.[290] It was also known as the Deep Space Probe Science

[289] "No Water Ice Detected From Lunar Prospector Impact," *NASA News* Release 99-119, October 13, 1999, *http://nssdc.gsfc.nasa.gov/planetary/text/lp_pr_19991013.txt* (accessed August 2, 2005).
[290] "Clementine," NSSDC Master Catalog, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-004A* (accessed April 24, 2006).

Experiment (DSPSE). Clementine was the DOD equivalent of a NASA "faster, cheaper, better" Discovery Program mission, built over a relatively short two-year development cycle and at a lower cost than more elaborate missions. The objectives of the mission were to test sensors and spacecraft components under extended exposure to the space environment and to make scientific observations of the Moon and the near-Earth asteroid 1620 Geographos. Observations incorporated imaging at various wavelengths including UV and infrared, laser ranging altimetry, and charged particle measurements and were to assess the surface mineralogy of the Moon and Geographos; obtain lunar altimetry from 60° N to 60° S latitude; and determine the size, shape, rotational characteristics, surface properties, and cratering statistics of Geographos.

Clementine was launched on January 25, 1994, from Vandenberg Air Force Base aboard a Titan IIG rocket. It was the first U.S. spacecraft launched to the Moon in more than 20 years.[291] After launch, the spacecraft remained in a temporary orbit until February 3, when a solid-propellant rocket ignited to send the vehicle toward the Moon. After two Earth flybys, on February 5 and February 15, it achieved lunar insertion on February 19. Lunar mapping took place during approximately two months in two parts. The first part consisted of a 5-hour elliptical polar orbit with a perilune of about 400 kilometers (249 miles) at 28° S latitude.[292] After one month of mapping, the orbit was rotated to a perilune of 29° N latitude, where it remained for one more month. This allowed global imaging as well as altimetry coverage from 60° S to 60° N.

During the mission's 71 days in lunar orbit, Clementine systematically mapped the lunar surface, transmitting about 1.6 million digital images to produce the first global digital map of the Moon. The digital data set covered 38 million square kilometers (14.7 million square miles) mapped in 11 colors in the visible and near infrared parts of the spectrum. By combining information obtained through 11 filters, multispectral image data was used to map the distribution of lunar rock and soil types. The mission also provided tens of thousands of high resolution and mid-infrared thermal images. The spacecraft produced views of previously unknown regions of the Moon, as well as areas already known but gathered from a different and unique perspective. Scientists measured the topography of large, ancient impact features, including the largest and deepest impact basin known in the solar system, extending some 1,600 miles (2,570 kilometers) in diameter and more than 7 miles (11 kilometers) deep.[293]

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[291] Asif Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, pp. 155–156.

[292] Lunar orbit closest to the Moon.

[293] "Clementine Produces First Global Digital Map of Moon," *NASA News* Release 94-84, May 26, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-084.txt* (accessed September 28, 2005).

The spacecraft used a radar-based technique to detect what appeared to be ice deposits in permanently shadowed regions of the lunar south pole (see figure 4-63). The project science team concluded that its radar signal detected from 110 million to 1.1 billion tons of water ice, over an upper area limit of 5,500 square miles (14,245 square kilometers) of south pole terrain. In December 1996, NASA and the DOD announced jointly that analysis of data obtained two years earlier suggested the "existence of ice in the permanently shaded south polar region of the Moon . . . ."[294] The Lunar Prospector[295] discovered further evidence of lunar ice in 1998. Indications, however, after the controlled crash of the Lunar Prospector into a crater near the south pole of the moon in 1999 "produced no observable signature of water."[296] Further radar studies using the Arecibo Observatory in Puerto Rico in 2003 produced no suggestion of large amounts of water ice, leading scientists to conclude that, if ice existed, it was widely scattered.[297]

After successfully mapping the entire surface of the Moon and completing 297 orbits on May 3, 1994, controllers fired Clementine's thrusters to inject it on a trajectory toward an August 24 rendezvous with the asteroid 1620 Geographos. However, the satellite suffered an on-board malfunction on May 7 preventing Clementine from performing the planned close flyby of Geographos and also from pointing its cameras and sensors. Preliminary analysis traced the cause of the malfunction to the on-board computer that controlled most of the satellite's systems and attitude control thrusters. The computer activated several thrusters during a 20-minute telemetry interrupt with the ground station, which depleted all the fuel in the attitude control system tanks. The spacecraft went into an uncontrollable tumble at about 80 revolutions per minute with no spin control.

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[294] "Statement from Dr. Wesley Huntress, Associate Administrator, Office of Space Science, on Clementine Ice Discovery," *NASA News* Release,(no number), December 3, 1996, (NASA History Office Folder 5728). Also "Clementine–DSPSE," *http://www.cmf.nrl.navy.mil/clementine.html* (accessed September 2, 2005). "DOD News Briefing: Discovery of Ice on the Moon," United States Department of Defense, *http://www.dod.mil/transcripts/1996/t120496_t1203moo.html* (accessed September 27, 2005).

[295] "Lunar Prospector Finds Evidence of Lunar Ice," *HQ Bulletin* (March 23, 1998): 3 (NASA History Office Folder 5728).

[296] "No Water Ice Detected from Lunar Prospector Impact," *NASA News* Release 99-119, October 13, 1999, *http://nssdc.gsfc.nasa.gov/planetary/text/lp_pr_19991013.txt* (accessed September 27, 2005).

[297] "Arecibo Radar Shows No Evidence of Thick Ice at Lunar Poles, Despite Data from Previous Spacecraft Probes, Researchers Say," *Cornell News*, November 12, 2003, *http://www.news.cornell.edu/releases/Nov03/radar.moonpoles.deb.html* (accessed May 20, 2006). Also Rick Callahan, "Water on the Moon? Scientists Await Definitive Answer," November 12, 2003, *http://www.space.com/scienceastronomy/moon_ice_030112.html* (accessed May 20, 2006). Mike Nolan and Ellen Howell, "Don Campbell Steps Down," *NAIC/AO Newsletter*, no. 37 (April 2004), National Astronomy and Ionosphere Center, Arecibo Observatory, *http://www.naic.edu/%7Enewslet/no37/NAICNo37.pdf* (accessed May 20, 2006).

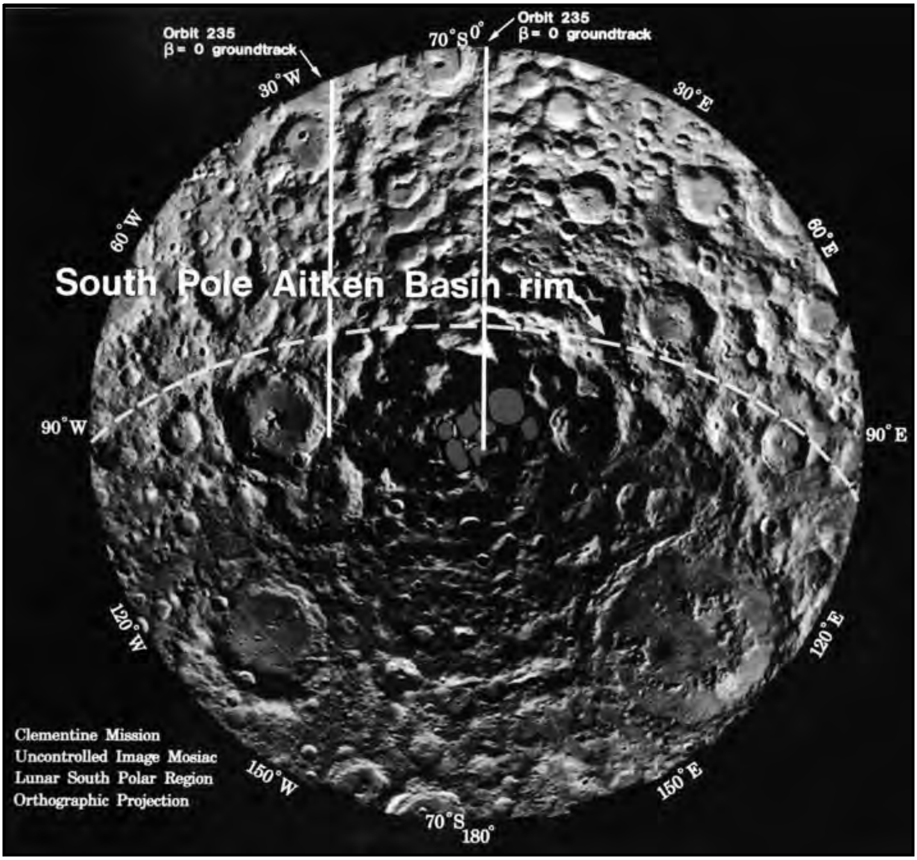

Figure 4–63. South Pole of the Moon with Ice Marked in Blue. (Naval Research Lab Photo http://www.cmf.nrl.navy.mil/clementine/water/moon_ice.JPG*)*

Controllers were forced to cancel the journey to Geographos and return the vehicle to the vicinity of Earth where engineering studies continued and the spacecraft was to test sensor resistance during repeated passes through the Van Allen belts. To accomplish this, it would be necessary to prevent Clementine from returning to the vicinity of the Moon because that would put the spacecraft into orbit around the Sun. However, because of poor Sun angles, the solar panels did not generate enough power to keep the spacecraft far enough from the Moon, lunar gravity took control of Clementine, and the spacecraft slipped into orbit around the Sun. Spacecraft operations were terminated on August 8, 1994.

The spacecraft remained inoperative with a discharged battery for about six months until more optimal Sun angles provided battery charging and automatic heaters warmed the spacecraft.[298] Contact using NASA's DSN was first attempted on February 8, 1995, and the first intermittent radio signals were received from Clementine on February 20. Full engineering studies

[298] Siddiqi, p. 155.

began on March 17, and positive assessments of the spacecraft's health and functionality were made. Based on those reviews, a number of engineering experiments were conducted including slowing the spin rate by firing the propulsion system. Sensor images were taken and stored on board. Since the distance from Earth was growing daily, poor signals prevented full image downlinks. However, substantial data was obtained on the performance of the spacecraft and its components in deep space under stressful conditions. The last spacecraft communications occurred on May 10, 1995. Official notice was given to the DSN to discontinue mission support on July 12, 1995.[299]

Clementine was managed by the Ballistic Missile Defense Organization and built by the Naval Research Laboratory (NRL). Its instruments were constructed by industry and the Lawrence Livermore Laboratory. NASA researchers served on the science team, and the Agency provided lunar and asteroid navigation and use of its DSN. This landmark project demonstrated that small, highly capable satellites could be built and launched for less than $100 million and in less than two years, using advanced miniaturized technology and a streamlined management approach.[300] Table 4–72 provides mission details.

Mars Missions

Exploration of Mars was a prime focus of NASA's planetary missions beginning with the 1965 Mariner 4 mission and continuing with the Viking lander missions of the 1970s. After Viking, 17 years passed before the next attempt—the unsuccessful 1992 Mars Observer mission. Four years later, NASA was more successful; the two missions launched by the United States succeeded.[301] The Mars Global Surveyor was first in the Mars Surveyor series of spacecraft missions to Mars to be launched at "each opportunity" (every 26 months when the position of the two planets made for optimum travel time) over the next decade. This mission carried six scientific instruments to study the Martian atmosphere, surface, and interior.

Launched a month later, the Mars Pathfinder, a mission in the Discovery Program, carried a lander and small rover robot named Sojourner. This mission, which captured the attention of people worldwide, focused on the following three major areas of investigation: the search for evidence of past life on Mars; understanding the Martian climate and its lessons for the past and future of Earth's climate; and understanding the geology and resources that could be used to support future human missions to Mars. The unifying theme of the Mars exploration program was the search for water—a key requirement for life.

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[299] Paul A. Regeon et al, "The Clementine Lunar Orbiter," *www.pxi.com/praxis_publicpages/pdfs/Lun_Orb_Gifu.pdf* (accessed September 28, 2005).

[300] "Clementine Failure," *Satellite News*, May 29, 1994, *http://www.totse.com/en/media/cable_and_satellite_television_hacks/satnews.html* (accessed September 29, 2005).

[301] The Russian Mars '96 mission to Mars was unsuccessful because of a launch failure.

Taking advantage of the late 1998/early 1999 Mars launch opportunity, NASA launched two additional Mars missions. Both the Mars Climate Orbiter and the Polar Lander failed.

Mars Observer

After a 17-year gap since the last U.S. mission to Mars, NASA launched the Mars Observer on September 25, 1992. The spacecraft was developed from a commercial, Earth-orbiting communications satellite converted into an orbiter for Mars. The payload of science instruments was to study the surface, atmosphere, interior, and magnetic field of Mars from Martian orbit. The instruments focused on Martian geology, geophysics, and climate. The spacecraft also carried a radio relay package to receive information from the planned Mars Balloon Experiment for retransmission back to Earth carried on the future Soviet Mars '94 mission. The Mars Observer mission was designed to operate for one full Martian year (687 Earth days) to permit observations of the planet through its four seasons.

At the end of 337 days traveling toward Mars, the mission ended on August 22, 1993, when contact was lost with the spacecraft shortly before it was to enter orbit around Mars. No significant scientific data was returned.

An independent investigation board convened to determine the cause of the failure. It reported that the most probable cause was a leak that had continued during the spacecraft's 11-month flight to Mars, causing tubing to rupture. The released helium and monomethyl hydrazine put the spacecraft into a spin. The high spin rate caused the spacecraft to go into "contingency mode," interrupting the stored command sequence and failing to switch on the transmitter. The released fuel most likely also damaged critical electrical circuits.[302]

The Mars Observer was to have been the first in a series of lower-cost spacecraft to Mars. But it had been many years since NASA had sent a spacecraft to Mars, and scientists were anxious to include larger numbers of more sophisticated instruments. Costs and the development schedule both grew, as the mission took 11 years to launch from the time it was conceived in 1981; the final cost was more than $800 million. The resulting spacecraft had more capabilities but did not turn out to be more reliable. Observer's failure helped push the Agency toward the "faster, better, cheaper" approach, where several smaller missions could be launched for the price of one large, expensive mission.[303] Table 4–73 provides further mission details.

[302] "Mars Observer Investigation Report Released," *NASA News* Release 94-1, January 5, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-001.txt* (accessed August 18, 2005).
[303] McCurdy, *Faster, Better, Cheaper*, pp. 18–19, 120.

Mars Global Surveyor

In 1993, NASA began the Mars Surveyor Program with the objective of conducting a series of missions to explore Mars. NASA established and gave responsibility to the Mars Program Office for defining objectives for sending two missions to Mars at each biennial launch opportunity. JPL established a project office to manage development of specific spacecraft and mission operations.

The first of these missions was the Mars Global Surveyor, the first successful mission to Mars in two decades. It launched on November 7, 1996, and entered Martian orbit on September 12, 1997. After a year and a half trimming its orbit from a looping ellipse to a circular track around the planet, the spacecraft began its prime mapping mission in March 1999. It observed the planet from a low-altitude, nearly polar orbit over the course of one complete Martian year, the equivalent of almost two Earth years. Mars Global Surveyor completed its primary mission on January 31, 2001, and entered an extended mission phase.

The core of the Mars Global Surveyor spacecraft was a rectangular bus housing computers, the radio system, solid-state data recorders, fuel tanks, and other equipment. Attached to the outside were several rocket thrusters, which were fired to adjust the spacecraft's path during the cruise to Mars and to modify the spacecraft's orbit around the planet. To minimize costs, most of the spacecraft's instruments and electronics were duplicates or spares from the Mars Observer mission. The spacecraft design also incorporated new hardware—the radio transmitters, solid state recorders, propulsion system, and composite material bus structure.

The spacecraft orbited the planet to allow one side of the bus, called the nadir deck, to always face the Martian surface. The science instruments–the MOC, MOLA, ER, and the TES—were attached to the nadir deck, along with the Mars Relay Radio System. The magnetometer sensors were mounted on the ends of the solar arrays.

The bus had two solar array wings that always pointed toward the Sun. They provided 980 watts of electricity for operating the spacecraft's electronic equipment and for charging the nickel hydrogen batteries. The batteries provided electricity when the spacecraft was mapping the dark side of Mars. The dish-shaped high-gain antenna was mounted on the end of a boom, preventing the solar arrays from blocking the spacecraft's view of Earth while it orbited Mars. This steerable antenna pointed toward Earth even though the spacecraft's position was continuously adjusted during mapping to keep the nadir deck pointed toward Mars. The radio system, which included the high-gain antenna, also functioned as a science instrument. Researchers used it in conjunction with NASA's DSN ground stations for the radio science investigations. Figure 4–64 shows a diagram of the spacecraft. To maintain appropriate operating temperatures, most of the outer exposed parts of the spacecraft and the science instruments were wrapped in thermal blankets.

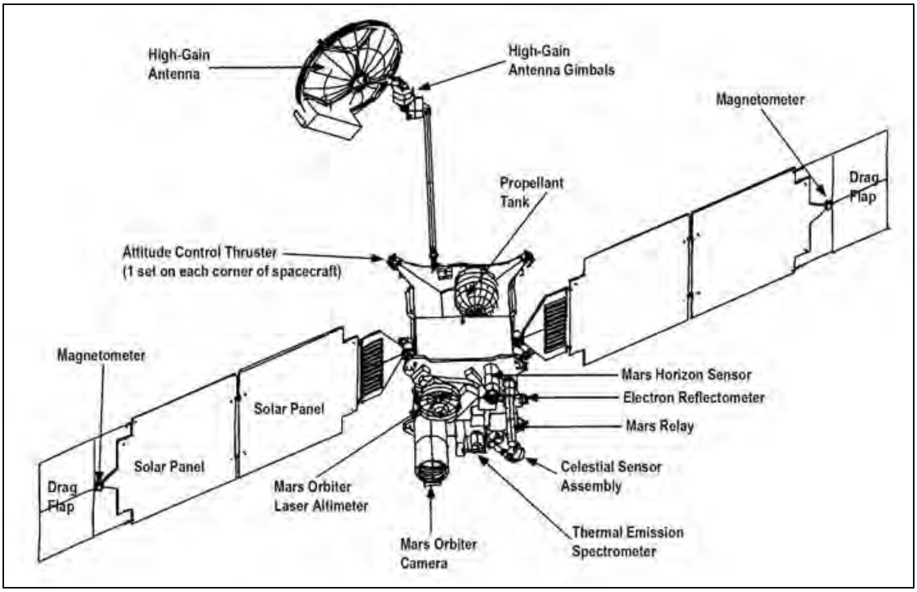

Figure 4–64. Mars Global Surveyor.[304]

The spacecraft used aerobraking to trim its initial, highly elliptical capture orbit and lower it to a nearly circular mapping orbit. Aerobraking had been successfully demonstrated during the 1988 Magellan mission to Venus. Aerobraking was necessary because the mass limits imposed by the lifting capabilities of the Delta II launch vehicle prevented the spacecraft from carrying enough propellant to put itself into its final low-altitude mapping orbit with an engine firing. With aerobraking, the spacecraft dipped into the upper fringes of the Martian atmosphere during each of its orbits every time it reached the point in its orbit closest to the planet. Friction generated by movement of drag panels at the ends of the solar panels slowed the spacecraft slightly, causing the spacecraft to lose some of its momentum during each orbit. This lowered the spacecraft's orbit point that was farthest from Mars.

Following its capture into Mars orbit on September 12, 1997, the Mars Global Surveyor made its closest approach to Mars, beginning an aerobraking phase intended to last for four months but which took a year and a half to complete. On September 17, 1997, the spacecraft dipped into the upper fringes of the Martian atmosphere for 27 seconds, allowing the drag on its solar panels to begin the long aerobraking process of circularizing its orbit.[305] A problem occurred on October 6 when the latch on one of the solar panels appeared to crack, and the panel flexed

[304] "Mars Global Surveyor," Fact Sheet, Jet Propulsion Laboratory, *http://www.jpl.nasa.gov/news/fact_sheets/mgs.pdf* (accessed August 10, 2005).
[305] "Mars Global Surveyor Detects Martian Magnetic Field as Aerobraking Begins," *NASA News* Release 97-204, September 17, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-204.txt* (accessed August 11, 2005).

past its design position, moving more than 20 degrees. The Martian atmosphere had become twice as dense as it had during previous passes, thus exerting 50 percent more pressure than expected on the solar array.

Mission operators raised the spacecraft's orbit on October 12 to adjust the pressure level. On November 7, the mission operators resumed lowering the spacecraft's orbit around Mars at a more gradual pace. As a result, aerobraking took much longer than anticipated, extending the phase by several months and changing the spacecraft's final science mapping orbit.[306] Originally, the mapping phase was to have begun in the spring of 1998; but because of the delay, the mapping phase did not begin until more than a year later.[307] In the meantime, on March 26, 1998, aerobraking was suspended until the spacecraft moved into the proper position with respect to the Sun before beginning the next round on September 23, 1998. To maximize the efficiency of the mission, beginning on March 27, 1998, the spacecraft turned on its payload of science instruments and began a set of scientific observations from its interim elliptical orbit.

When aerobraking ended and the spacecraft was set in its mapping orbit with systems deployed and instruments checked out, the Mars Global Surveyor started creating a global portrait of Mars by traveling over a different part of Mars each orbit. The primary mapping mission began on April 4, 1999.[308] It lasted nearly one complete Martian year, the equivalent of nearly two Earth years, ending on January 31, 2001, when the mapping mission moved immediately into the extended mission phase.

The mission studied the entire Martian surface, atmosphere, and interior. It sent thousands of images back to Earth and returned more data about the planet than all other Mars missions combined. Early in the mission, scientists used information from the spacecraft's magnetometer to confirm the existence of a planet-wide magnetic field. Its laser altimeter provided the first three-dimensional views of the Martian north pole and insight into the processes shaping it. It imaged the Viking 1 and 2 landing sites, the Mars Pathfinder landing site, and the "Face on Mars" during passes over the planet (see Figure 4–65). For the first time in Mars exploration, a spacecraft captured the full evolution of a Martian dust storm.

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[306] "Mars Global Surveyor To Resume Aerobraking," *NASA News* Release 97-249, October 30, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-249.txt* (accessed August 11, 2005).

[307] MarsNews.com, *http://www.marsnews.com/missions/mgs/* (accessed August 10, 2005).

[308] "MSOP Status Report Overview, Prepared by Mars Surveyor Operations Project Manager," NASA Jet Propulsion Laboratory, April 9, 1999, *http://marsprogram.jpl.nasa.gov/mgs/status/wkreport/current.html* (accessed August 11, 2005).

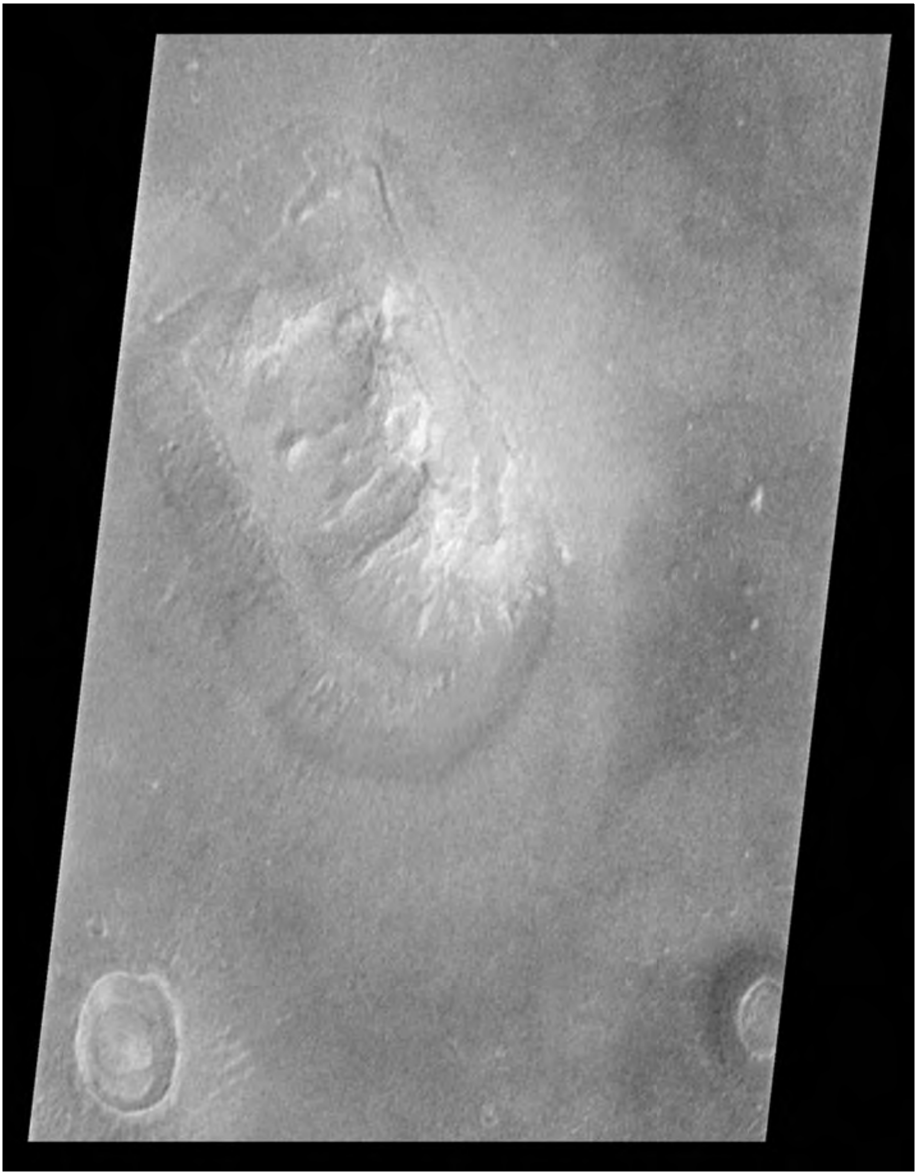

Figure 4–65. On April 6, 1998, approximately 375 seconds after the Mars Global Surveyor spacecraft made its 220th close approach to Mars, it acquired an image of a "face" from a distance of 444 kilometers (275 miles). The image had a resolution of 4.3 meters (14.1 feet) per pixel, making it 10 times better than the image acquired by the Viking spacecraft in 1976. The full image covered an area 2.7 miles (4.4 km) wide and 25.7 miles (41.5 km) long. Image processing was applied to improve the visibility of features. What some saw to be eyes, a nose, and lips were most likely peaks and ridges. This photo shows part of the image, containing the "face" and a couple of nearby impact craters and hills. It was "cut" out of the full image and reproduced separately. (NASA-JPL Photo No. PIA01440)

The spacecraft also returned new information about the deeply layered terrain and mineral composition of the Martian surface and highly magnetized crustal features, providing clues about the planet's interior (see Figure 4–66). Close-up views of the Elysium Basin revealed the first evidence of huge plates of solidified lava. The views also provided evidence for active dunes near the planet's north pole; the dunes had sands that hopped or rolled across the surface after the surveyor approached Mars. New temperature data and close-up images of the Martian moon Phobos indicated that millions of years of meteoroid impacts had pounded the surface of that small body into powder at least 1 meter (3 feet) thick; some impacts started landslides that left dark trails marking the steep slopes of giant craters. Data from the thermal emission spectrometer revealed new mineralogical and topographic evidence suggesting that Mars once had abundant water and thermal activity. Table 4–74 provides additional mission details.

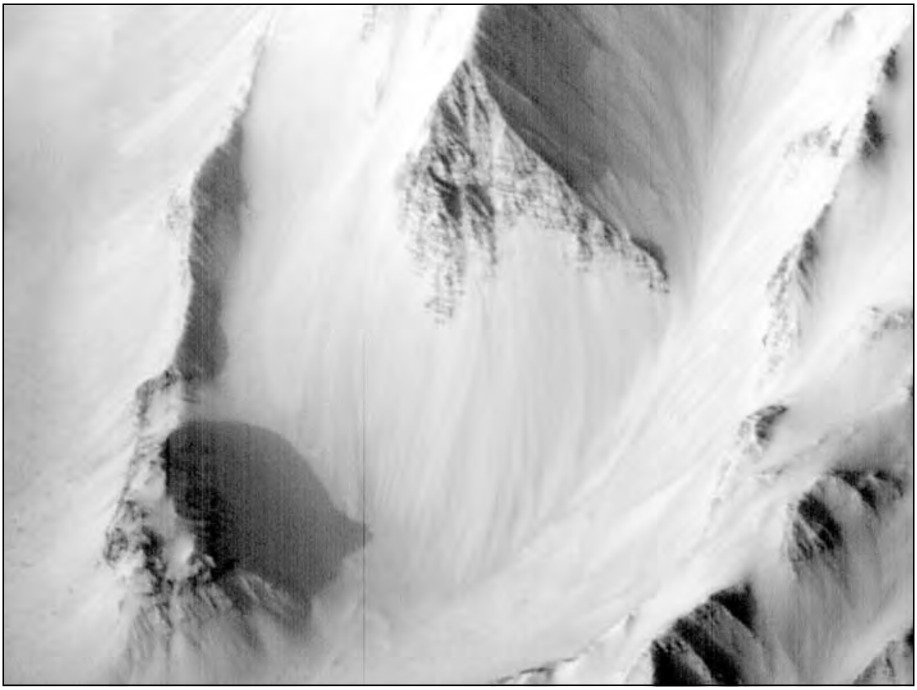

Figure 4–66. This image revealed light and dark layers in the rock outcrops of the canyon walls. In the notable triangular mountain face (at center), some 80 layers, typically alternating in brightness and varying in thickness from 5 meters to 50 meters (16 feet to 160 feet), are clearly visible. This type of bedrock layering had never been seen before in Valles Marineris. It called into question common views about the upper crust of Mars, for example, that there was a deep layer of rubble underlying most of the Martian surface, and argued for a much more complex early history of the planet. (MOC Image No. 560380579.1303 P013-03. NASA/JPL/ Malin Space Science Systems)

Mars Pathfinder

The Mars Pathfinder, a Discovery mission, was the last of the three 1996 Mars missions to leave Earth, but it was the first to arrive because of its shorter flight path. The mission demonstrated an innovative approach to landing an instrumented lander and free-ranging robotic rover on the surface of Mars. It also returned an unprecedented amount of data. The lander, formally named the Carl Sagan Memorial Station following its successful touchdown, and the microrover, named Sojourner after U.S. civil rights crusader Sojourner Truth, both outlived their design lives—the lander by nearly 3 times, and the rover by 12 times.

The spacecraft used an original method to directly enter the Martian atmosphere, assisted by a parachute to slow its descent and a giant system of airbags to cushion the impact (see Figure 4–67).

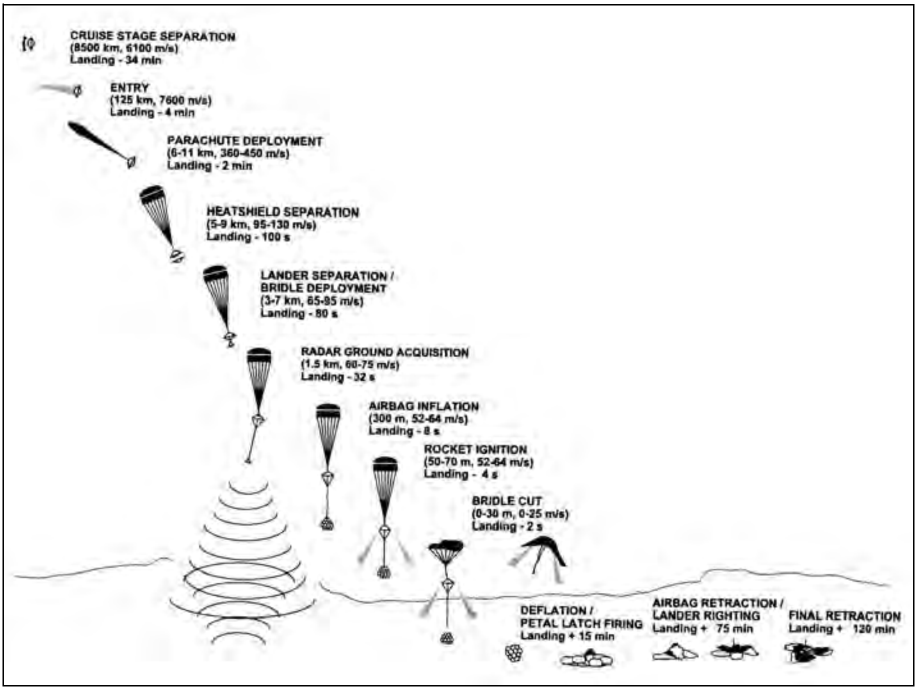

Figure 4–67. Mars Pathfinder Entry, Descent, and Landing.

The Mars Pathfinder touched down on July 4, 1997, at 16:57 Universal Time at a velocity of about 18 meters per second (40 miles per hour). It bounced about 15 meters (50 feet) into the air, bouncing another 15 times and rolling before coming to rest approximately 2.5 minutes after impact and about 1 kilometer (1.2 miles) from the initial impact site. One of the rockiest parts of Mars, the landing site in the Ares Vallis region was at 19.33°N, 33.55°W in Mars' Northern Hemisphere. This site was chosen because scientists believed it was a relatively safe surface to land on and it contained a wide variety of rocks deposited during an ancient flood.

The Mars Pathfinder's Sojourner Rover (formally named the Microrover Flight Experiment) rolled onto the Martian surface on July 6 at about 05:40 Universal Time. The rover was a technology experiment itself, designed to determine microrover performance in the poorly understood Martian terrain so that future rover designs would be effective in navigating and moving about the surface of Mars. The rover was limited to a weight of 11.5 kilograms (25.4 pounds). Another 6 kilograms (13.3 pounds) were allocated to lander-mounted rover telecommunications equipment, structural support of the rover, and its deployment mechanisms. The microrover had a height of 28 centimeters (10.9 inches), with ground clearance of 13 centimeters (5 inches) (see figure 4–68).

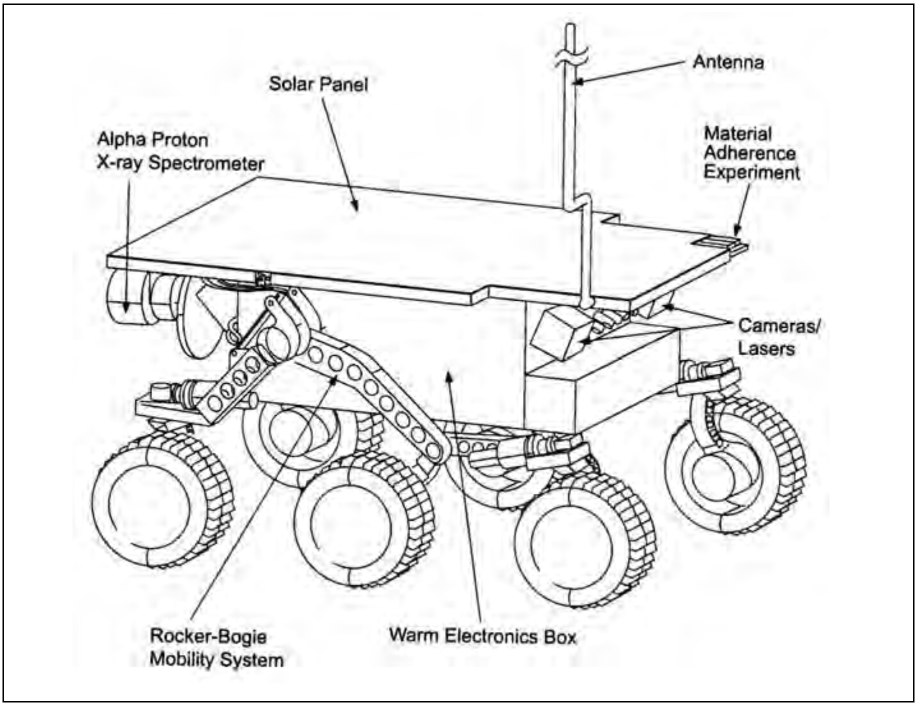

Figure 4–68. Mars Pathfinder's Sojourner Microrover.

The allowed lander stowage space for the Sojourner microrover was only 20 centimeters (7.8 inches), forcing it to "squat" to a height of 18 centimeters (7 inches) with its chassis and wheels folded up during its trip to Mars. Once its solar cells were exposed to the Sun, the Sojourner powered up and unfolded to its full height before leaving the lander.

The microrover was a six-wheeled vehicle of a rocker-bogie design, allowing it to travel over obstacles a wheel diameter (13 centimeters or 5.1 inches) in size. Each wheel was independently actuated and geared, providing superior climbing capability in soft sand. The front and rear wheels could be steered independently, allowing the vehicle to turn in place. The vehicle had a top speed of 0.4 meters (1.3 feet) per minute. A 22-square-meter (237-square-foot) solar panel powered the microrover. Nine batteries backed up the solar panel. The combined panel/battery system allowed microrover power users to draw up to 30 watts of peak power.[309] Microrover components not designed to survive ambient Mars temperatures, which reach -110°C (-166°F) during a Martian night, were contained in the warm electronics box, an insulated and heated container maintaining components between -40°C (-40°F) and +40°C (104°F) during a Martian day.

An integrated set of computing and power distribution electronics provided control. The on/off switching of the drive or steering motors controlled vehicle motion. While stopped, the computer updated its measurement of distance traveled and heading using the averaged odometry and on-board gyroscope. This provided an estimate of progress to the goal location.

Modems on the microrover and lander provided command and telemetry. The microrover was the link commander of the ultra high frequency system. During the day, the microrover regularly requested transmission of any commands sent from Earth and stored on the lander. When commands were unavailable, the microrover transmitted any telemetry collected during the last interval between communication sessions. The telemetry received by the lander from the microrover was stored and forwarded to Earth. In addition, this communication system provided a "heartbeat" signal during vehicle driving. While stopped, the microrover sent a signal to the lander. Once acknowledged by the lander, the microrover proceeded to the next stopping point along its route.

At the end of each sol of microrover travel, the camera system on the lander took a stereo image of the vehicle in the terrain. Those images were displayed at the control station. The operator could designate points in the terrain to serve as goal locations for the microrover. The coordinates of these points were transferred into a file containing the commands for execution by the microrover on the next sol. In addition, the operator used a model that, when overlayed on the image of the vehicle, measured the location and heading of the vehicle. This information was also transferred into the command file to be sent to the microrover on the next sol to correct any navigation errors.[310]

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[309] "A Description of the Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/descrip.html* (accessed August 23, 2005).

[310] "A Description of the Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/descrip.html* (accessed August 23, 2005).

The Pathfinder lander represented very advanced technology. The lander's three solar panels supplied up to 1,200 watt-hours of electrical power per day. At night, the lander operated on rechargeable silver-zinc batteries with a capacity of more than 40 amp-hours. For communications, Pathfinder had a high-gain antenna for high-speed, 2,250-bit-per-second communications with NASA's DSN. Its low-gain antenna sent information at a lower rate of 40 bits per second but did not need to be actively pointed at Earth.

The Imager for Mars Pathfinder was the Pathfinder's main imaging system. The Atmospheric Structure Instrument/Meteorology Package (ASI/MET) mast, the Pathfinder's weather tower, collected atmospheric information from a variety of temperature, pressure, and wind sensors. See Figure 4–69 for a drawing of the lander and Table 4–75 for further mission details.[311]

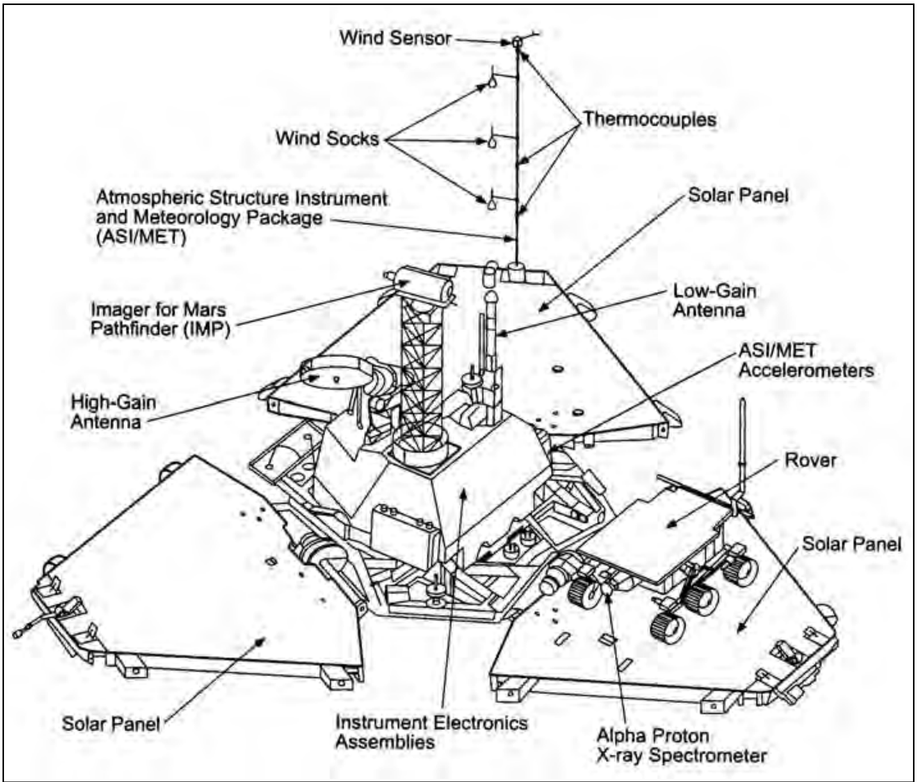

Figure 4–69. Mars Pathfinder Lander.

From landing until the final data transmission on September 27, 1997, the Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more

[311] "Pathfinder and Sojourner Explore Mars," *http://www.spacetoday.org/SolSys/Mars/MarsExploration/MarsPathfinder.html* (accessed August 23, 2005).

than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors. Findings from the investigations carried out by scientific instruments on both the lander and rover suggested that Mars was once warm and wet, with water existing in its liquid state and a thicker atmosphere.[312]

Mars '96

Mars '96 (originally called Mars '94) was a Russian mission consisting of an orbiter, two soft landers, and two surface penetrators to study Mars. The orbiter carried 12 instruments, as well as seven plasma-measuring instruments and three astrophysics instruments. Additional instruments were located on the landers and penetrators for measurements at the Martian surface (see Table 4–76). The United States contributed an instrument called the Mars Oxidant Experiment, an experiment that was to fly on one of the Russian landers or "small autonomous stations."

The main scientific objective of this mission was to investigate the evolution of the Martian atmosphere, surface, and interior. The mission was to consist of seven phases: launch and injection toward Mars; cruise (including two midcourse corrections); small station release and orbiter deflection maneuver; orbit insertion; orbit corrections; penetrator release; and mapping operations.

The mission lifted off on November 16, 1996, from Baikonur Cosmodrome in the Republic of Kazakhstan on a Proton launch vehicle. The spacecraft was not inserted into the interplanetary trajectory to Mars because of a malfunction in Block D (the third stage of the rocket). During the third revolution around Earth, the spacecraft reentered Earth's atmosphere and fell into the Pacific Ocean.[313] The spacecraft sank carrying 270 grams (9.5 ounces) of plutonium-238, part of its energy source.

Mars 1998–1999 Missions

In 1995, the Mars Program Office identified two missions for launch during late 1998–early 1999, the Mars Climate Observer and the Mars Polar Lander. To manage the missions, JPL created the Mars Surveyor Project '98 Office, an office responsible for designing the missions, developing both spacecraft and all payload elements, and integrating, testing, and launching both flight systems. In March 1996, after formation of the project office, the Mars Surveyor Program established the Mars Surveyor Operations Project, which was tasked with operating all Mars Surveyor Program missions.[314]

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312 "Mars Pathfinder," NASA's Mars Exploration Program, NASA Jet Propulsion Laboratory, *http://mars.jpl.nasa.gov/missions/past/pathfinder.html* (accessed August 11, 2005).

313 "Robotic Spacecraft Mission to Mars: Summary," *http://www.iki.rssi.ru/mars96/mars96hp.html* (accessed September 20, 2005).

314 Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," March 13, 2000, p. 10 (NASA History Office Folder 17919).

Taking advantage of the December 1998–January 1999 launch opportunity, NASA launched two missions to Mars. Both missions were designed, and their payloads selected, to address the science theme "Volatiles and Climate History" on Mars. They were to focus directly on the climate-history and resources themes of the Mars Surveyor Program while supporting the life-on-Mars theme through characterization of climate change and its evolving impact on the distribution of water.

The Mars Climate Orbiter and Mars Polar Lander Missions' scientific strategy was the following:

- Use seasonal and diurnal cycles of dust, water, and carbon dioxide to understand the processes of climate change during longer time scales.
- Characterize global atmospheric structure and circulation to explain the roles of atmospheric transport of volatiles and dust.
- Land on, and explore, a site having physical evidence of ancient climates, atmospheric evolution, and more recent, possibly periodic climate change.
- Locate surface ice reservoirs and search for local subsurface ice.
- Acquire data needed to validate and extend model simulations of climate processes and climate change.
- Emphasize comparative study of the climates of Earth and Mars and their potential implications for the origin and development of life.
- The major scientific measurement objectives for the Mars Surveyor Program 1998 missions were the following:
- Systematically observe the thermal structure and dynamics of the global atmosphere and the radiative balance of the polar regions, thereby providing a quantitative climatology of weather regimes and daily to seasonal processes.
- Determine the variations with time and space of the atmospheric abundance of dust and of volatile material (i.e., carbon dioxide and water, both vapor and ice) for one full Martian year.
- Identify surface reservoirs of volatile material and dust and observe their seasonal variations; characterize surface compositional boundaries and their changes with time; and search for near-surface ground ice in the polar regions.
- Explore and quantify the climate processes of dust storm onset and decay; atmospheric transport of volatiles and dust; and mass exchange between the atmosphere, surface and subsurface.
- Search for evidence characterizing ancient climates and more recent periodic climate change.

Mars Climate Orbiter

The Mars Climate Orbiter was designed to function as an interplanetary weather satellite and communications relay for the Mars Polar Lander. The orbiter, a combined graphite composite-aluminum honeycomb structure similar to the material used on commercial aircraft, carried two science instruments: a copy of an atmospheric sounder that flew on the Mars Observer spacecraft lost in 1993, and a new, lightweight color imager combining wide-angle and medium-angle cameras (see Figure 4–70).[315] During orbiter development, NASA officials applied the guiding principles of the "faster, cheaper, better" Discovery Program, capping mission costs and requiring the spacecraft to fit on a Delta II launch vehicle.[316]

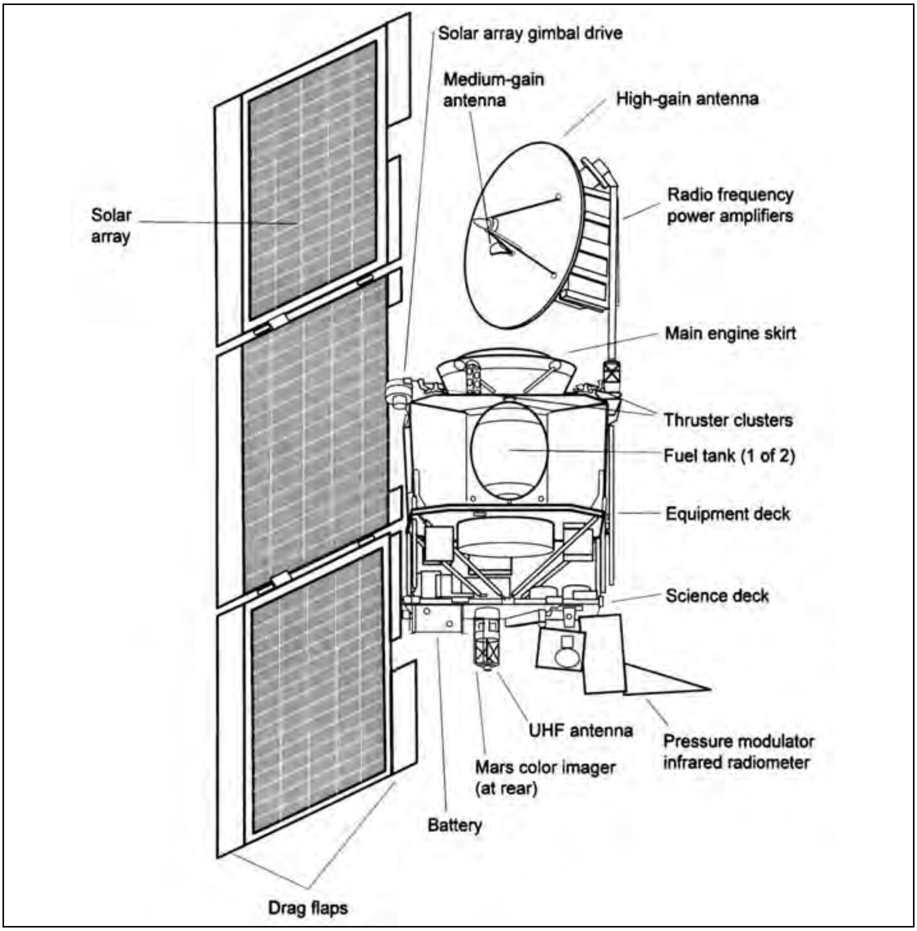

Figure 4–70. Mars Climate Orbiter.[317]

[315] "Mars Climate Orbiter," NASA's Mars Exploration Program, *http://mars.jpl.nasa.gov/missions/past/climorb.html* (accessed August 11, 2005).
[316] McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program,* p. 56.
[317] "Mars Climate Orbiter Arrival Press Kit," September 1999, p. 21, *http://www.jpl.nasa.gov/news/press_kits/mcoarrivehq.pdf* (accessed August 11, 2005).

The spacecraft was launched on December 11, 1998, on top of a Delta II ELV from Cape Canaveral Air Force Station, Florida. Nine and one-half months after launch, in September 1999, the spacecraft was to fire its main engine to achieve an elliptical orbit around Mars. It then was to skim through the Martian upper atmosphere for several weeks, using aerobraking to move into a lower circular orbit. Friction against the spacecraft's single 5.5-meter (18-foot) solar array was to lower the altitude of the spacecraft as it dipped into the atmosphere, reducing its orbital period from more than 14 hours to 2 hours.[318]

Until the morning of September 23, 1999, all information coming from the orbiter looked normal. At approximately 2 a.m. Pacific Daylight Time, the orbiter fired its main engine to go into orbit around Mars. The engine burn began as planned 5 minutes before the spacecraft passed behind the planet as seen from Earth. However, flight controllers did not detect a signal when the spacecraft was expected to emerge from behind the planet, and no further communication from the spacecraft was received. Later in the day, controllers announced that the spacecraft was believed lost.[319]

Almost immediately, Associate Administrator for the Office of Space Science Edward Weiler established the Mars Climate Orbiter Mission Failure Mishap Investigation Board to look independently into all aspects of the failed mission.[320] After review, the failure board determined that the spacecraft had entered the Martian atmosphere at a lower-than-expected trajectory, at approximately 60 kilometers (37 miles) rather than 150 kilometers (93 miles). The minimum survivable altitude was 85 kilometers (53 miles). According to Arthur G. Stephenson, head of the Failure Board, the "root cause" of the loss of the spacecraft was "the failed translation of English units into metric units in a segment of ground-based, navigation-related software."[321] This "failure to recognize and correct an error in the transfer of information between the Mars Climate Orbiter spacecraft team in Colorado and the mission navigation team in California," information critical to the maneuvers required to place the spacecraft in proper orbit around Mars, led to spacecraft loss because of the resulting incorrect altitude.[322] Table 4–77 provides further mission details.

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[318] Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," Appendix B, p. 37 (NASA History Office Folder 17919).

[319] "NASA's Mars Climate Orbiter Believed To Be Lost," Mars Polar Lander Release, September 23, 1999, *http://mars.jpl.nasa.gov/msp98/news/mco990923.html* (accessed August 11, 2005).

[320] Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," p. 10.

[321] "Mars Climate Orbiter Failure Board Releases Report, Numerous NASA Actions Underway in Response," *NASA News* Release 99-134, November 10, 1999, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1999/99-134.txt* (accessed August 11, 2005).

[322] "Likely Cause of Orbiter Loss Identified," Jet Propulsion Laboratory, *Universe* (October 1, 1999): 1 (NASA History Office Folder 17919).

Mars Polar Lander

The Mars Polar Lander was the second of two spacecraft launched toward Mars during the December 1998–January 1999 Mars launch opportunity. Also modeled after Discovery Program projects, the Mars Polar Lander was an ambitious mission to set a spacecraft down on the frigid terrain near the edge of Mars's south polar cap and dig for water ice with a robotic arm. In addition to its instruments and experiments. The lander carried two small probes from the New Millennium Program. Called Deep Space 2, the probes were designed to smash into the Martian surface to test new technologies for future planetary descent probes. The Mars Polar Lander and Deep Space 2 were lost at arrival on December 3, 1999. See Table 4–78 for mission details.

Comet Rendezvous Asteroid Flyby–Cassini-Huygens

The CRAF and Cassini-Huygens planetary missions were to build on the discoveries made through the Pioneer and Voyager missions. They were planned initially to be built around the new Mariner Mark II spacecraft with common design, fabrication, test, and integration elements to minimize costs. Both missions had international collaborators. Germany was to provide the propulsion system and one science instrument for the CRAF mission. The ESA contributed the Huygens science probe as well as science instruments and scientist participation to Cassini. The Italian Space Agency, Agenzia Spaziale Italiana, contributed Cassini's radio antenna.

Comet Rendezvous Asteroid Flyby

The CRAF mission was proposed in October 1985 when NASA's Solar System Exploration Committee recommended authorizing a comet rendezvous/asteroid flyby in FY 1987 for a 1990–1992 launch.[323] In October 1986, NASA selected the scientific payload, and in November announced the selection of 38 possible science investigations for the CRAF mission, which would be managed by JPL. The mission would be the first to use the new Mariner Mark II spacecraft. The CRAF mission was to conduct the first long-term study of a comet and its ejected gases and assess organic molecules present at the beginning of the solar system and their potential contribution to the origin of life. The spacecraft would rendezvous with the comet Kopff in 1996, fly in formation with it for three years, and fire an instrumented penetrator into the comet's nucleus in 1997. The spacecraft also was to make close flybys of two asteroids on its way to the comet encounter.[324]

[323] *Astronautics and Aeronautics, 1985: A Chronology* (National Aeronautics and Space Administration Special Publication-2000-4025: Washington, DC, 1988), p. 51.
[324] "NASA Selects Science Investigations for CRAF," Jet Propulsion Laboratory News Release, November 9, 1986, *http://www.jpl.nasa.gov/releases/80s/release_1986_1109.html* (accessed September 20, 2005).

Congress first funded the CRAF and Cassini missions jointly in the FY 1990 budget (prepared in 1989), contingent on a cost containment plan for the missions. Failure to stay within a set percentage of the plan's funding profile would result in termination of the CRAF mission.[325] Planned launch had by this time moved to August 1995. However, due to cost overruns and federal budget constraints, the CRAF program was cancelled in January 1992. FY 1992 funds were used to terminate the program, and any remaining funds were transferred to the Cassini program. Development of the Mariner Mark II spacecraft also was cancelled, requiring Cassini to redesign its spacecraft.

Cassini-Huygens

The Cassini-Huygens mission was a follow-on to the brief reconnaissance of Saturn performed by Pioneer 11 in 1979 and the Voyager 1 and Voyager 2 encounters in 1980 and 1981. The mission was named for two 17th century astronomers. Italian-French astronomer Jean-Dominique Cassini made several key discoveries about Saturn between 1671 and 1684 and established that Saturn's rings are split largely into two parts by a narrow gap. The Dutch scientist Christiaan Huygens discovered Titan, the largest of Saturn's moons, in 1655 and was responsible for many important Saturn findings.[326]

The mission began in 1982 when the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Sciences in the United States formed a joint working group. The group charter was to study possible modes of cooperation between the United States and Europe in the field of planetary science. As a result of their involvement in the studies, European scientists proposed a Saturn orbiter and Titan probe mission to the ESA, suggesting a collaboration with NASA.

In 1983, the U.S. Solar System Exploration Committee recommended that NASA include a Titan probe and radar mapper in its core program and also consider a Saturn orbiter. During 1984–1985, NASA and the ESA completed a joint assessment of a Saturn orbiter-Titan probe mission. In 1986, the ESA's Science Program Committee approved Cassini for initial conceptual study, with a conditional start in 1987.

During 1987–1988, NASA performed further design and development work on the standardized Mariner Mark II spacecraft and on a group of outer planet missions to be accomplished with the new spacecraft line. This was an early effort to reduce the cost of planetary exploration by producing multiple spacecraft for different missions made with the same basic spacecraft components off the same assembly line. The Cassini and CRAF missions were the first two missions chosen for further study. At the same time in

[325] "Chronological History Fiscal Year 1990 Budget Submission," p. 86 (NASA History Office Folder no. 10599).

[326] "Cassini Launch Press Kit," October 1997, pp. 3–4, *http://www.jpl.nasa.gov/news/press_kits/cassini.pdf* (accessed September 20, 2005).

Europe, the ESA carried out a Titan probe conceptual study in collaboration with a European industrial consortium led by Marconi Space Systems. The ESA renamed the Titan probe Huygens as the first medium-sized mission of its Horizon 2000 space science program.

Congress approved funding for Cassini and the comet-asteroid mission in 1989, and NASA and the ESA simultaneously released announcements of opportunity for scientists to propose scientific investigations for the missions. In 1992, Congress placed a funding cap on the Mariner Mark II program that effectively ended the new spacecraft line and also cancelled the CRAF mission. Cassini was restructured to reduce total program cost, mass, and power requirements.

The design of Cassini resulted from extensive tradeoff studies that considered cost, mass, reliability, durability, suitability, and availability of hardware. Moving parts were eliminated from the spacecraft wherever the functions could be performed satisfactorily without them. Thus, early designs that had included moving science instrument platforms or turntables were discarded in favor of instruments fixed to the spacecraft body whose pointing required rotation of the entire spacecraft. Tape recorders were replaced with solid-state recorders. Mechanical gyroscopes were replaced with hemispherical resonator gyroscopes. An articulated probe relay antenna was discarded in favor of using a high-gain antenna to capture the radio signal of the Huygens probe. A deployable high-gain antenna of the type used for the Galileo mission was considered and abandoned.[327]

One Cassini component generated controversy. Cassini uses RTGs, which contain plutonium, to generate the spacecraft's electrical power. RTGs enable spacecraft to operate at significant distances from the Sun or in other areas where solar power systems are unfeasible. The United States has used RTGs on 23 missions before Cassini, including Galileo, Ulysses, the earlier Pioneer, Viking, and Voyager missions, and the Apollo Moon landers. However, despite the successful record, critics feared that an accident during the planned flyby of Earth could bring the spacecraft too close to Earth and "shoot lethal plutonium onto Earth." Critics also contended that a launch accident would result in a "radioactive shower."[328] NASA maintained that even on the three occasions when there had been malfunctions on a mission using RTGs, the generators remained intact and did not release plutonium into the environment even in an explosion. The plutonium on Cassini was well shielded from intense heat, pressure, and shrapnel. Produced by the Department of Energy exclusively for space applications, the material was processed into 72 insoluble ceramic pellets encased in iridium and high-strength graphite blocks designed to withstand reentry into Earth's

[327] "Cassini-Huygens Saturn Arrival Press Kit," June 2004, pp. 11–12, *http://www.nasa.gov/pdf/60116main_cassini-arrival.pdf* (accessed September 20, 2005).

[328] "Cassini: Controversies Abound," CNN Interactive, *http://www.cnn.cm/SPECIALS/cassini/controversy* (accessed September 20, 2005).

atmosphere or an explosion at launch. Further, the ceramic pellets were designed to resist vaporization and would break into chunks, not powder that could be inhaled, on impact. Figure 4–71 shows a drawing of an RTG.

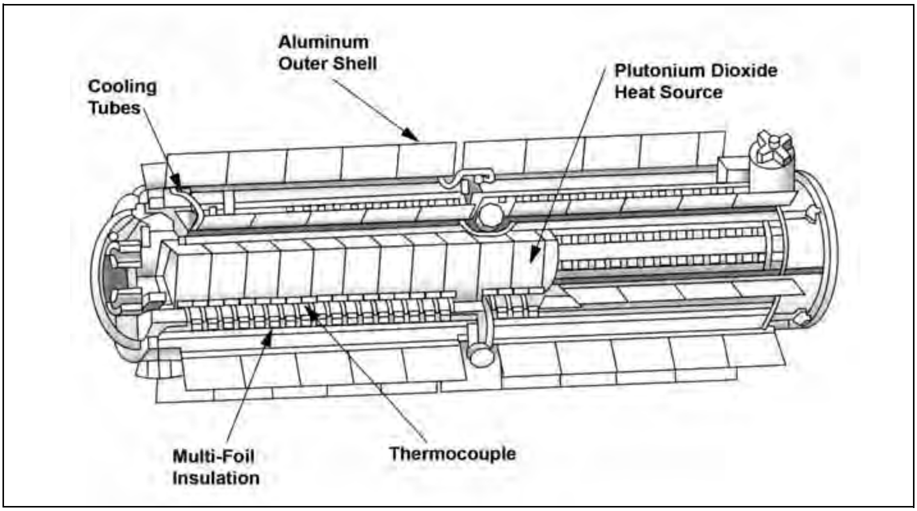

Figure 4–71. Radioisotope Thermoelectric Generator.

Cassini launched on October 15, 1997, on a journey to cover 3.5 billion kilometers (2.2 billion miles). Because of Cassini's large size, it could not be sent directly to Saturn on any available launch vehicle. Four gravity assists were required. Cassini's interplanetary trajectory took it by Venus twice, then past Earth and Jupiter. The spacecraft flew past Venus on April 26, 1998, at an altitude of 284 kilometers (176 miles) and on June 24, 1999, at 600 kilometers (370 miles) before swinging past Earth on August 18, 1999, at 1,171 kilometers (727 miles). The fourth and final gravity assist was from Jupiter on December 30, 2000, at an altitude of 9,723,890 kilometers (6,042,145 miles). This boosted Cassini the remaining distance to Saturn. The Huygens probe was bolted to Cassini.[329] Figure 4–72 shows Cassini's interplanetary trajectory.

Spacecraft and Instruments

The Cassini-Huygens spacecraft is the most highly instrumented and scientifically capable planetary spacecraft ever flown, equipped with a total of 18 instruments, 12 on the orbiter and 6 on the Huygens probe. Many of these sophisticated instruments are capable of multiple functions. The orbiter's instruments gather data for 27 diverse science investigations. Cassini's payload represents the technical efforts of 260 scientists from the United States and 17 European nations.

[329] "Cassini-Huygens Saturn Arrival Press Kit," June 2004, p. 35, *http://www.nasa.gov/pdf/60116main_cassini-arrival.pdf* (accessed September 20, 2005).

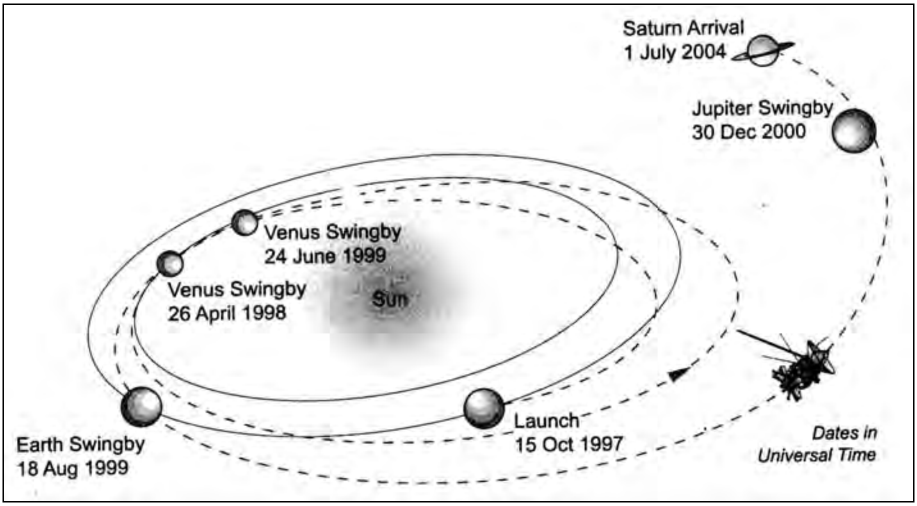

Figure 4–72. Cassini Interplanetary Trajectory.

The Huygens Probe system, built by an industrial consortium led by Aerospatiale, was supplied by the ESA. The system includes the probe that enters Titan's atmosphere after separation from the orbiter and probe support equipment (PSE) that remains attached to the orbiter.

The PSE includes a number of engineering subsystems and the electronics necessary to track the probe; recover the data gathered during its descent and process and deliver the data to the orbiter, which is then transmitted from the orbiter to the ground. The PSE consists of four electronic boxes aboard the orbiter—two probe support avionics, a receiver front end, and a receiver ultrastable oscillator; the spin eject device; and the harness (including the umbilical connector) that provides power, RF, and data links between the probe support avionics, probe, and orbiter.[330]

The probe itself consists of the Entry Assembly, which cocoons the Descent Module (DM) and provides orbiter attachment; umbilical separation and ejection; cruise and entry thermal protection; and entry deceleration control. The assembly is jettisoned after entry, releasing the DM. This module comprises an aluminum shell and inner structure containing the six instruments and all the experiments and probe support subsystems, including the parachute descent and spin control devices.

Cassini is one of the largest interplanetary spacecraft ever launched. Loaded with fuel and the Huygens probe and launch vehicle adapter, it weighed 5,712 kilograms (12,593 pounds) at launch. More than half the spacecraft's total mass was propellant. On the launch pad, the spacecraft stood 6.8 meters (22.3 feet) high and was 4 meters (13 feet) wide. Its magnetometer is mounted on an 11-meter (36-foot) boom extending from the spacecraft, and

[330] "Huygens," European Space Agency, *http://huygens.esa.int/science-e/www/category/index.cfm?fcategoryid=4828* (accessed September 20, 2005).

three other 10-meter (32-foot) antenna booms extend outward from the spacecraft. Multilayer blanketing material covering most of the spacecraft and its instrument housings protects Cassini against the extreme heat and cold of space. The blanketing material also maintains the needed room temperature operating environment for computers and other electronic systems. Layers of mylar in the blankets protect against micrometeoroids in interplanetary space.

The orbiter's main body consists of a lower equipment module, a propulsion module, and an upper equipment module. A fixed 4-meter (13-foot)-diameter high-gain antenna tops the stack. A remote sensing pallet containing cameras and other remote sensing instruments and a fields and particles pallet containing instruments that study magnetic fields and charged particles sit part way up the spacecraft. The whole spacecraft must be turned to point the instruments toward their targets, although three of the instruments can turn about one axis. The orbiter has 12 engineering subsystems governing spacecraft components and functions. A diagram of the spacecraft can be seen in figure 4–73. Mission details can be found in Table 4–79.

Ongoing Planetary Missions

Four Pioneer and two Voyager spacecraft launched in previous decades continued operating into the 1990s.

Pioneer Missions

Pioneer 6 was the first of four NASA spacecraft designed to study interplanetary phenomena in space. Launched in 1965, Pioneer 6 continued to operate into the 1990s. By December 1990, Pioneer 6 had circled the Sun 29 times (traveling 24.8 billion kilometers) (15.4 billion miles) and had been operational for 20 years—a record for a deep space probe. Its original slated lifetime had been only six months. On December 15, 1996, the spacecraft's primary transmitter failed, but during a track on July 11, 1996, ground controllers switched on the backup transmitter. Of the spacecraft's six scientific instruments, two still continued to function (the plasma analyzer and cosmic-ray detector).

NASA maintained contact with the spacecraft once or twice each year. For example, 1 hour's worth of scientific data was collected on July 29 and December 15, 1995, (although the primary transmitter failed soon after that), and again on October 6, 1997, more than 30 years after launch. The probe's solar arrays continued to deteriorate, although the transmitters could be turned on at perihelion when the solar flux was strong enough to provide sufficient power. On December 8, 2000, to commemorate its 35th anniversary of operation, ground controllers established successful contact with the spacecraft for about 2 hours.[331] Two Pioneer planetary missions, Pioneer 10 and 11 launched in 1972 and 1973 continued to operate into the 1990s.

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[331] Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, p. 52.

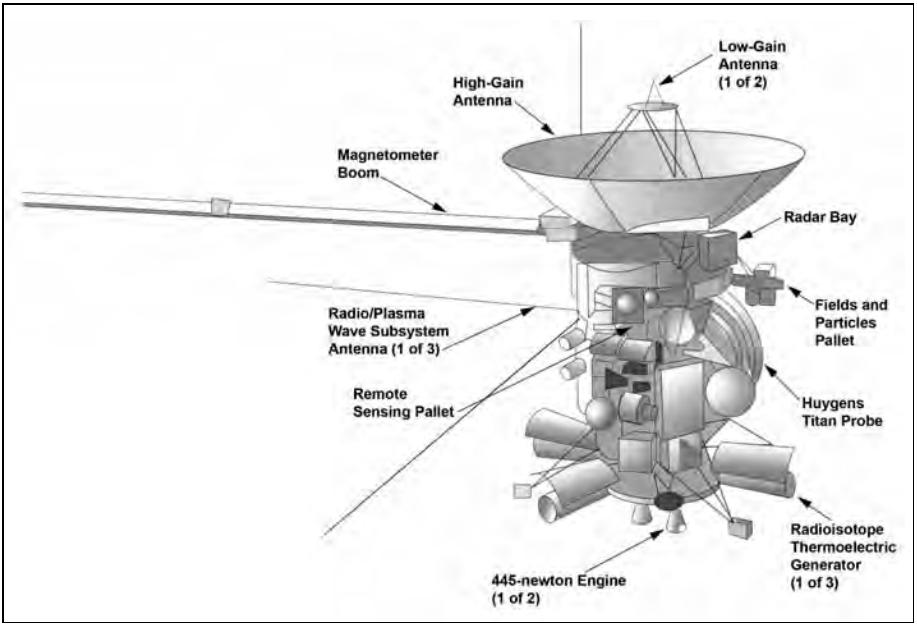

Figure 4–73. Cassini Spacecraft.

Pioneer 10 attained a milestone on September 22, 1990, when it reached 50 times farther from the Sun than the Sun was from Earth—a distance of 50 astronomical units. The spacecraft had left our solar system planets behind on June 13, 1983. Pioneer 10 was the first spacecraft to cross the asteroid belt, fly by Jupiter, and return pictures and a description of the planet's magnetic field, interior structure and atmosphere, and the mass of its moons. The spacecraft's most important finding about the outer solar system was the extent of the Sun's heliosphere, originally thought to end at the orbit of Jupiter. But at almost 10 times farther away, Pioneer 10 was still within the solar heliosphere.[332]

Both Pioneer 10 and Pioneer 11 provided data to NASA scientists in 1989 allowing them to produce "celestial constants," the first "pure" measurements of the various kinds of background light in our solar system, galaxy, and universe. Scientists determined that background light from beyond the solar system was made up of approximately 82 percent light from faint stars. Most of the remaining light was galactic light diffused by dust and less than 0.6 percent originated beyond the galaxy. This data provided a benchmark in many areas of astronomy and physics. The work also provided a clue to the chemical composition of solar, galactic, and cosmic dust; gave an accurate measure of the Sun's position above the plane of the galaxy; and described how cosmic dust scattered light.[333]

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[332] "Pioneer 10 Marks New Epoch in Solar System Exploration," *NASA News* Release 90-125, September 18, 1990, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1990/90-125.txt* (accessed September 30, 2005).

[333] "Pioneers Make First Measurements of Interstellar Light," *NASA News* Release 89-186. December 27, 1989, *http://web.archive.org/web/20000613212615/spacelink.nasa.gov/NASA.News/NASA.News.Releases/Previous.News.Releases/89.News.Releases/89-12.News.Releases/89-12-17* (accessed August 16, 2005).

Pioneer 10 observed its 10th anniversary of leaving the solar system planets in June 1993. Five of its 11 instruments were still sending back data through the spacecraft's 7.5-watt radio signal. To that date, Pioneer 10 had transmitted more than 170 billion bits of science data and was continuing to transmit data daily.[334] Another major milestone occurred on March 2, 1997, when the spacecraft reached its 25th year in space 6.2 billion miles (10 billion kilometers) from Earth.[335] The Pioneer 10 science mission officially ended on March 31, 1997. Since that time, Pioneer 10's weak signal has been tracked by NASA's DSN as part of a new advanced-concept study of communication technology in support of NASA's future Interstellar Probe mission. Its last signal was received on January 22, 2003.[336]

Pioneer 11 crossed the orbit of Neptune on February 23, 1990, becoming the fourth spacecraft to leave the solar system at a distance of 2.8 billion miles (4.5 billion kilometers) from Earth. (At that date, because of Pluto's eccentric orbit, Neptune was farther from Earth than Pluto.) Pioneer 11 provided scientists with their closest view of Jupiter in December 1974, passing within 26,600 miles (42,800 kilometers) of its cloud tops. In 1979, Pioneer 11 approached within 13,000 miles (20,921 kilometers) of Saturn, taking the first close-up pictures of the planet. The spacecraft continued sending back limited data on the solar wind, magnetic field, and cosmic rays, but by September 1995, although two instruments were still operational, Pioneer 11 could no longer be maneuvered to point its antenna accurately at Earth. On September 30, after the spacecraft traveled beyond the orbit of Pluto and more than 4 billion miles (6.4 billion kilometers) from Earth into interstellar space, Pioneer 11 ceased daily communications with NASA as controllers terminated routine contact with the spacecraft. Controllers began using the DSN antennae to listen for the spacecraft's signal only about 2 hours every two to four weeks.[337] The last communication from Pioneer 11 was received in November 1995 when Earth moved out of view of the spacecraft's antenna. Both Pioneer 10 and Pioneer 11 carried a plaque for communicating with any intelligent species that might find the spacecraft (see Figure 4–74).

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[334] "Pioneer Celebrates 10 Years Beyond the Known Solar Planets," *NASA News* Release 93-110. June 11, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-110.txt* (accessed September 30, 2005).

[335] "Pioneer 10 Spacecraft Nears 25th Anniversary, End of Mission," *NASA News* Release 97-31, February 27, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-031.txt* (accessed September 30, 2005).

[336] "Pioneer 10 Spacecraft Sends Last Signal," *NASA News* Release 03-082, February 25, 2003, *http://www.nasa.gov/home/hqnews/2003/feb/HP_news_08082.html* (accessed September 30, 2005).

[337] "Pioneer 11 To End Operations After Epic Career," *NASA News* Release 95-163, September 29, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-163.txt* (accessed September 30, 2005).

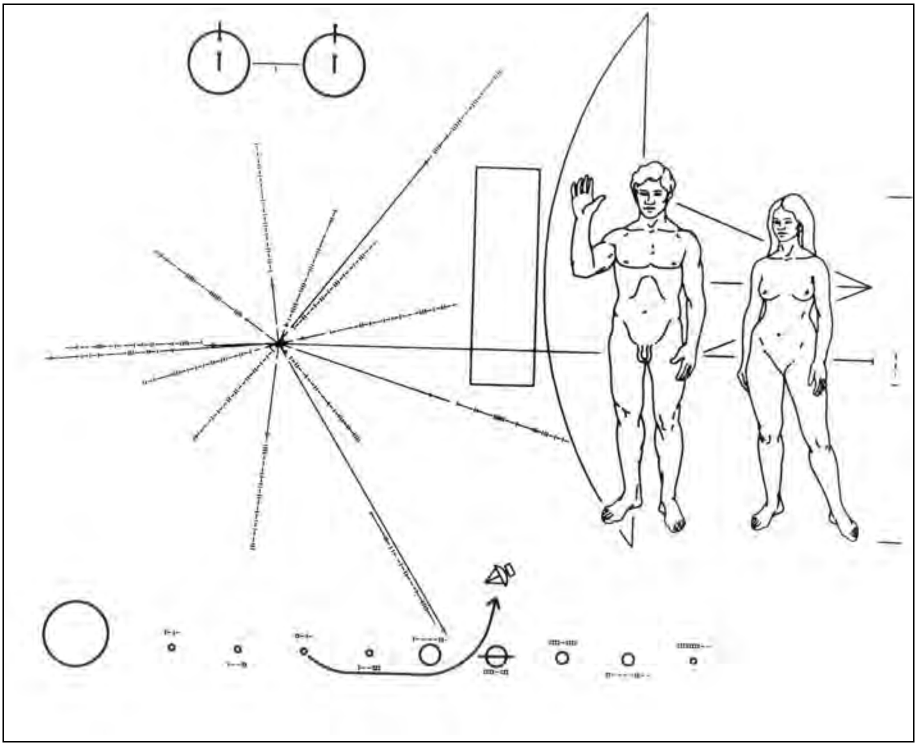

Figure 4–74. Pioneer 10 and Pioneer 11 carry this pictorial plaque. It was designed to show scientifically educated inhabitants of some other star system who might intercept it from where, and by what kind of beings, it came. The design was etched into a 6 inch by 9 inch (15 cm by 23 cm) gold-anodized aluminum plate and is attached to each spacecraft's antenna support struts in a position to help shield it from erosion by interstellar dust. (NASA Photo No. 72-H-192)

Pioneer Venus (Pioneer 12) was launched in 1978. Although its planned primary mission duration was only eight months, Pioneer 12 operated until October 1992. The spacecraft performed long-term observations of the Venusian atmosphere and surface features. Pioneer 12 returned global maps of the planet's clouds, atmosphere, and ionosphere; measurements of the atmosphere-solar wind interaction; and radar maps of 93 percent of the planet's surface. Additionally, the spacecraft used several opportunities to make systematic UV observations of several comets in the 1980s.[338]

Starting in September 1992, controllers used the remaining fuel in a series of maneuvers to keep raising periapsis altitude for as long as possible. On October 8, 1992, its fuel supply was exhausted, and the spacecraft plunged through the Venusian atmosphere as a flaming meteor.[339]

[338] "Pioneer 12," Quicklook, Mission and Spacecraft Library, Jet Propulsion Laboratory, *http://samadhi.jpl.nasa.gov/msl/QuickLooks/pioneer12QL.html* (accessed September 9, 2005).
[339] "The Pioneer Missions," *http://spaceprojects.arc.nasa.gov/Space_Projects/pioneer/PNhist.html* (accessed September 9, 2005).

The spacecraft returned evidence for early oceans on Venus and gave new support for the presence of lightning on the planet, phenomena doubted by some scientists. Data showed that Venus, which had become hot and dry, once had 3.5 times as much water as thought earlier—enough to cover the entire surface between 25 feet (7.6 meters) and 75 feet (22.9 meters) deep. Data also suggested that, at Pioneer's lowest altitude of 80 miles (29 kilometers), "whistler" radio signals, believed generated by Venus's lightning, were the strongest ever detected. They were the same as the radio signals used in most lightning studies on Earth. Pioneer 12 penetrated 7 miles (11.3 kilometers) below the peak of Venus's ionosphere, which tended to block the radio signals. At that altitude, the magnetic fields that channeled the signals were the strongest ever seen on Venus's night side.

During a three-month period, Pioneer 12 provided data from 80 miles to 210 miles (129 kilometers to 338 kilometers) altitude. The spacecraft found the beginning of Venus's real, mixed atmosphere at 80 miles. Below 85 miles (137 kilometers), the spacecraft identified various waves and a four-day oscillation of Venus's atmosphere-top. The neutral atmosphere above 185 miles (298 kilometers) was more than 10 times denser and 1,800°F (982°C) hotter than thought.[340]

Voyager

Voyager 1 and Voyager 2, identical spacecraft, were launched on September 5 and August 20, 1977, respectively. During the first 10 years of its mission, Voyager 1 encountered Jupiter and Saturn, scanned Saturn's primary moon Titan, and was flung by Saturn's gravity up out of the ecliptic plane. Voyager 2 followed Voyager 1 to Jupiter and Saturn, and then the spacecraft proceeded to Uranus and Neptune, using the gravity of each planet to boost it to the next.

As Voyager 2 approached Neptune, the spacecraft made several discoveries. Images from the spacecraft revealed three additional new moons, bringing the total number of known moons to six. The new moons occupied nearly circular and equatorial orbits around the planet. All moved in the same direction the planet rotated, making the large moon Triton, which occupied a retrograde orbit, even more of an oddity in the Neptune system. The three moons orbited at distances of about 32,300 miles (52,000 kilometers), 38,000 miles (61,155 kilometers), and 45,400 miles (73,000 kilometers) from the planet's center.

Neptune investigators also found two ring arcs, or partial rings, in images returned by Voyager 2. The two ring arcs were apparently associated with two of the new Neptunian moons found by Voyager. The ring arcs may be composed of debris associated with the moons or may be remnants of moons

[340] Peter Waller, "Pioneer Venus Orbiter Final Results Provide Evidence for Oceans and Lightning on Venus," *Astrogram*, Ames Research Center (April 2, 1993): 1.

that were ground down or torn apart through collisions. Astronomers suspected the existence of such an irregular ring system around Neptune, but Voyager's photographs were the first evidence of their existence.

Voyager found evidence of a magnetic field from intense radio emissions from Neptune. The intensity of the emissions indicated that Neptune's magnetic field was similar in intensity to the fields of Earth and Uranus. Voyager's cameras also captured a 5-mile (8-kilometer) high, geyser-like plume of dark material erupting from the surface of Triton. This was the first time that geyser-like phenomena were seen on any object in the solar system other than Earth since Voyager earlier discovered eight active geysers shooting sulfur above the surface of Jupiter's moon.

On August 25, 1989, Voyager 2 flew within 5,000 kilometers (3,000 miles) of Neptune, the closest encounter to the planet and the highlight of the spacecraft's "Grand Tour" of the outer planets. At the time, the planet was the most distant member of the solar system from the Sun. (Figure 4–75 shows an image of Neptune's rings.) Following its closest approach to Neptune, the spacecraft flew southward, below the ecliptic plane onto a course to interstellar space and the heliopause. Reflecting the Voyager's new transplanetary destinations, the extended project became known as the Voyager Interstellar Mission.

Figure 4–75. Voyager 2 acquired this image of Neptune's rings in its encounter of the planet in August 1989. In Neptune's outermost ring, 39,000 miles (62,764 kilometers) out from the planet, material mysteriously clumps into three arcs. (NASA-JPL Photo No. P35060)

On February 17, 1998, Voyager 1 became the most distant human-made object, reaching almost 70 times farther from the Sun than Earth. At a distance of 6.5 billion miles (10.4 billion kilometers) from Earth and traveling at a speed of 39,000 miles per hour (62,764 kilometers per hour) away from the Sun, the spacecraft outdistanced Pioneer 10 in their opposite journeys away from the Sun. At the same time, Voyager 2 was 5.1 billion miles (8.1 billion kilometers) from Earth, departing the solar system at a speed of 35,000 miles per hour (56,327 kilometers per hour).[341] Experts estimate that both spacecraft have enough electrical power to continue operating until about 2020.[342] Table 4–80 lists selected Voyager events.

Attached Shuttle Payload Bay Science Missions

With every Space Shuttle mission, NASA had a platform for performing scientific experiments. NASA used the Shuttle's microgravity environment for a variety of smaller experiments; small, self-contained payloads; and large experimental missions. Astronauts used the Shuttle's capabilities for investigations in atmospheric physics; Earth observation; space plasma physics; life sciences; materials science; astronomy; solar physics; and technology. Among these were the Spacelab missions and commercial investigations, such as those carried in SPACEHAB modules, which are described in the individual Shuttle mission tables in chapter 3. Attached space science missions are described more fully in this section.

In addition, the Space Shuttle launched and retrieved a number of small satellites; some were free-flying and others suspended at the end of the Shuttle's robot arm. They are described below.

Astro-1

Astro-1 began in 1978 with an announcement of opportunity for instruments to travel aboard the Space Shuttle and use the unique capabilities of Spacelab. Three telescopes, the HUT, UIT, and WUPPE, evolved as a payload listed as OSS-3 through OSS-7. In 1982, the mission was renamed Astro. The WFC was added to the payload in 1984 to make detailed studies of Comet Halley, which was due to move through the inner solar system in the spring of 1986, the original Astro-1 launch date. The instruments were constructed, and the observatory had completed Spacelab integration and testing by January 1986. Astro-1, consisting of the HUT, UIT, WUPPE, and WFC, was ready for orbiter installation when the *Challenger* accident

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[341] "Voyager 1 Now Most Distant Human-Made Object in Space," *NASA News* Release 98-30, February 13, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-030.txt* (accessed September 30, 2005).

[342] Mary Hardin, "Voyager 1 Now Most Distant Human-Made Object in Space," Jet Propulsion Laboratory, *Universe* 28 (February 20, 1998): 1, 3.

occurred, delaying future Space Shuttle missions. During the delay, the instruments were removed from Spacelab and stored. Periodic checks were made during storage and a number of parts were replaced.[343]

Also, because Comet Halley was no longer in position for detailed observation, the WFC was removed in the spring of 1987. In March 1988, the BBXRT was added to the Astro-1 payload. The addition allowed study of supernovae and other objects in x-ray and UV wavelengths.

Astro-1 was installed in *Columbia*'s payload bay on March 20, 1990, and launch occurred on December 2.[344] It was a dedicated Spacelab mission to conduct astronomical observations in the UV spectral regions. Its primary objectives were to obtain the following:

- Imagery in the spectral range from 1,200 angstroms to 3,100 angstroms (UIT)
- Spectrophotometry in the spectral region from 425 angstroms to 1,850 angstroms (HUT)
- Spectrapolarimetry from 1250 angstroms to 3,200 angstroms (WUPPE)
- X-ray data in the bandpass between 0.3 keV and 12 keV (BBXRT)

Astro-1 was the first Spacelab mission devoted to a single scientific discipline—astrophysics. It was an extremely productive science mission despite the loss of both data display units used for pointing the telescopes and operating experiments during the mission. The loss affected crew-aiming procedures and forced ground teams at Marshall Space Flight Center to aim the UV telescopes while the flight crew fine-tuned the telescopes's orientation. The returned data volume was less than half of that originally planned, and the science return was approximately 67 percent of the stated goals of the mission.[345]

Astro-1's UV and x-ray telescopes made 231 observations of 130 unique astronomical targets during a 10-day period, capturing the first views of many celestial objects in extremely short UV wavelengths, taking the first detailed UV photographs of many astronomical objects, and making the first extensive studies of UV polarization.[346] The instruments observed for a total of 143 hours. All three UV telescopes observed the Cygnus Loop, the remnant of an explosion some 40,000 years ago. Observations detected a much higher temperature and greater velocity of its shock wave than had been predicted. The telescopes also studied the Crab Nebula, a relatively young supernova remnant.

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[343] "Space Shuttle Mission STS-35 Press Kit," December 1990, p. 39, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_038_STS-035_Press_Kit.pdf* (accessed August 22, 2005). The IPS and other Spacelab facilities were needed for the HUT.

[344] "Space Shuttle Mission STS-35 Press Kit," December 1990.

[345] "Astro 1," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1* (accessed August 30, 2005).

[346] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).

The HUT, developed at The Johns Hopkins University, obtained spectra of significant examples of almost every major class of astronomical object, ranging from distant galaxies and quasars to stars, star clusters, and clouds of gas and dust in our own galaxy as well as observing familiar objects within our solar system. HUT scientists learned about conditions in the cores of active galaxies, obtaining evidence for a new path of stellar evolution for old stars residing in these galaxies. The telescope also found new evidence for a hot, gaseous halo surrounding the Milky Way galaxy. The HUT made several observations of Jupiter and its moon Io, studying the dynamic nature of their relationship. Scientists used the HUT's more detailed spectra to reinterpret data gathered by the Voyager spacecraft in the late 1970s.[347]

Astronomers used HUT data to study various diffuse nebulae in our galaxy. They learned about the characteristics of dust near hot stars and the speeds of shock waves produced by supernova explosions. Astronomers also gathered information on the chemical composition of this tenuous material in interstellar space. The HUT also observed a handful of binary star systems called cataclysmic variable stars, in which two stars are locked in very tight orbits about each other. Objects studied in our solar system included the plasma produced by events relating to Jupiter's magnetic field and Io. The HUT observed a comet as the last observation made on the mission.[348] The HUT obtained spectra of 77 individual celestial targets on Astro-1.[349]

The UIT, sponsored by NASA's Goddard Space Flight Center, obtained a large number of images, including clusters of young, hot massive stars; globular clusters containing old stars, some of which were unusually hot; spiral galaxies rich with star-forming activity; and smaller "irregular" galaxies that could experience sudden bursts of star formation.[350] The UV images picked out hot stars in late stages of evolution, where hydrogen had been depleted from the cores, and burning helium provided energy. By comparing photographs taken in different wavelengths, scientists could measure the temperature and brightness of individual stars. The UIT also identified rings of massive star formation in several galaxies, including thousands of individual hot stars in other galaxies for later study by the Hubble Space Telescope. The telescope also revealed that the shapes of galaxies seen in UV wavelengths were strikingly different from their familiar forms in visible light.[351] The UIT obtained 821 exposures of 66 targets.[352]

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[347] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 21, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).
[348] "Achievements of Astro-1," *http://praxis.pha.jhu.edu/astro1/astro1_summary.html* (accessed August 25, 2005).
[349] "Hopkins Ultraviolet Telescope (HUT)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=2* (accessed August 30, 2005).
[350] "The Ultraviolet Imaging Telescope," *http://praxis.pha.jhu.edu/instruments/uit.html* (accessed August 25, 2005).
[351] "Space Shuttle Mission STS-67 Press Kit," March 1995, pp. 19–20, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).
[352] "Ultraviolet Imaging Telescope (UIT)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=3* (accessed August 30, 2005).

The WUPPE, built at the University of Wisconsin, was a pioneering effort to explore polarization and photometry in the UV spectrum. The instrument measured polarization by splitting the beam of radiation entering the telescope into two perpendicular planes of polarization. The beams were then passed through a spectropolarimeter and focused on separate array detectors for photometric measurements. The WUPPE found that the amount of polarized light coming from these stars was less than was seen in visible light and less than expected in the UV, indicating that some of the UV polarized light was being removed by the gas in the disk around the star. The wavelengths in the UV where polarized light was missing told astronomers that there were apparently atoms of gaseous iron in the disks close to be stars (stars that were spinning very fast).

The WUPPE also used half a dozen bright stars to illuminate the interstellar medium, shedding new light on the chemical composition and physical nature of the dust between stars in the Milky Way. Surfaces of these dust grains were thought to provide a safe haven for the formation of molecules, clouds of which were the “womb” for the formation of each generation of new stars. Astro-1 observations revealed that some parts of the galaxy seem to have dust grains that might look like tiny hockey pucks, while other parts seem to have a mixture of several sizes, shapes, and kinds of dust grains. The WUPPE made 98 observations of 75 targets on Astro-1, eight of which were spectrum-only (no polarimetry).[353]

The flight of the BBXRT marked the first opportunity for performing x-ray observations over a broad energy range (0.3 keV–12 keV) with a moderate energy resolution (typically 90 eV and 150 eV at 1 keV and 6 keV, respectively). This energy resolution, coupled with an extremely low detector background, made the BBXRT a powerful tool for the study of continuum and line emission from cosmic sources. The observing program was designed to be an even mix of galactic and extragalactic targets, although the galactic center region was not available due to the time of year that the BBXRT was launched.

The BBXRT, designed and built at the Laboratory for High Energy Astrophysics at NASA’s Goddard Space Flight Center, was in orbit for almost nine days. The detector system was powered for nearly the entire time, collecting source, background, or calibration data. The instrument behaved almost flawlessly on orbit. Although the BBXRT’s observing efficiency was reduced due to problems in the spacecraft’s pointing systems, it achieved a total of 185,000 seconds of observation time on cosmic x-ray sources. An additional 100,000 seconds of the total available observing time was usable for studies of the diffuse x-ray background. A total of 157 observations of 82 x-ray sources was achieved, with typical observation times ranging from 300 seconds to 3,000 seconds. See Table 4–81 for further details.

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[353] “Wisconsin Ultraviolet Photopolarimetry Experiment (WUPPE),” NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=1* (accessed August 30, 2005).

Astro-2

The Astro-2 mission launched on STS-67 on March 2, 1995, for a 16 1/2-day mission, nearly twice as long as Astro-1. The Astro-2 mission was a dedicated Spacelab mission to conduct astronomical observations in the UV spectral regions.

Astro-2 marked the second flight of the Astro-1 suite of science instruments as the three Astro-1 UV telescopes were reassembled to form the Astro-2 observatory. The BBXRT was not used on Astro-2. An improved HUT, the UIT, and the WUPPE were mounted on an improved IPS on a Spacelab pallet in *Endeavour*'s cargo bay. The IPS furnished a stable platform, kept the telescopes aligned, and provided various pointing and tracking capabilities to the telescopes. During Astro-1, the IPS had difficulty locking onto guide stars properly, forcing the crew to manually point the IPS and track targets. In general, the astronauts were able to provide pointing stability of about 2 arc seconds to 3 arc seconds or better. However, in "optical hold," the IPS should be able to achieve sub-arc-second stability. After the Astro-1 mission ended, a team extensively modified and tested the IPS software and made other improvements to ensure the IPS worked properly for Astro-2.[354]

A new feature for Astro-2 was "community involvement." As well as the scientists and engineers who developed the instruments, guest investigators also used the Astro-2 telescopes for their own observations. The addition of the guest investigator teams produced an even broader range of attempted observations and brought the total list of different science programs to 23.

The UIT and WUPPE did not change from Astro-1. The UIT's cameras imaged about two dozen large spiral galaxies for inclusion in an atlas of such galaxies and made the first UV images of the entire Moon. The telescope also studied the rare, hot stars that were 100 times as hot as the Sun; elliptical galaxies; and some of the faintest galaxies in the universe. Investigators were disappointed, upon developing UIT film, to learn that one of its two cameras had malfunctioned undetected on orbit, but an initial assessment showed that 80 percent of science objectives were still met.

The WUPPE measured photometry and polarization of UV radiation from astronomical objects, greatly expanding the database on UV spectropolarimetry. Targets for interstellar medium study included dust clouds in the Milky Way and the nearby galaxy, the Large Magellanic Cloud. The WUPPE also studied several types of stars, including Wolf-Rayet and Be stars, and capitalized on the opportunity to study three recently exploding novae.[355]

The HUT performed spectroscopy in the far UV region of the spectrum to identify the physical processes and chemical composition of a celestial object. Its science program for Astro-2 expanded on results from Astro-1 and also

[354] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 27–30.
[355] "Space Shuttle Mission Chronology–STS-67," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-67.htm* (accessed August 30, 2005).

broke new ground. By observing more active galaxies, elliptical galaxies, cataclysmic variables, and nebulae, the Astro-2 HUT observations provided a broader understanding of the phenomena involved in these objects.

Improvements to the HUT made it three times more sensitive than on the Astro-1 mission. The HUT's increased sensitivity, along with increased observation time and technical improvements to the IPS, enabled HUT scientists to gather five times more data than they did during the Astro-1 mission. It obtained higher-quality spectra and observed objects too faint to see previously, permitting the pursuit of new science programs.[356] The HUT, considered a complement to the Hubble Space Telescope, made 385 science pointings at 260 unique astronomical targets during the mission, collecting enough data to meet its primary mission objective of detecting the presence of intergalactic helium, a telltale remnant of the Big Bang explosion that began the universe. The HUT also studied Io and the Venusian and Martian atmospheres and, in conjunction with the Hubble Space Telescope, took UV measurements of Jupiter's aurora.[357] The HUT's scientific achievements on Astro-2 are described in Table 4–82.

Diffuse X-ray Spectrometer

The University of Wisconsin–Madison built the DXS experiment, and it was flown as an attached payload on the January 1993 flight of STS-54. Its main scientific goal was to obtain spectra of the diffuse soft x-ray background. This dataset allowed researchers to learn about the region of space for several hundred light years around the solar system.

The experiment consisted of two identical instruments, each mounted to a 200-pound (91-kilogram) plate, attached to the side of the Shuttle bay. Each instrument consisted of a detector, its associated gas supply, and electronics. The two large-area Bragg crystal spectrometers covered the energy range from 0.15 keV to 0.28 keV. Each detector contained a curved panel of Bragg crystals mounted above a position-sensitive proportional counter. A spectrum would be dispersed across the counter, with all portions of the spectrum being measured simultaneously. This eliminated the problem in conventional Bragg spectrometers of false features being introduced by a time-varying background. Yet while all wavelengths were measured at the same time, the various wavelengths came from different directions in the sky. Thus, the spectrometers were rocked back and forth about an axis perpendicular to the dispersed direction to obtain complete spectral coverage along an arc of the sky.[358]

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[356] "The Astro-2 Mission," *http://praxis.pha.jhu.edu/astro2/astro2_mission.html* (accessed August 30, 2005).

[357] "Achievements of Astro-2," *http://praxis.pha.jhu.edu/astro2/astro2_achieve.html* (accessed August 30, 2005).

[358] "The Diffuse X-ray Spectrometer," *http://heasarc.gsfc.nasa.gov/docs/dxs/dxs_about.html* (accessed August 25, 2005).

Throughout the 80 orbit nights of DXS data collection time during the Shuttle mission, the orbiter was oriented so that the DXS detectors repeatedly scanned the same arc on the sky—within 10 degrees of the galactic plane from longitudes of 150 degrees to 300 degrees. The sky covered was divided into five distinct regions: Auriga, MonoGem, Puppis, Vela, and Crux.[359]

The DXS obtained the first high-resolution spectra of the diffuse soft x-ray background in the energy band from 0.15 keV to 0.28 keV (43 angstroms to 84 angstroms), measuring the arrival direction and wavelength of incident low-energy x-rays. From this information, the DXS scientists could determine the spectrum (brightness at each wavelength) of the diffuse soft x-ray background from each selected region of the sky. By analyzing these spectral features, scientists could identify the temperature, the ionization state, and the elements constituting this plasma. From this data, they could tell whether the plasma was young and heated in the last 100,000 years or old and heated millions of years ago. Previous experiments could not measure the spectrum of the diffuse soft x-ray background. With its spectral determination capability, the DXS made this type of measurement possible for the first time.

The DXS investigation was proposed and selected in response to a 1978 announcement of opportunity to conduct scientific investigations aboard the Space Shuttle. NASA selected DXS and four other astrophysics investigations, including three UV instruments and one x-ray telescope that flew in December 1990 on the STS-35/Astro-1 mission. All had scientific objectives and requirements that could be accomplished in a 5-day to 10-day Shuttle mission. The DXS was originally manifested to fly with the BBXRT on the second Shuttle High Energy Astrophysics Laboratory flight. In the remanifesting that followed the *Challenger* accident, the BBXRT flew on Astro-1, and the DXS moved to STS-54.[360] The DXS was part of the Goddard Space Flight Center Shuttle Payload of Opportunity Carrier system and a Hitchhiker payload.

The SPARTAN Program

The SPARTAN program provided a series of less costly, reusable, free-flying space platforms to perform various scientific studies. The program was conceived in the late 1970s to take advantage of the opportunity offered by the Space Shuttle to provide more observation time for the increasingly more sophisticated experiments than the 5 to 10 minutes allowed by sounding rocket flights. Its astrophysics experiments evolved from NASA's sounding rocket program.[361] SPARTANs carried a variety of scientific instruments and offered

[359] "The Diffuse X-ray Spectrometer Shuttle Package," *http://heasarc.gsfc.nasa.gov/docs/dxs/dxs.html* (accessed August 25, 2005).
[360] "Space Shuttle Mission STS-54 Press Kit," January 1993, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_053_STS-054_Press_Kit.pdf* (accessed August 25, 2005).
[361] "Spartan 201-5," Payloads STS-95, *http://www.shuttlepresskit.com/STS-95/payload9.htm* (accessed August 25, 2005).

the scientific community the capability to conduct astrophysics investigations in space between the capabilities offered by small payloads remaining in the orbiter and larger satellites orbiting Earth for long periods of time.

SPARTAN satellites were launched aboard the Space Shuttle and deployed from the orbiter, where they performed preprogrammed missions. Scientific data was collected during each mission and recorded using a tape recorder and, in many cases, film cameras. There was no command and control capability after deployment; batteries provided power, and attitude control was accomplished with pneumatic gas jets. The three-axis stabilized spacecraft weighed 1,300 kilograms (2,866 pounds) with 500 kilograms (1,102 pounds) allotted to experiments. Its operational mission usually lasted about 45 hours. At the end of its mission, the SPARTAN was retrieved by the orbiter and returned to Earth for recovery of the data, refurbishment, and preparation for future missions.[362]

The SPARTAN program's primary scientific missions related to solar physics. The SPARTAN spacecraft could also be programmed to conduct stellar astronomy; Earth fine pointing; spacecraft technology experiments and demonstrations; and microgravity science and technology experiments.

Two groups of SPARTAN science missions flew during the 1989–1998 decade. The SPARTAN 201 flew five times; the SPARTAN 204 flew one mission. Another SPARTAN, the SPARTAN 207, flew a technology mission. Table 4–83 lists Spartan 201 missions.

SPARTAN 201

SPARTAN 201 was a small, rectangular satellite performing remote sensing of the solar wind and the Sun's extremely hot corona to increase our knowledge of the Sun's effects on Earth. Its scientific objective was to probe the physics of solar wind acceleration by observing the hydrogen, proton, and electron temperatures and densities, as well as the solar-wind velocities, in a variety of coronal structures at locations from 1.5 solar radii to 3.5 solar radii from the Sun. The spacecraft consisted of a service module containing attitude control; thermal control; payload function control; power distribution systems; and an instrument carrier, a cylindrical container holding the SPARTAN spacecraft's two instruments. On the bottom of the spacecraft was the upper portion of the release/engage mechanism (REM). The lower half of the REM was attached to the spacecraft's payload bay support structure. The two halves of the REM mated to hold the spacecraft in place on the support structure and unlatch to allow the satellite to be deployed.

The pair of complementary instruments, the Ultraviolet Coronal Spectrometer, provided by the SAO at Harvard, and the White Light Coronograph, designed and built by the National Center for Atmospheric Research High Altitude Observatory,

[362] "Spartan 201-01," NSSDC Master Catalogue: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-023B* (accessed August 25, 2005).

performed co-registered observations and measured emissions of the Sun's extended corona. The instruments were mated and co-aligned inside the SP201 Instrument Carrier, a 0.43-meter (1.4-foot)-diameter and 3-meter (9.8-foot)-long cylinder with an aperture door that was opened after the satellite's release from the Shuttle.[363] The spectrometer measured the velocities, temperatures, and densities of the coronal plasmas. The white-light coronograph measured the intensity and polarization of the electrons in the coronal white light.[364] Both of these instruments had been used in previous sounding rocket flights.

SPARTAN 201-01 (Solar Physics)

SPARTAN 201-01 was launched aboard *Discovery* on mission STS-56. It was deployed three days after launch and retrieved two days later. The SPARTAN acquired more than 20 hours of coronal observations. The primary targets during the mission were north and south polar coronal holes, a southeast helmet streamer, and an active region above the west limb.

After landing at Kennedy Space Center, and removal from the orbiter, SPARTAN 201-01 was returned to Goddard Space Flight Center where the instruments were removed from the spacecraft. The UV coronal spectrometer was subsequently sent to the SAO for postflight calibration and preparation for Spartan 201-02.

SPARTAN 201-02 (Coordinated Observations–Ulysses)

SPARTAN 201-02 was launched from *Discovery* during the STS-64 mission on September 13, 1994 and retrieved on September 15.[365] The main goal of the mission was to observe the extended solar corona coincident with the passage of the Ulysses spacecraft over the south pole of the Sun. Flying 50 miles behind *Discovery*, SPARTAN 201-02 obtained high precision spectral line profiles of H I Lyman alpha. This data was used to determine proton kinetic temperature and outflow velocities in the regions where the solar wind detected by Ulysses originated. Data also indicated that the corona had changed as the solar minimum phase of the solar cycle was approached.[366]

[363] "The Spartan 201 Carrier," *http://cfa-www.harvard.edu/cfa/spartan/* (accessed August 25, 2005).
[364] "Spartan Solar Studies (WLC, UVCS)," Experiments: STS-95, *http://www.shuttlepresskit.com/STS-95/experiment17.htm* (accessed August 25, 2005).
[365] *Aeronautics and Space Report of the President, Fiscal Year 1994 Activities* (Washington, DC: National Aeronautics and Space Administration, 1995), p. 74.
[366] "Spartan 201 Missions," *http://www.cfa.harvard.edu/cfa/spartan/history.html* (accessed August 25, 2005).

SPARTAN 201-03 (Coordinated Observations–Ulysses)

SPARTAN 201-03, launched from *Endeavour* on STS-69 in September 1995, was coordinated with the passage of the Ulysses spacecraft over the north solar pole. The primary targets for the Ultraviolet Coronal Spectrometer on this flight were the north coronal hole and the boundary regions between coronal holes and streamers.

The SPARTAN 201-03 science mission succeeded in obtaining a unique set of UV spectroscopy, visible polarized brightness observations, and coordinated Ulysses in situ measurements of solar wind.[367] By comparing the data collected by the SPARTAN's two telescopes and combining the observations from this mission, the previous SPARTAN mission, and from Ulysses and ground-based instruments, scientists gained a much more complete picture of the origin of the solar wind. The coordinated results provided new insight into the unknown source of energy heating the solar corona and accelerating the solar wind particles. No previous mission had focused specifically on these fundamental questions.[368]

SPARTAN 201-04 (Calibration Flight–SOHO)

This SPARTAN mission developed problems soon after deployment from STS-87 in November 1997. After it was released from *Columbia*, the satellite failed to perform a pirouette maneuver because of an incomplete initialization sequence. The spacecraft was sent into a spin when *Columbia*'s robotic arm bumped it during a retrieval attempt.

After spacewalking astronauts recaptured the free flyer four days after deployment, NASA was cautiously optimistic that the flyer could be deployed for a shortened mission. The mission had to be cancelled because *Columbia* would not have had enough propellant for the rendezvous and capture activities.

Postflight testing and review of data tapes at Kennedy Space Center in January 1988 confirmed that the SPARTAN satellite was healthy and had performed as expected in off-nominal conditions. All flight data correlated well with in-flight predictions and assessments.[369] (Figure 4–76 shows the SPARTAN held by the Shuttle's robotic arm.)

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[367] "Spartan 201 Missions."

[368] "Spartan 201-5," Payloads: STS-95, *http://www.shuttlepresskit.com/STS-95/payload9.htm* (accessed August 25, 2005).

[369] "Spartan 201-05 To Fly on STS-95," *NASA Facts*, Goddard Space Flight Center, FS-1998,09-022-GSFC, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/spartan.pdf* (accessed August 25, 2005).

Figure 4–76. The SPARTAN 201-04 Satellite, held in the grasp of the Space Shuttle Columbia*'s Remote Manipulator System Arm, is backdropped over white clouds and blue waters of the Pacific Ocean. The photo was taken during STS-87. (NASA Photo No. STS087-706-020)*

SPARTAN 201-05 (Calibration Flight–SOHO)

SPARTAN 201-05 was a reflight of the STS-87 SPARTAN 201-04 mission, which had developed problems shortly after being deployed from the Shuttle. This flight, on STS-95, was coordinated with observations made by SOHO, an international mission between the ESA and NASA. In particular, the SPARTAN Ultraviolet Coronal Spectrometer was used to determine the instrumental profile of the H I Lyman alpha line for SOHO's Ultraviolet Coronal Spectrometer.

The SPARTAN spacecraft spent two days gathering data before being retrieved and stored on the Shuttle once more. On this mission, astronauts tested a device called the Video Guidance Sensor, part of an automated docking system being prepared for use on the ISS. This laser system provided precise measurements of how far away the Shuttle was from a target and how fast it was moving toward or away from the target. Before grappling SPARTAN, *Discovery* backed away from the satellite to test the maximum range capability of the guidance system.

On the next day of the mission, astronauts again removed SPARTAN from its payload bay cradle for several hours of data collection. Cameras were pointed at a series of targets on the SPARTAN and on the Shuttle cargo bay to test the Orbiter Space Vision System, which used remote camera views to give a robot arm operator the ability to see areas outside the direct viewing area. The system was to be used extensively during the next Space Shuttle flight to help the robot arm join the first two ISS modules. Following the Orbiter Space Vision System test, an astronaut used the Video Guidance System to assist in rebirthing the SPARTAN in the payload bay.[370]

SPARTAN 204 Mission: UV Astronomy (Stellar)

SPARTAN 204 was flown on one Space Shuttle mission, STS-63, in February 1995. The crew lifted it from its support structure in the *Discovery* payload bay with the orbiter remote manipulator system arm on flight day two (February 4), where it remained suspended for observation of orbiter glow phenomenon and thruster jet firings. SPARTAN 204 was released from *Discovery* on February 7 to carry out about 40 hours of observations of galactic dust clouds using its FUVIS; it was retrieved February 9. The FUVIS was provided by the Naval Research Laboratory and sponsored by the Department of Defense Space Test Program.[371]

The instrument studied celestial targets in the interstellar medium, the gas and dust that filled the space between the stars and the material from which new stars and planets were formed. It obtained far UV spectroscopy of diffuse sources, both natural and human-made. The data acquired from natural sources, such as diffuse nebulae and the galactic background, provided information on interstellar gas and dust. Data acquired from sources such as Shuttle surface glow and plume emissions from its reaction control system thrusters provided information on the effect of these objects traveling through space. A better understanding of these effects might provide a way to detect and track ballistic and orbiting vehicles.[372]

[370] "STS-95 Day 6 Highlights," *http://science.ksc.nasa.gov/shuttle/missions/sts-95/sts-95-day-06-highlights.html* and *http://science.ksc.nasa.gov/shuttle/missions/sts-95/sts-95-day-07-highlights.html* (accessed August 25, 2005).

[371] "Spartan 204," NSSDC Master Catalogue, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1995-004B* (accessed August 26, 2005). Also *http://science.ksc.nasa.gov/shuttle/missions/sts-63/mission-sts-63.html* (accessed August 26, 2005). The NSSDC Master Catalogue gives the date of Spartan deployment as February 6. The Mission Chronology gives it as Flight Day 2: February 7, which is used here.

[372] "Spartan," NASA Science, *http://science.hq.nasa.gov/missions/satellite_66.htm* (accessed August 25, 2005). Also "Space Shuttle Mission Chronology: STS-63," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-63.htm* (accessed August 25, 2005).

ASTRO-Shuttle Pallet Satellite Missions

The ASTRO-SPAS program was a joint German-U.S. endeavor based on a memorandum of understanding between NASA and the German Space Agency, DARA. The ASTRO-SPAS was a German-built spacecraft designed for launch, deployment, and retrieval from the Space Shuttle. Once deployed by the Shuttle's RMS, the SPAS operated quasi-autonomously for several days in the Shuttle vicinity (see figure 4–77). After completion of the free-flight phase, the RMS retrieved the spacecraft, and the Shuttle returned it to Earth. The program was very cost efficient, owing to the versatility and the retrievability of the carrier.

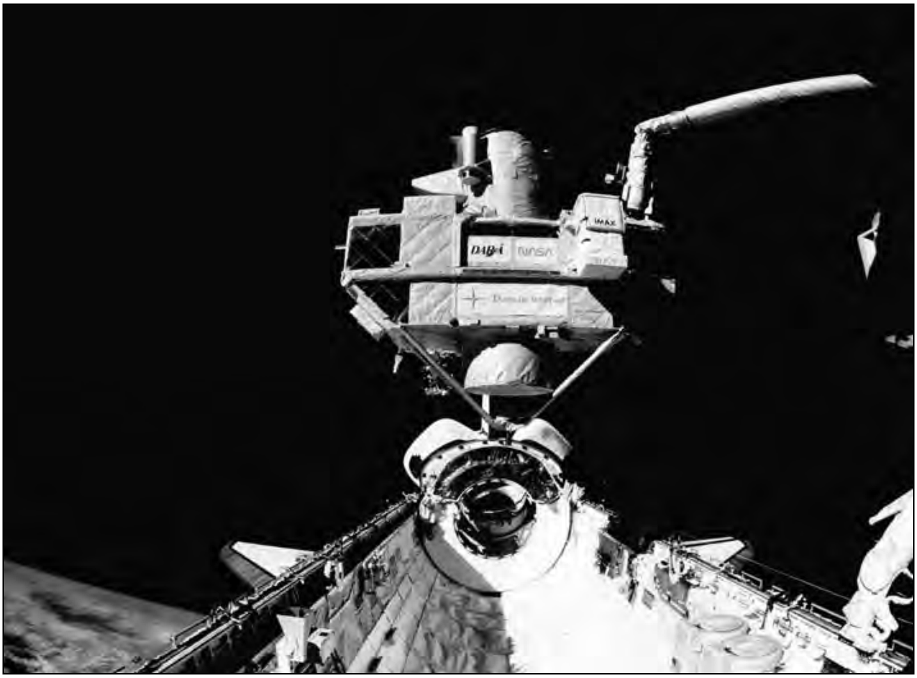

Figure 4–77. ORFEUS-SPAS II at the Robot Arm of Space Shuttle Columbia. *(Institut für Astronomie und Astrophysik)*

The ASTRO-SPAS spacecraft could trace its heritage back to the SPAS-01 satellite of June 1983, the SPAS-01A of February 1984, and the Infrared Background Signature Survey, an experiment performed on STS-39 in April 1991. The SPAS versatility permitted it to support a wide range of scientific applications, including two infrared-sensing ORFEUS-SPAS missions and two CRISTA-SPAS Earth science missions that mapped trace gases in Earth's middle and upper atmosphere.[373]

[373] "Space Shuttle Mission STS-80 Press Kit," November 1996, p.18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005).

The spacecraft's structure subsystem was a truss framework made of carbon fiber tubes with titanium nodes. Its standardized, interchangeable equipment support panels also served as mounting plates for subsystem and payload components. This resulted in a very rigid, stable, lightweight optical platform. The spacecraft was equipped with extensive on-board facilities and resources for scientific payloads. Power for all spacecraft and payload systems was provided by a powerful space-qualified lithium-sulfite ($LISO_2$) battery pack and its power distribution system. Thermal regulation was passive, accomplished with multilayer insulation blankets. Data was recorded through an on-board processor and data tape recorder, and it was stored for postflight analysis. Precise attitude control was achieved by a three-axis stabilized cold gas system combined with a star tracker and a specially developed spaceborne GPS receiver. Interactive command and control was provided by an S-band link via the Extended Range Payload Communications Link on the Shuttle. The Extended Range Payload Communications Link communicated with the ground via the Ku system. The spacecraft had a grapple fixture for deploy and rebirth with power and data interfaces for spacecraft checkout while attached to the RMS.[374]

ORFEUS-SPAS Missions

The first of two ORFEUS-SPAS astrophysics missions flew on STS-51 in September 1993. The second flew on STS-80 in November/December 1996. Both missions used the same satellite and science instruments and had similar scientific objectives (see Table 4–84). Both performed astronomical observations at very short wavelengths, specifically the far UV (90 nanometers to 125 nanometers) and EUV (40 nanometers to 90 nanometers) wavelengths. German and U.S. research institutions provided the ORFEUS-SPAS science payload, which was funded through the German Space Agency, DARA, and NASA.

The missions observed some of the coldest (several degrees above absolute zero) and hottest (more than 1 million degrees) matter in our galaxy. The core payload was the 1-meter-diameter UV telescope with the FUV Echelle spectrograph and the EUV spectrograph built into the telescope.[375] The Astronomical Institute, Tübingen, together with Landessternwarte Heidelberg Research Group, developed the design and construction of the telescope and FUV spectrograph.[376] The telescope had a 2.4-meter (7.9-foot) focal length. An iridium coating on the primary mirror improved its

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[374] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 9 (NASA History Office Electronic Document 30982).

[375] The FUV spectrometer also was called the Tubingen Ultraviolet Echelle Spectrometer (TUES). The EUV spectrometer also was called the Berkeley Extreme and Far-UV Spectrometer (BEFS). "ORFEUS-SPAS I," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1993-058C.html* (accessed August 29, 2005).

[376] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 10 (NASA History Office Electronic Document 30982).

reflectivity for UV wavelengths. The carbon fiber epoxy compound tube structure provided essential stability against mechanical and thermal load deformations.

A secondary, but highly complementary, payload was the IMAPS. In addition to the astronomy payloads, ORFEUS-SPAS carried the SESAM, and ORFEUS-SPAS I carried the RICS.

The EUV spectrograph was directly exposed to light reflected off the main mirror. It covered the spectral range from 40 nanometers to 115 nanometers, offering a resolution of about 5,000 over the whole bandwidth. To achieve this unprecedented resolution over such a wide bandwidth, a completely new design was used that produced high-quality spectra. The EUV spectrograph was built by the Space Astrophysics Group at the University of California, Berkeley.

The FUV Echelle spectrograph was operated alternately with the EUV spectrograph by flipping a mirror into the beam reflected off the primary mirror. The FUV spectrograph covered the wavelength range from 90 nanometers to 125 nanometers and provided a spectral resolution on the order of 10,000.

The IMAPS was a separate instrument attached to the SPAS framework and operated independently of the ORFEUS telescope spectrographs. The IMAPS covered the 95-nanometer to 115-nanometer band. This wavelength was very important for studying principal constituents of the medium. The IMAPS also had a very high spectral resolving power, permitting it to disentangle the Doppler shifts of parcels of gas moving very slowly with respect to each other.[377] The IMAPS had been successfully flown on several sounding rocket missions. The IMAPS was operated for about one day during the ORFEUS-SPAS I mission and for more than two days during the ORFEUS-SPAS II mission. During that time it observed the brightest galactic objects at extremely high resolutions. This resolution allowed study of fine structures in interstellar gas lines.

The SESAM experiment was a passive carrier for state-of-the-art optical surfaces and potential future detector materials. The SESAM investigated the effects of the space environment on materials and surfaces in different phases of a Space Shuttle mission, including launch, orbit, and reentry into Earth's atmosphere. A number of different optical coats were exposed for various lengths of time during the mission and then analyzed postflight for degradation in reflectivity. Data from this experiment was to be used in the planning and use of optical coatings for future flights.

The RICS aboard ORFEUS-SPAS I was a modified IMAX cargo bay camera mounted to the ORFEUS-SPAS. The RICS took footage of the orbiter during deployment and retrieval for a motion picture. The system was enclosed in a container to protect it from contamination and provide a

[377] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 12 (NASA History Office Electronic Document 30982).

controlled environment for the camera and film. The container's door opened for filming operations. At the same time, RMS operations and the ORFEUS-SPAS satellite was filmed by another IMAX camera aboard the Shuttle.

The RICS did not give the Payload Operations Center on the ground or the crew the ability to view scenes being filmed in real-time. Therefore, an EVA Maneuvering Unit Television (EMU-TV), a video camera with a transmitter and associated electronics, was mounted to the ORFEUS-SPAS. Its FOV was co-aligned with the RICS, so viewers on the orbiter and on Earth saw the same scene seen by the RICS. Figure 4–78 shows the ORFEUS-SPAS I configuration.

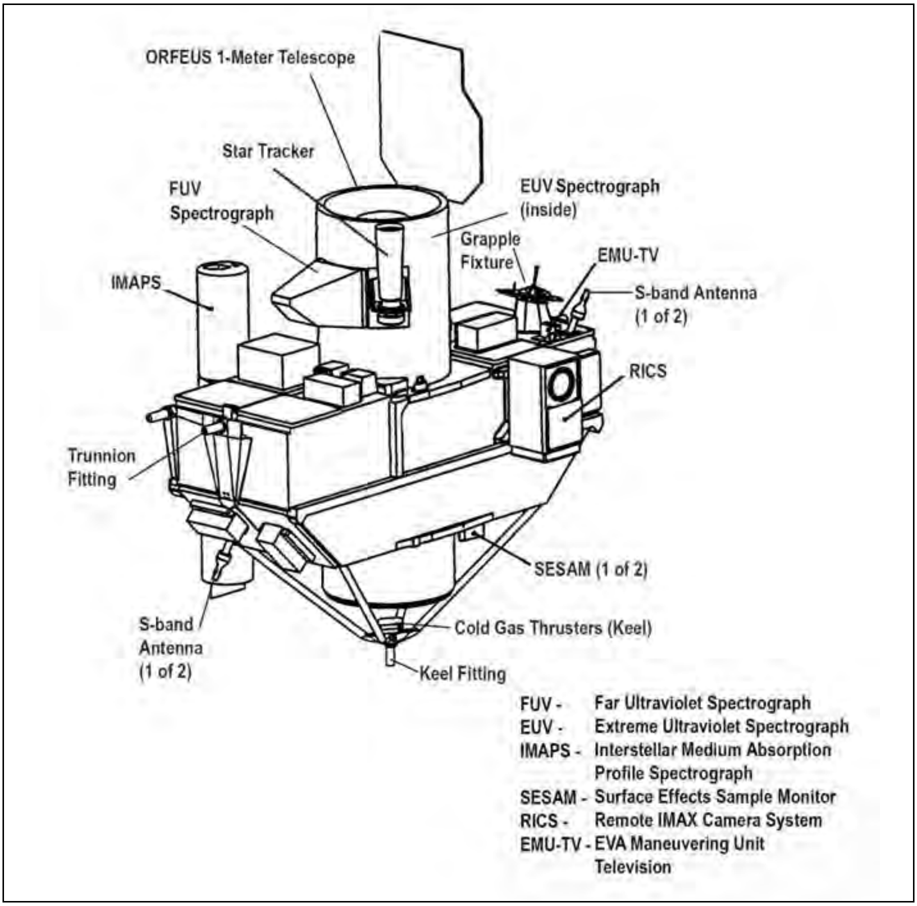

Figure 4–78. ORFEUS-SPAS I Configuration.

The ORFEUS-SPAS I mission provided valuable information in a largely unexplored region of the electromagnetic spectrum. The mission provided information on the details of the structure and dynamics of interstellar gas clouds and insight into how molecular hydrogen was created in interstellar space. The mission also studied neutral and ionized gas in the interstellar medium from the local solar neighborhood out to the distant halo of our galaxy. ORFEUS-SPAS I obtained spectra of a very diverse group of important astrophysical objects, including a compact interacting binary star with an enormous magnetic field, three hot white dwarf stars, and the distant active galaxy PKS2155-304.[378] The FUV spectrograph failed to record scientifically usable data during this mission. The EUV spectrograph obtained far-UV spectra of about 75 objects. The IMAPS returned approximately 600 spectral images of 10 targets.[379]

The ORFEUS-SPAS II mission took advantage of improved instrument performance and met the need for additional observation time.[380] It made half the observing time during the mission available to the general science community. Including the instrument teams, the ORFEUS-SPAS II mission had more than 40 research teams worldwide receiving and analyzing data from the mission. The mission acquired spectra of numerous celestial objects during 14 days of observations. The mission achieved an efficiency of 62.5 percent for all instruments. Unlike the first ORFEUS-SPAS mission when the FUV spectrograph did not record any scientifically usable data, the spectrometer operated successfully during this mission, returning about 239 spectra of 62 targets. The EUV spectrograph obtained far-UV spectra of about 105 objects, and the IMAPS returned approximately 3,900 spectra of about 29 targets.[381]

This mission also carried the Student Experiment on ASTRO-SPAS (SEAS). Students from the German high school of Ottobrunn built this electrolysis experiment consisting of eight experiment chambers containing various metal salt solutions and two electrodes. Metal "trees" of different shapes could grow on one electrode. Photographs taken of the process during the mission were compared with those of identical experiments conducted on the ground under the full effects of Earth's gravity.

The German Space Agency, DARA, developed an innovative educational program for students in 170 German high schools teaching astronomy, physics, and computer science. The classes were designed to prepare the students to use ORFEUS-SPAS data in their study of general astronomy, the life and death of stars, and stellar spectral analysis. The classes also prepared them to work with online satellite data.[382]

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[378] "Space Shuttle Mission STS-80 Press Kit," November 1996, pp. 15–16, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005),

[379] "ORFEUS-SPAS I," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1993-058C.html*. Also "ORFEUS-SPAS Tubingen Ultraviolet Echelle Spectrometer (TUES)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=1*, "ORFEUS-SPAS, Berkeley Extreme and Far-UV Spectrometer (BEFS)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=2*, and "ORFEUS-SPAS, Interstellar Medium Absorption Profile Spectrograph (IMAPS)" *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=3* (accessed August 29, 2005).

[380] "ORFEUS-SPAS II," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1996-065B.html* (accessed August 29, 2005).

[381] "ORFEUS-SPAS II," NSSDC Master Catalog: Spacecraft.

[382] "Space Shuttle Mission STS-80 Press Kit," November 1996, p. 17, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005).

Table 4–1. Space Science Launched Missions (1989–1998)

Launch Date	Mission	Objectives	Discipline	Remarks
May 4, 1989	Magellan	To place a satellite carrying a radar sensor into orbit around Venus to obtain data on the planet's surface	Planetary	Launched from Space Shuttle STS-30/*Atlantis*
October 18, 1989	Galileo	To launch a spacecraft into successful trajectory toward Jupiter to allow close-range studies over a period of two years	Planetary	Launched from Space Shuttle STS-34/*Atlantis*
November 18, 1989	Cosmic Background Explorer (COBE)	To launch a satellite to enable it to measure diffuse infrared radiation (cosmic background)	Astrophysics	Launched using the last NASA-owned Delta
April 25, 1990	Hubble Space Telescope	To perform a variety of astronomical observations as a long-term (15-year) international observatory with many different scientific goals and observational modes	Astrophysics	Launched from STS-31/*Discovery*; joint mission with the ESA
June 1, 1990	Roentgen Satellite (ROSAT)	To conduct an all-sky survey for six months using imaging telescopes to measure positions of x-ray and EUV sources while obtaining fluxes and spectral information	Astrophysics	International cooperative satellite with Germany and the United Kingdom; launched by the United States
July 25, 1990	Combined Release and Radiation Effects Satellite (CRRES)	To launch satellite into a highly elliptical geosynchronous transfer orbit to enable performance of active chemical release experiments in the ionosphere and magnetosphere	Space physics	A joint NASA–U.S. Air Force payload launched by the first commercial Atlas launch vehicle

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
October 6, 1990	Ulysses	To investigate properties of the solar wind; the structure of the Sun-wind interface; the heliospheric magnetic field; solar radio bursts and plasma waves; solar x-rays; solar and galactic cosmic rays; and interstellar and interplanetary neutral gas and dust	Solar physics	Deployed by Space Shuttle STS-41/ *Discovery*; joint NASA-ESA mission
April 7, 1991	Compton Gamma Ray Observatory (CGRO)	To measure gamma radiation covering most of the celestial sphere and explore the fundamental physical processes powering it	Astrophysics	The second “Great Observatory”; deployed from Space Shuttle STS-37/*Atlantis*; a NASA cooperative program with Germany, with co-investigator support from the Netherlands, ESA, the United Kingdom, and the United States
August 30, 1991	Yohkoh/Solar-A	To study explosive energy releases from the Sun and identify the conditions preceding these energy releases so they can be predicted	Solar physics	Japanese mission (NASA and Japan jointly provided the Soft-X-ray Telescope); launched by Japan
June 7, 1992	Extreme Ultraviolet Explorer (EUVE)	To launch a satellite to make both spectroscopic and wideband observations across the entire EUV spectrum	Astrophysics	Reentered Earth’s atmosphere over central Egypt on January 30, 2002, in a planned mission termination; burned up in the atmosphere

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
July 3, 1992	Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX)	To launch the first spacecraft in a new series of Small Explorers designed to investigate anomalous cosmic rays, galactic cosmic rays in the vicinity of Earth, solar energetic particles, and other space physics phenomena	Space physics	First Small Explorer mission; carried scientific instruments from the United States and Germany
July 24, 1992	Geotail	To investigate the geomagnetic tail region of the magnetosphere	Space physics	Japanese satellite launched by the U.S., part of the Global Geospace Science (GGS) program
September 25, 1992	Mars Observer	To study the geology, geophysics, and climate from a Mars orbit	Planetary	Successful launch but contact was lost before entering Mars orbit
February 20, 1993	Advanced Satellite for Cosmology and Astrophysics (ASCA) (originally called Astro-D)	To conduct x-ray spectroscopy of astrophysical plasmas, especially the analysis of discrete features such as emission lines and absorption edges	Astrophysics	Japanese mission launched by Japan; carried part of a U.S. payload; also called Asuka
January 25, 1994	Clementine	To test in space 23 advanced technologies for high-tech, lightweight missile defense; to provide images of the surface of the Moon	Technology demonstrator/ planetary	Joint DOD-NASA mission; DOD launch
November 1, 1994	Wind	To provide comprehensive measurements of radio and plasma wave phenomena occurring in the solar wind upstream of Earth's magnetosphere and in key regions of the magnetosphere from Lagrangian L1 orbit[a]	Space physics	Part of the International Solar-Terrestrial Physics (ISTP) program; GGS mission

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
December 2, 1995	Solar and Heliospheric Observatory (SOHO)	To study the Sun's internal structure by observing velocity oscillations and radiance variations and to look at the physical processes that form and heat the Sun's corona and that give rise to the solar wind from Lagrangian L1 orbit	Space physics	ESA-NASA mission; part of the International Solar-Terrestrial Physics (ISTP) program
December 30, 1995	Rossi X-ray Timing Explorer (RXTE)	To study the structure and dynamics of compact x-ray sources; including accreting neutron stars; white dwarfs; black holes in our galaxy; and compact, massive objects thought to be present in the nuclei of active galaxies	Astrophysics	Was the last large Explorer mission
February 17, 1996	Near Earth Asteroid Rendezvous (NEAR)	To perform multiple asteroid flybys and rendezvous with the asteroid Eros and gather data on its composition and physical properties	Planetary	First mission flown under NASA's Discovery Program
February 24, 1996	Polar	To perform multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere	Space physics	Part of GGS program and ISTP program

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
April 30, 1996	Beppo-SAX	To observe x-ray sources from 0.1 keV to 300 keV across large regions of the sky; to monitor large regions of the sky with a resolution of 5 arc minutes in the range 2 keV to 30 keV to study long-term variability of sources down to 1 mCrab and detect x-ray transient phenomena[b]	Astrophysics	Italian/Dutch celestial x-ray monitoring telescope; NASA provided launch vehicle, launch site, and data archiving
August 21, 1996	Fast Auroral Snapshot Explorer (FAST)	To investigate the plasma physics of the auroral phenomena occurring around both of Earth's poles	Space physics	Part of ISTP program
November 4, 1996	High-Energy Transient Experiment (HETE); Scientific Applications Satellite-B (SAC-B)	HETE: To carry out the first multi-wavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments; SAC-B: To study solar physics and astrophysics through the examination of solar flares, gamma-ray burst sources, and the diffuse soft x-ray cosmic background	Astrophysics	Argentinian mission launched by U.S.; Unsuccessful due to launch vehicle failure
November 7, 1996	Mars Global Surveyor	To orbit Mars during a two-year period and collect data on the Martian surface morphology; topography; composition; gravity; atmospheric dynamics; and magnetic field	Planetary	Designed as a rapid, low-cost recovery of the unsuccessful Mars Observer mission objectives
November 16, 1996	Mars '96 (Mars 8)	To land on Mars and investigate the evolution of its atmosphere, surface, and interior	Planetary	Russian mission launched from Russia with U.S. instrument on board; failed on launch

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
December 4, 1996	Mars Pathfinder	To demonstrate the feasibility of low-cost landings on Mars and explore the Martian surface	Planetary	Second NASA Discovery mission
August 25, 1997	Advanced Composition Explorer (ACE)	To determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and Galactic matter from the Lagrangian L1 orbit	Space physics	Began from an unsolicited proposal
October 15, 1997	Cassini/Huygens	To explore Saturn and its system of rings and moons from orbit	Planetary	An international collaboration between NASA, the ESA, and the Italian Space Agency
January 7, 1998	Lunar Prospector	To create the first complete compositional and gravity maps of the Moon from lunar orbit	Planetary	Successfully demonstrated “faster, better, cheaper” approach[c]
February 26, 1998	Student Nitric Oxide Explorer (SNOE)	To measure the effects of energy from the Sun and magnetosphere on the density of nitric oxide in Earth’s upper atmosphere	Solar physics/ space physics	First mission in NASA’s Student Explorer Demonstration Initiative (STEDI) program
April 2, 1998	Transition Region and Coronal Explorer (TRACE)	To image the solar corona and transition region at high angular and temporal resolution	Solar physics	The power of TRACE to perform detailed studies of the solar atmosphere made this observatory unique among the current group of spacecraft studying the Sun

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
October 24, 1998	Deep Space 1 (DS 1); Students for the Exploration and Development of Space (SEDSAT)	DS 1: To test innovative technologies appropriate for future deep space and interplanetary missions SEDSAT: To contribute to the development and utilization of advanced technology for the general space program	Technology demonstrator	DS 1: First mission under NASA's New Millennium program; SEDSAT: Microsatellite developed and operated by students at the University of Alabama, Huntsville
December 5, 1998[d]	Submillimeter Wave Astronomy Satellite (SWAS)	To better understand star formation by determining the composition of interstellar clouds and establishing the means by which those clouds cooled as they collapsed to form stars and planets	Astrophysics	Provided new information about the physical conditions (density and temperature) and chemistry in star-forming molecular clouds
December 11, 1998	Mars Climate Orbiter	To operate simultaneous investigations of Mars' atmosphere, climate, and surface with Mars Polar Lander	Planetary	Communication with spacecraft lost; unsuccessful mission

[a] An orbit around Earth-Sun L1 point, which is about four times the distance to the Moon or 1/100 the distance to the Sun–about 1 million miles (1,609,344 km) away from Earth.

[b] mCrab = milliCrab, one thousandth of the intensity of the Crab nebula. X-ray astronomers use this unit when comparing observations from different x-ray detectors on different instruments.

[c] Howard McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program*, (Baltimore, MD: The Johns Hopkins University Press, 2001), p. 5.

[d] Launch took place at 16:57 Pacific Standard Time on December 5, 1998. Some references state this as December 6, reflecting Eastern Standard Time and Universal Time, but fail to indicate the time zone being used.

Table 4–2. Attached/Retrieved NASA Space Science Missions

Launch Date	Mission	Objectives	Remarks
December 2, 1990	Astro-1	To provide around-the-clock observations and measurements of UV radiation from celestial objects such as hot stars, galactic nuclei, and quasars[a]	Carried on STS-35/*Columbia*
January 13, 1993	DXS	To collect data on stars and the surrounding galactic gases	Hitchhiker experiment on STS-54/ *Endeavour*
April 11, 1993	SPARTAN 201-01	To study the velocity and acceleration of the solar wind and observe aspects of the Sun's corona	Released from STS-56/*Discovery* and retrieved at end of mission
September 13, 1993	ORFEUS-SPAS	To investigate very hot and very cold matter in the universe using the retrievable ASTRO-SPAS spacecraft built by Germany	Released from STS-51/*Discovery* and retrieved at end of mission
December 2, 1993	First Hubble Servicing Mission	To restore the planned scientific capabilities and reliability of the Hubble Space Telescope and validate the on-orbit servicing concept for Hubble Space Telescope	Accomplished through series of EVAs on STS-61/*Endeavour* mission
September 13, 1994	SPARTAN 201-02	To explain how the Sun generates the solar wind	Released from STS-64/*Discovery* and recovered at end of mission
February 7, 1995	SPARTAN 204	To observe galactic dust clouds and study celestial targets in the interstellar medium, the gas and dust that filled the space between the stars, and the material from which new stars and planets were formed using the FUVIS provided by the Naval Research Laboratory; to obtain far UV spectroscopy of diffuse sources, both natural and human-made[b]	Released from STS-63/*Discovery* and recovered at end of mission

Table 4–2. Attached/Retrieved NASA Space Science Missions (Continued)

Launch Date	Mission	Objectives	Remarks
March 2, 1995	Astro-2	To expand on results obtained on Astro-1 mission; to use the three UV telescopes to make simultaneous observations of objects such as stars, galaxies, and quasars	Carried on STS-67/*Endeavour*
September 8, 1995	SPARTAN 201-03	To study the solar corona and galactic clusters using x-ray, far UV, and visible light instruments	Released from STS-69/*Endeavour*'s bay and recovered at end of mission
November 20, 1996	ORFEUS-SPAS	To launch a deployable/retrievable astronomical platform and obtain UV spectra for both astrophysically interesting sources and the intervening interstellar medium	Deployed and retrieved on STS-51/ *Discovery* mission; collaborative U.S.-German Shuttle Astro-SPAS mission
February 11, 1997	Second Hubble Space Telescope Servicing Mission	To repair or replace Hubble Space Telescope instruments and parts to improve productivity and increase lifetime of the telescope	Accomplished through a series of EVAs on STS-82/*Discovery* mission
November 19, 1997	SPARTAN 201-04	To study the origins of the solar wind	Unable to be deployed by STS-87/ *Discovery*
October 29, 1998	HOST/SPARTAN 201-05	HOST: To test the instruments that would be used for the third Hubble Space Telescope Servicing Mission; SPARTAN: To study the origins of the solar wind	Reflight of SPARTAN 201-05 mission on STS-95/*Discovery*

[a] "Space Shuttle Mission STS-35 Press Kit," p. 5, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_038_STS-035_Press_Kit.pdf* (accessed May 8, 2006).
[b] "SPARTAN," *http://science.hq.nasa.gov/missions/satellite_66.htm* (accessed May 8, 2006).

Table 4–3. Authorized Budget (FY 1989–FY 1998) (in thousands of dollars[a])

	1989	1990[b]	1991	1992	1993	1994	1995	1996	1997	1998
Physics and Astronomy	761,600	914,500	985,000	1,104,600[c]	1,096,000[d]	1,094,700[e]	1,081,700[f]	1,167,600[g]	—	—
Planetary Exploration	410,300	366,900[h]	337,200[i]	299,300	472,200[j]	622,200[k]	691,300[l]	827,800[m]	—	—
Space Science (Total)	1,171,900	1,281,400	1,322,200	1,403,900	1,568,200	1,716,900	1,773,000	1,995,400	2,107,400[n]	2,079,800[o]
Change	—	9.3%	3.2%	6.2%	11.7%	9.5%	3.3%	12.5%	5.6%	–1.3%
Rate of Inflation[p]	—	5.4%	4.2%	3.0%	3.0%	2.6%	2.8%	2.9%	2.3%	1.6%

[a] The annual appropriations bills typically did not designate amounts specifically for space science activities. Thus, the Agency used the authorization bill (when passed) and committee proceedings as the basis for its annual operating plan.

[b] No authorization bills were passed for FYs 1990, 1991, and 1994. Figures reflect bills introduced but not passed.

[c] Became P.L. 102–195. Included $3 million for carrying out scientific programs that were otherwise eliminated from the Space Station.

[d] Specified $22,000,000 for the Shuttle Test of Relativity Experiment.

[e] Stated that $20,000,000 was "for augmenting the funding for Mission Operations and Data Analysis (MO&DA) activities by that amount."

[f] Stated in August 3, 1994 version of H.R. 4489. No final authorization bill was passed.

[g] Stated that $51,500,000 was for the Gravity Probe B and "that no funds are authorized for the Space Infrared Telescope Facility."

[h] Did not include amount for CRAF/Cassini mission, which was authorized separately.

[i] Did not include $1,600,000,000 for CRAF/Cassini mission, which was "not to exceed $1,600,000,000 for development, launch, and 30 days of operations thereof…." (Introduced H.R. 5649 *National Aeronautics and Space Administration Multiyear Authorization Act of 1990* and S. 916 agreed to by House.)

[j] Specified $10,000,000 for Magellan mission operations.

[k] Stated that $65,000,000 was "for augmenting funding for Mission Operations and Data Analysis activities and to initiate development of a Mars Environmental Survey mission" (H.R. 2200).

[l] Included $128.7 million for the Discovery Program and $4 million for Venus data analysis. Stated in August 3, 1994 version of H.R. 4489. No final authorization bill was passed.

[m] Stated that $30 million was for New Millennium spacecraft, including $5 million for NASA's participation in Clementine 2.

[n] Amount specified in H.R. 3322, passed by House.

[o] Specified $47.6 million for Gravity Probe B; $5 million for participation in Clementine 2; $3.4 million for the Near Earth Object Survey; $528.4 million for MO&DA, of which $150 million was to be for data analysis; and $5 million for the Solar B program. (H.R. 1275).

[p] Rate of inflation calculated from Bureau of Labor Statistics Inflation Calculator, *http://www.bls.gov/*.

Table 4–4. Programmed Budget (FY 1989–1998) (in thousands of dollars)

	1989	1990	1991	1992	1993	1994	1995[a]	1996	1997	1998
Physics and Astronomy	737,400	859,434	969,167	1,036,677	1,034,861	1,149,000	—	—	—	—
Planetary Exploration	416,600	390,848	473,700	534,221	475,598	771,900	—	—	—	—
Space Science (Total Programmed)	1,155,989	1,252,272	1,444,858	1,572,890	1,512,452	1,922,894	2,032,600[b]	2,175,900[c]	1,969,300[d]	2,043,800
Change	—	8.3%	15.4%	8.9%	–3.8%	27.1%	5.8%	7.1%	–9.4%	3.8%

[a] Beginning with FY 1995 programmed amounts, NASA no longer split the Space Science budget categories into Physics and Astronomy and Planetary Exploration. Although it is possible to individually look at figures for specific space science missions, the budgets for items such as Mission Operations and Data Analysis and Research and Analysis do not indicate whether funds are going toward Physics and Astronomy or Planetary Exploration projects.

[b] Included $255,600,000 million for Launch Services.

[c] Included $245,300,000 million for Launch Services.

[d] Included $240,600,000 million for Launch Services.

Table 4–5. Physics and Astronomy Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization[a]	Programmed
1989	791,600/734,100	761,600	737,400
1990	894,500/861,378	914,500[b]	859,434
1991	985,000/975,100	—	969,167
1992	1,140,600/1,047,300	1,104,600[c]	1,036,677
1993	1,113,500/1,103,860	—	1,034,861
1994	1,074,700/1,067,600	—	1,149,000
1995	1,058,700/1,195,500	—	—
1996	1,131,100/[d]	—	—

[a] If no authorized amount is stated, Congress did not designate an authorized amount for Physics and Astronomy.
[b] Amount stated in proceedings. No authorization bill was passed.
[c] Included $3,000,000 million to carry out scientific programs that were otherwise eliminated from the Space Station.
[d] Physics and Astronomy was no longer a separate budget category.

Table 4–6. Hubble Space Telescope Development Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	102,200/104,900	104,900
1990	67,000/81,800	81,800
1998	—	144,900[a]

[a] Hubble Space Telescope development was reinstated to provide new flight hardware, subsystems, and instruments to extend the telescope's operational life and enhance its capabilities. There was no budget submission for the Hubble Space Telescope development funds in FY 1998.

Table 4–7. Gamma Ray Observatory Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	41,900/50,900	50,900
1990	26,700/35,100	41,200
1991	—/22,000	22,000

Table 4–8. Global Geospace Science Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1989	101,400/64,400	64,400	n/a
1990	112,300/67,200	57,600	n/a
1991	98,500/96,600	96,600	n/a
1992	65,300/75,300	75,300	n/a
1993	60,100/72,647	72,647	n/a
1994	—/13,300	27,600	n/a
1995	—/40,000	40,000	612,600[b]
1996	5,400/—	—[c]	30,100[d]
1997	—	—	25,600[e]
1998	—	—	15,800

[a] Part of the U.S. contribution to the ISTP program.

[b] Included costs for FY 1995 and prior for experiment and spacecraft development for Wind and Polar spacecraft, U.S. contributions to the ISTP program as well as a 2.5-year period of MO&DA, launch support, and unique tracking and data acquisition required during the missions. Wind launched in November 1994 and Polar launched in February 1996.

[c] No budget line item in FY 1996 (revised), FY 1997, and FY 1998 budgets.

[d] Included budget authority for MO&DA, launch support, and tracking and data support.

[e] FY 1997 and FY 1998 budget authority included costs associated with MO&DA and tracking and data support.

Table 4–9. Advanced X-Ray Astrophysics Facility Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full-Cost)[a]
1989	27,000/16,000	16,000	n/a
1990	44,000/44,000	44,000	n/a
1991	113,000/101,200	101,200	n/a
1992	211,000/151,000	150,740	n/a
1993	174,000/168,337	168,337	n/a
1994	260,300/241,300	239,300	n/a
1995	234,300/234,300	224,300	1,101,100[b]
1996	237,600/237,600	237,600	510,500
1997	178,600/178,600	184,400	321,400
1998	92,200/95,800	112,200	273,200

[a] Full-cost budget estimates encompassed early development of the mirror technology; the design and development phase; establishment of a mission-unique science center and preflight ground system development, followed by amounts for the first year of a five-year period (through 2002) of mission operations and science data analysis; the purchase of the inertial upper stage and integration activities; the average cost (including recurring costs for improvements and upgrades) of a FY 1998 Space Shuttle flight; mission-unique tracking and data support costs; and construction of the X-Ray Calibration Facility. These budget estimates also included a pro forma distribution of the average costs of a Space Shuttle.

[b] Total of FY 1995 and prior years.

Table 4–10. Payload and Instrument Development Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989	77,100/71,700	70,500
1990	71,400/90,655	93,038
1991	97,200/94,600	92,600
1992	115,900/116,500	118,300
1993	78,200/99,340	74,240
1994	53,400/59,500	59,500
1995	47,900/53,900	66,000
1996	33,100/30,700	25,900
1997	16,900/16,900	16,900
1998	12,300/18,000	18,000

[a] Payload and instrument development included a wide range of instrumentation—from early test, checkout, and design of instruments for long-duration free-flying missions to international flights of opportunity. The exact instruments funded in this category changed from year-to-year as mission status changed.

Table 4–11. Shuttle/Spacelab Payload Mission Management and Integration Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989	61,500/69,700	67,700
1990	86,100/81,248	75,109
1991	89,100/88,800	88,800
1992	88,000/88,000	78,000
1993[b]	101,100/94,018	94,100

[a] This category included funds to manage the mission planning, integration, and execution of all NASA Spacelab and attached Shuttle payloads. Was included with Space Science Physics and Astronomy budget categories until creation of OLMSA in 1993.

[b] Transferred to OLMSA program. See chapter 3.

Table 4–12. Explorer Development Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full-Cost)
1989	82,100/82,100	82,100	n/a
1990	93,200/91,800	88,352	n/a
1991	100,800/99,800	99,800	n/a
1992	107,900/105,000	109,100	n/a
1993	112,500/115,832	115,832	n/a
1994	123,300/123,300	123,300	n/a
1995	120,400/120,400	120,400	363,800[b]
1996	129,200/132,200	132,200	199,600[c]
1997	135,000/125,000	117,500	186,400
1998	142,700/113,500	169,300	200,500

[a] The program provided frequent, relatively low-cost missions taken as funding availability permitted within an essentially level program funding profile.

[b] Included costs for FY 1995 and prior, specifically for RXTE, ACE, and FUSE. Funding for FY 1995 and future years included the design and development phase, launch services, mission-unique tracking and data acquisition support, and MO&DA.

[c] Budget authority for FY 1996, FY 1997, and FY 1998 included funds for RXTE, ACE, and FUSE, Medium Explorers, Small Explorers, University Explorers, and Planning and Future Developments.

Table 4–13. Physics and Astronomy Mission Operations and Data Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	156,200/143,200	142,400
1990	204,800/202,400	215,723
1991	293,900/313,300	311,900
1992	388,400/380,800	375,200
1993	440,900/415,385	415,402
1994	416,200/420,700	405,200
1995	441,700/432,400	—
1996	428,600/—[a]	—

[a] Separate MO&DA budget category for Physics and Astronomy disestablished; combined with MO&DA for Planetary Exploration.

Table 4–14. Physics and Astronomy Research and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	89,100/85,800	85,100
1990	112,500/109,500	104,942
1991	122,500/100,800	98,267
1992	103,100/70,500	69,937
1993	81,400/71,558	71,558
1994	72,200/71,100	71,100
1995	67,200/75,400	—
1996	90,400/—[a]	—

[a] Separate Research and Analysis budget category for Physics and Astronomy disestablished. Combined with Research and Analysis for Planetary Exploration.

Table 4–15. Space Science Supporting Research and Technology[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1995	—[b]	220,400
1996	—/238,900	239,400
1997	259,200/246,000	426,600
1998	311,200/541,700	894,000

[a] Referred to both as Supporting Research and Technology and as Research and Analysis in accompanying narrative. This budget category supported research in space physics; astrophysics; planetary exploration; mission study and technology development; Space Infrared Telescope Facility (SIRTF) Advanced Technology Development (ATD); Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) ATD; Origins ATD; exploration technology development; information systems; and high-performance computing and communications.
[b] Budget category not established at time of budget submission.

Table 4–16. Space Infrared Telescope Facility (SIRTF) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)[a]
1996	—[b]	—	15,000
1997	—[c]	—	24,900
1998	92,200/55,400	70,200	81,400

[a] Budget authority for FY 1996 and FY 1997 included costs for development of the mission. It did not include amounts for definition phase studies carried out before FY 1996. FY 1998 budget authority included MO&DA in preparation for an anticipated launch in FY 2002.
[b] No budget request for this category included at time of budget submission.
[c] No budget request for this category included at time of budget submission.

Table 4–17. Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1997	—/18,200	25,900	26,900[a]
1998	48,200/52,700	64,400	56,900[b]

[a] Included budget authority for mission development. Costs for definition phase studies carried out from April 1996 to April 1997 are not in this figure.
[b] Included budget authority for mission development and launch support in anticipation of a January 2000 launch.

Table 4–18. Stratospheric Observatory for Infrared Astronomy Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1998	—[a]	45,800

[a] Included with Suborbital Program in prior years.

Table 4–19. Suborbital Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	45,100/45,400	45,400
1990	53,500/52,700	52,700
1991	55,000/55,000	55,000
1992	61,000/60,200	60,100
1993	65,300/64,843	64,843
1994	69,500/69,500	69,500
1995	67,200/67,200	67,200
1996	106,700/88,000	88,000
1997	69,100/64,100	59,900
1998	84,400/83,300	—[a]

[a] Programmed amount not stated. Included with Supporting Research and Technology and Stratospheric Observatory for Infrared Astronomy budget categories.

Table 4–20. Gravity Probe-B Development/Relativity Mission Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1993	—[a]	27,000	n/a
1994	—/42,400	42,400	n/a
1995	50,000/50,000	50,000	219,800[b]
1996	51,500/51,500	51,500	51,500
1997	59,600/59,600	59,600	66,400[c]
1998	45,600/57,300	70,800	60,300

[a] Budget category not established at time of submission.
[b] Included costs for FY 1995 and prior. Budget authority for FY 1995 and prior and FY 1996 included costs for mission and experiment development. They did not include the amounts for the definition phase studies carried out from FY 1995 through FY 1997, but they did provide the amounts for the Shuttle Test of Relativity Experiment program initiated in FY 1988 and subsequently restructured into a ground test program only.
[c] Costs for FY 1997 and FY 1998 included estimated budget authority for development and launch support in anticipation at the time of a launch in October 2000.

Table 4–21. Information Systems Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	25,002
1994	26,500/26,500[b]	26,500
1995	26,500/26,100	—[c]
1996	25,900/—	—

[a] Budget category not established at time of submission.
[b] Moved to Space Applications budget category.
[c] No programmed amount shown in funding documents.

Table 4–22. Planetary Exploration Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	404,000/416,600	416,600
1990	396,900/391,686	390,848
1991	485,200/457,100	473,700
1992	627,300/535,600	534,221
1993	487,200/473,615	475,598
1994	557,200/654,300	771,900
1995	707,300/817,100	—[a]
1996	827,800/—[b]	—

[a] No programmed amount stated for Planetary Exploration.
[b] Separate Planetary Exploration budget category disestablished.

Table 4–23. Galileo Development Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	61,300/73,400	73,400
1990	17,400/17,127	17,127

Table 4–24. Ulysses Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	10,300/10,300	10,300
1990	14,500/14,252	14,252
1991	3,300/3,034	2,757

Table 4–25. Magellan Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	33,900/43,100	43,100

Table 4–26. Mars Observer Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	102,200/102,200	102,200
1990[a]	100,500/98,922	98,922
1991	68,900/78,528	88,528
1992	54,400/76,900	85,000[b]
1993	—	—

[a] Became “Mars Observer Development” in 1990 when Mars Balloon Relay Experiment became a separate budget category.

[b] Mars Observer was launched in September 1992.

Table 4–27. Planetary Exploration Mission Operations and Data Analysis Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989[b]	112,700/110,700	110,700
1990	155,400/156,856	155,956
1991	173,500/161,175	170,152
1992[c]	150,500/156,100	160,721
1993	170,300/163,482	163,465
1994	160,700/141,700	130,700
1995	127,700/117,200	544,600[d]
1996	127,800/563,800	563,600
1997	592,400/583,300	596,500
1998	507,400/528,500	138,700

[a] Objectives of the planetary MO&DA program were in-flight operation of planetary spacecraft and acquisition and analysis of data from those missions.
[b] Mission operations for Galileo began in October 1989 for the spacecraft's six-year journey to Jupiter. The Magellan spacecraft was launched in May 1989 and arrived at Venus in August 1990.
[c] Mars Observer mission operations began in October 1992 when the spacecraft was launched.
[d] Included total MO&DA for all Space Science missions, both Physics and Astronomy and Planetary Exploration missions.

Table 4–28. Planetary Exploration Research and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	83,600/76,900	76,900
1990	79,100/70,610	70,672
1991	89,500/67,866	67,766
1992	93,200/90,700	76,600
1993	106,900/101,680	101,680
1994	126,400/115,100	107,600
1995	115,100/108,400	—[a]
1996	109,100/—	—

[a] Separate Planetary Exploration Research and Analysis funding category discontinued.

Table 4–29. Comet Rendezvous Asteroid Flyby (CRAF)/Cassini Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1990[a]	30,000/29,519	29,519	n/a
1991	148,000/145,000	143,000	n/a
1992	328,000/210,700[b]	210,700	n/a
1993	210,000/204,953	204,953	n/a
1994	266,600/266,600	166,600	n/a
1995	255,000/255,000	255,000	1,335,500[c]
1996	191,500/191,500	191,500	281,500[d]
1997	106,700/89,600	74,600	187,800
1998	9,000/—	—	91,400[e]

[a] Assumed new start status for the CRAF and Cassini missions in FY 1990. The FY 1990 appropriations bill stated that "no funds…may be used to enter into contracts…for the comet rendezvous and asteroid flyby and Cassini missions (CRAF/Cassini) if the estimated total budget authority for development of the two spacecraft, through launch plus 30 days of the Cassini mission, exceeds $1,600,000,000." H.R. 2916, *Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Act, 1990*.

[b] The FY 1992 revised estimate reflected a $117.3 million reduction as directed by Congress that required a 15–month launch delay for CRAF from February 1996 to May 1997 and a 23–month delay of the Cassini launch from November 1995 to October 1997. In FY 1993, budget restrictions resulted in termination of the CRAF mission. Consequently, FY 1992 funding was used to terminate CRAF development activities and for major rebaselining for Cassini to reflect the new launch date, new launch trajectories, and the transition from a combined mission environment to a single mission scenario.

[c] Included funding for FY 1995 and prior fiscal years, including costs associated with the CRAF mission cancelled in 1993.

[d] FY 1996 and FY 1997 budget figures included funds for spacecraft and instrument development, launch support, and tracking and data support.

[e] FY 1998 budget authority included spacecraft and instrument development, MO&DA, launch support, and tracking and data support in anticipation of an October 1997 launch.

Table 4–30. Mars Balloon Relay Experiment Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1990	—[a]/4,400	4,400
1991	2,000/1,497	1,497
1992	1,200/1,200	1,200

[a] Budget category not included at time of initial budget submission.

Table 4–31. Mars '94 Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]/3,500[b]	3,500
1994	3,500/3,500	4,400
1995[c]	1,400/2,199	1,400

[a] Budget category not included at time of initial budget submission.

[b] The Mars '94 mission (renamed Mars '96) was a Russian mission composed of an orbiter and two soft landers for deployment on the Martian surface. The United States was to provide two soil oxidation instruments, one for flight aboard each of the two landers. No funds were originally requested in the FY 1993 budget. Later in the FY 1993 budget process, funding was reallocated from the Mars Observer mission operations and Voyager-Neptune data analysis.

[c] During FY 1994, final integration and testing of the two U.S. science instruments was nearing completion, and shipment of the flight units to Russia was scheduled for May 1994 for integration with the rest of the science payload. However, Russian technical problems delayed project completion beyond the October 1994 launch opportunity. This required a two-year launch delay to October 1996, necessitating refurbishment of the instruments and replanning their delivery to Russia for final integration with the rest of the science payload. FY 1995 funding provided ongoing support for the U.S. science investigators associated with all aspects of the science payload. The one-year prime mission was to begin upon arrival at Mars in September 1997. FY 1996 funding was provided to establish science data formatting, archival, and dissemination requirements before initiation of the prime mission.

Table 4–32. Discovery Funding History[a] (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1994	—/127,400	127,400	n/a
1995	129,700/129,700	129,700	345,500[b]
1996	103,800/102,200	102,200	137,500[c]
1997	74,800/76,800	76,800	104,700[d]
1998	106,500/76,500	100,000	146,400[e]

[a] The Discovery Program provided frequent access to space for small planetary missions. The Discovery Program included the Mars Pathfinder, NEAR, Lunar Prospector, and Future Missions budget categories. Future missions not launched by the end of 1998 included the Stardust mission, which had been selected in November 1995.

[b] Included full costs for FY 1995 and prior years for NEAR development, launch support, and tracking and data support; also included Mars Pathfinder development, the microrover, launch support, and tracking and data support.

[c] FY 1996 costs were for NEAR development, MO&DA, launch support, and tracking and data support; Mars Pathfinder development, microrover, launch support, and tracking and data support; Lunar Prospector development; Stardust Phase A/B (concept and definition analysis), development, and launch support; and development of future missions.

[d] FY 1997 budget authority was for NEAR mission operations and data analysis and tracking and data support; Mars Pathfinder microrover, MO&DA, launch support, and tracking and data support; Lunar Prospector development and MO&DA; Stardust development and launch support; and development of future missions.

[e] FY 1998 budget authority was for NEAR MO&DA and tracking and data support; Mars Pathfinder MO&DA and tracking and data support; Lunar Prospector MO&DA; Stardust development and launch support; development of future missions; and future missions' ELVs.

Table 4–33. Mars Surveyor Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1994	—[b]	14,600	n/a
1995	78,400/59,400	59,400	94,800[c]
1996	108,500/111,900	111,900	145,100[d]
1997	90,000/90,000	90,000	142,900[e]
1998	139,700/145,200	187,900	202,500[f]

[a] Included Mars Global Surveyor, Mars Orbiter and Lander, and future Mars missions.
[b] No budget category established at time of budget submission.
[c] Included costs for FY 1995 and prior years for Mars Global Surveyor development, launch support, and tracking and data support.
[d] FY 1996 costs were for Mars Global Surveyor development, launch support, and tracking and data support; 98 Mars Orbiter/Lander development and launch support; and future Mars missions development.
[e] FY 1997 budget authority was for Mars Global Surveyor MO&DA, launch support, and tracking and data support; 98 Mars Orbiter/Lander development and launch support; and future Mars missions development.
[f] FY 1998 budget authority was for Mars Global Surveyor MO&DA and tracking and data support, 98 Mars Orbiter/Lander development and launch support, and future Mars missions development and launch support.

Table 4–34. Space Science New Millennium Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1995	—[a]/10,500	—	10,500[b]
1996	30,000/30,000	43,500	47,200[c]
1997	21,500/48,600	—	53,700[d]
1998	75,700	—	108,600[e]

[a] No budget category established at time of initial budget submission.
[b] Included costs for FY 1995 and prior years for Advanced Technology Development, predecessor to the New Millennium Program.
[c] FY 1996 costs were for New Millennium Development (including Deep Space 1 and Deep Space 2 development) and launch support.
[d] FY 1997 budget authority was for New Millennium Development (including Deep Space 1 and Deep Space 2 development), Advanced Radioisotope Thermoelectric Generator, and launch support.
[e] FY 1998 budget authority was for New Millennium Development (including Deep Space 1 and Deep Space 2 development), Outer Planet Technology, Advanced Radioisotope Thermoelectric Generator, the Center for Integrated Space Microsystems, and launch support.

Table 4–35. Advanced Space Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1996	—[a]	143,300
1997	—/132,000	—[b]
1998	151,200/—[c]	—

[a] Budget category not established at time of budget submission.
[b] No programmed amount stated.
[c] Not included in revised budget submission.

Table 4–36. Explorer Missions (1989–1998)

Date	Explorer No.	Mission
November 18, 1989	66	COBE
June 7, 1992	67	EUVE
July 3, 1992	68	SAMPEX (Small Explorer mission)
December 30, 1995	69	RXTE
August 21, 1996	70	FAST (Small Explorer mission)
August 25, 1997	71	ACE
February 26, 1998	72	SNOE (STEDI mission)
April 2, 1998	73	TRACE (Small Explorer mission)
December 6, 1998	74	SWAS (Small Explorer mission)

Table 4–37. Cosmic Background Explorer Mission Characteristics

Launch Date/Launch Site	November 18, 1989 / Vandenberg Air Force Base
Date of Reentry	Last instrument turned off December 23, 1993
Launch Vehicle	Delta 5920
NASA Role	Design, development, flight operations, development of the analysis software, and production of the final mission data sets
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• Investigate the beginnings of organization of matter into galaxies, voids, and clusters of galaxies following the Big Bang. • Examine departures from perfect uniformity that must have occurred shortly after the Big Bang, appearing as spectral irregularities and anisotropy in the microwave and far infrared cosmic background radiation. • Search for accumulated light from the very first stars and galaxies.
Orbit Characteristics:	
Apogee	900 km (559 mi)
Perigee	900 km (559 mi)
Inclination (deg)	99
Period (min)	103
Weight	2,206 kg (4,864 lb)
Dimensions	18 ft (5.5 m) long, 15 ft (4.6 m) diameter, 27 ft (8.2 m) deployed
Power Source	Solar array/batteries direct energy transfer
Prime Contractor	In-house project
Instruments and Experiments[b]	• DMR PI: George Smoot, University of California, Berkeley Searched for minute differences in the brightness of background radiation between different parts of the sky to determine whether the Big Bang was equally intense in all directions. The DMR mapped the sky at three wavelengths: 3.3 mm (0.13 in), 5.7 mm (0.22 in), and 9.6 mm (0.38 in). It had three separate receiver boxes, one for each wavelength, mounted so that neither the Sun nor Earth shone directly on them. Each box had two separate receivers tuned to the same frequency to improve the sensitivity of the measurements. • FIRAS PI: John Mather, Goddard Space Flight Center Surveyed the sky to determine whether the cosmic background radiation from the Big Bang had the predicted spectrum (intensity at each wavelength).

Table 4–37. Cosmic Background Explorer Mission Characteristics (Continued)

Instruments and Experiments[c]	Both FIRAS and the DMR could distinguish 1,000 separate parts of the sky. FIRAS picked up radiation by using a trumpet-shaped cone antenna in line with the spacecraft spin axis. Four detectors, each a tiny silicon resistance thermometer glued to a piece of blackened diamond a thousandth of an inch (0.0254 mm) thick and 5/16 inch (0.7.9375 mm) in diameter, were used to sense the radiation collected by the cone antenna. • DIRBE PI: Michael Hauser, Goddard Space Flight Center Searched for light from the earliest stars and galaxies, the luminous energy that may have occurred 200 million years after the Big Bang. DIRBE measured the collective glow of emissions of objects. It covered a wavelength range of 1 micrometer to 300 micrometers and used 10 wavelength filters. The experiment's unobscured, off-axis Gregorian telescope enabled DIRBE to distinguish between nearby and distant objects. This telescope had stops, baffles, and super-polished mirrors to minimize response to objects outside the desired field of view (FOV). Four on board internal reference sources allowed regular monitoring of the responsiveness of each detector. To give accurate colors and polarizations, all detectors made simultaneous observations of the same FOV.
Results	COBE provided strong evidence supporting the Big Bang theory. Data from FIRAS and DMR gave the precise spectrum and a detailed map of temperature variations in the microwave background radiation from the Big Bang. Using data from DIRBE, astronomers detected an infrared background glow across the sky produced by dust warmed by all the stars that have existed since the beginning of time. The infrared radiation put a limit on the total amount of energy released by all the stars in the universe. It also revealed that a surprisingly large amount of starlight in the universe cannot be seen directly by current optical telescopes, perhaps because stars are hidden by dust or are too faint or far away to be seen.[d] COBE completed its all-sky survey on June 18, 1990; helium depletion occurred on September 21, 1990.

[a] "COBE, Cosmic Background Explorer," *http://library01.gsfc.nasa.gov/gdprojs/projinfo/cobe.pdf* (accessed August 4, 2005).

[b] "COBE Observes Primeval Explosion," NASA Facts, Goddard Space Flight Center (NASA History Office Folder 5893).

[c] "COBE Observes Primeval Explosion," NASA Facts, Goddard Space Flight Center (NASA History Office Folder 5893).

[d] "Astronomers Discover an Infrared Background Glow in the Universe," Release STScI-1998-01, January 9, 1998, *http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/01/text* (accessed May 11, 2006).

Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics

Launch Date/Launch Site	June 7, 1992 / Cape Canaveral Air Force Station
Date of Reentry	January 30, 2002
Launch Vehicle	Delta II
NASA Role	Project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Mission objectives: • Carry out an "all-sky" survey in the EUV band of the electromagnetic spectrum (wavelengths from 70 angstroms to 760 angstroms). • Perform a "deep survey" of a representative portion of the sky (180 degrees by 2 degrees) at a sensitivity higher than that of the all-sky survey. • Produce maps and catalogs of positions and intensities for EUV sources observed in the all-sky and deep surveys. • Carry out, through a guest observer program, spectroscopic observations of a significant number of the brightest EUV sources in the sky. Science objectives: • Map the structure of the local interstellar medium using data from two simultaneous surveys of the sky. • Produce a catalog of EUV sources, including their positions and temperatures, and map their distribution in space. • Analyze the composition, temperature, and dynamics of EUV sources and identify, using the EUVE spectrometer, the physical mechanisms responsible for EUV emission.
Orbit Characteristics:	
Apogee	527 km (327 mi)
Perigee	515 km (320 mi)
Inclination (deg)	28.4
Period (min)	94.8
Weight	3,275 kg (720 lb) (on-orbit dry mass)[a]
Dimensions	4.5 m by 3 m (14.8 ft by 9.8 ft)
Power Source	Solar array, three 50-Ah batteries
Prime Contractor	Science payload: Space Sciences Laboratory, University of California, Berkeley Spacecraft platform: Fairchild Space
Instruments and Experiments	Science PI: Stuart Bowyer, University of California, Berkeley Instrument PI: Roger Malina, University of California, Berkeley Guest Observer Project Scientist: Carol Christian, University of California, Berkeley

Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Three scanning telescopes: — Two identical Wolter-Schwarzschild Type I grazing incidence mirrors, each with an imaging microchannel plate detector (Scanner A and B) FOV ~5 degrees diameter; two passbands 44 angstroms to 220 angstroms and 140 angstroms to 360 angstroms. — One Wolter-Schwarzschild Type II grazing incidence mirror, with an imaging microchannel plate detector FOV ~4 degrees diameter; two passbands 520 angstroms to 750 angstroms and 400 angstroms to 600 angstroms. • One Wolter-Schwarzschild Type II grazing incidence mirror Deep Survey/Spectrometer Telescope that split light with half of the light fed to an imaging Deep Survey microchannel plate detector and half the light fed to three separate spectrometers; each were combinations of a grating and microchannel plate detector. Each spectrometer had its own bandpasses: shortwave (70 angstroms to 190 angstroms), medium wave (140 angstroms to 380 angstroms), and longwave (280 angstroms to 760 angstroms).[b]
Results[c]	Interstellar Medium Highlights: • Measurement of unexpected ionization fraction (~25 percent) of the helium in the local interstellar medium. • Discovery of a new (auto-ionization) He I interstellar absorption feature at 206 angstroms; extraordinarily valuable as an interstellar helium diagnostic. • Discovering that upper limits to the diffuse background place new constraints on hot local bubble models. • Discovery of beta CMa (Canis Najoris) as a dominant hydrogen ionization source in the local interstellar medium. White Dwarf Highlights: • Discovering that the origin of the strong EUV opacity in hot hydrogen-rich white dwarfs was due to high *Z* elements, not He. • Discovery of a new class of massive white dwarfs. Cataclysmic Variable Highlights: • First direct determination of the accretion hotspot spatial structure. • Measurement of abundance anomalies in several systems. • Outburst spectra of dwarf novae were more complicated than current models.

Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics (Continued)

Results[d]	Cool Star Highlights: • First determination of the n_e in stellar coronae. • Discovery of high density (10^{13} cm^{-3}) coronal plasmas. • First measurement of stellar coronal abundances. • Found three abundance patterns: cosmic, "FIP (first ionization potentials) effect" enhanced, and metal deficient. • The EUVE had the best available data on the large number and variety of coronal flares; further observations were required to derive flare frequency, flare energy distribution, and plasma conditions.
	Solar System Highlights: • Discovery of EUV emission from Comet B2 Hyakutake. • First measurement of helium in the Martian atmosphere, indicating the outgassing of Mars was a factor of 30 weaker than that of Earth.
	Extragalactic Highlights: • At least 10 extragalactic sources were observed spectroscopically, including at least seven active galactic nuclei. • The spectrum of the Type 1 Seyfert NGC 5548 appeared to show two emission lines. Two other Seyfert galaxies (RXJ0437.4-4711 and Mrk 478) showed only continuum. • The brightest BL Lac object, PKS 2155-304, observed with the EUVE, showed evidence of absorption by partially ionized material in a relativistic jet. • The EUV flux from Mrk 421 appeared to be co-spatial with the TeV-producing region. • Detection of >20 extragalactic EUV sources. • Detection of a new 10^6 K gas component in clusters of galaxies.
	Other Highlights: • Detection of thermal EUV emission from neutron star surfaces. • Anomalous EUV emission from B-stars (factor of ~20 > models).

[a] "EUVE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc+1992-031A* (accessed August 5, 2005).

[b] "The EUVE Observatory," *http://heasarc.gsfc.nasa.gov/docs/euve/euve.html* (accessed August 5, 2005).

[c] "Top '10' EUVE Science Highlights," *http://archive.stsci.edu/euve/science/top10_scihl.html* (accessed August 5, 2005).

[d] "Top '10' EUVE Science Highlights," *http://archive.stsci.edu/euve/science/top10_scihl.html* (accessed August 5, 2005).

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics

Launch Date/Launch Site	July 3, 1992 / Vandenberg Air Force Base
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Scout
NASA Role	Spacecraft design, construction, integration, checkout, and operation; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• Determine conclusively whether anomalous cosmic rays are singly charged and measure their isotopic composition. • Measure precipitating magnetospheric relativistic electron fluxes, determining their intensity and latitude and local time dependence, for a range of solar activity levels in the declining phase of solar activity. • Measure elemental and isotopic abundances and charge states of energetic solar flare particles in large and small solar events, including events rich in 3He. • Measure galactic cosmic ray elemental abundances up to iron; also measure isotopic abundances for carbon; nitrogen; oxygen; neon; magnesium; silicon; argon; iron; and nickel.
Orbit Characteristics:	
Apogee	675 km (419 mi)
Perigee	550 km (342 mi)
Inclination (deg)	82
Period (min)	97
Weight	Spacecraft: 117 kg (258 lb) Instruments: 40 kg (88 lb)
Dimensions	1.5 m (4.9 ft) high by 0.86 m (2.8 ft) diameter (stowed)
Power Source	Solar arrays, nickel cadmium battery
Prime Contractor	Goddard Space Flight Center

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Instruments and Experiments	Mission PI: Dr. Glenn M. Mason, University of Maryland • Heavy Ion Large Area Proportional Counter Telescope (HILT) Co-Investigators: D. Hovestadt, B. Klecker, and M. Scholer, Max Planck Institute, Germany The HILT measured the charge, energy, and mass of cosmic rays in the energy range of about 8.0 MeV-310 MeV/nucleon. Measured galactic cosmic rays and solar energetic particles when it was near Earth's magnetic poles. Determined the energy and elemental composition of anomalous cosmic rays at energies where they were most abundant. Measured the direction, energy, and charge of each nucleus from helium to nickel. The instrument consisted of 1) an array of position-sensitive proportional counters at the entrance, followed by 2) an ionization chamber, 3) another array of position-sensitive proportional counters just before, and 4) a coplanar, 10-element, solid state array of detectors.[a] • Low Energy Ion Composition Analyzer (LEICA) PI: D. Hamilton, University of Maryland The LEICA was a mass spectrometer that identified incident mass and energy by simultaneously measuring the time-of-flight and residual kinetic energy of particles entering the telescope and stopping in one of four silicon solid-state detectors. Measured 0.5 MeV to 5 MeV for solar and magnetospheric ions. The LEICA and HILT were originally designed and constructed as Shuttle flight GASs. • Mass Spectrometer Telescope (MAST) Co-Investigators: E. Stone, California Institute of Technology, and T. von Rosenvinge, Goddard Space Flight Center The MAST determined the direction, energy, element, and isotope of atoms from all elements up to nickel. Isotopes entered the instrument with velocities between about 12 percent and 75 percent of the speed of light. Measured isotropic composition of elements from lithium to nickel in the range of 10 MeV to several hundred MeV.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Proton/Electron Telescope (PET) Co-Investigators: R. Mewaldt, NASA Jet Propulsion Laboratory; E. Stone, California Institute of Technology; and T. Von Rosenvinge, Goddard Space Flight Center The PET complemented the MAST by measuring the energy spectra and relative composition of protons (18 MeV to 250 MeV) and helium nuclei (18 MeV to 350 MeV/nuclei) coming from Earth's radiation belts, the Sun, interplanetary space, and interstellar space. Also measured the energy spectra of solar flare and precipitating electrons from 0.4 MeV to 30 MeV. Electrons moved at velocities very close to the speed of light and could significantly cause the destruction of ozone high in Earth's atmosphere.
Results[b]	Successfully investigated the composition of local interstellar matter and solar material and the transport of magnetospheric charged particles into Earth's atmosphere. The SAMPEX made discoveries in the following areas: • Anomalous Cosmic Rays — Discovery of the precise location of trapped anomalous cosmic rays in the magnetosphere. — Measurement of the elemental composition of trapped anomalous cosmic rays, including C, N, O, and Ne. — "Early" return of the anomalous cosmic ray component in the 1992 solar minimum period, well before the relativistic ions. — Discovery that trapped anomalous cosmic rays are the dominant component of high-energy (>10 MeV/nuc) ions heavier than helium in the magnetosphere. — Determination that anomalous cosmic rays nitrogen, oxygen, and neon are singly charged. — Determination that the upper limit of anomalous cosmic ray O^{2+} is less than 10 percent of the total anomalous cosmic ray oxygen, thus limiting acceleration timescales in the heliosphere. — Discovery that the interplanetary spectrum of anomalous oxygen extends to at least 100 MeV/nucleon, implying that the anomalous cosmic ray acceleration mechanism (termination shock?) accelerates particles to at least 1.6 GeV.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Results	— Discovery (in collaboration with Voyager, Ulysses, and Pioneer spacecraft) that the intensity of anomalous cosmic ray oxygen ions increases with heliolatitude during the 1993 approach to solar minimum, in contrast to the opposite behavior observed at the previous solar minimum; this confirms predictions of one class of particle transport theories that include particle drift. — Demonstration (in collaboration with Voyager, Ulysses, and Pioneer spacecraft) that the radial gradients of anomalous cosmic rays are much smaller in the current solar minimum than during the previous solar minimum in 1987. • Solar Energetic Particles — Determination of "normal" solar system isotopic abundances for Ne and Mg in the large solar particle events of October and November 1993. Excesses (factor 4) of neutron-rich isotopes of Ne and Mg in 3He-rich solar particle events. — Demonstration that high-energy (>25 MeV/nucleon) Si and Fe ions in the large solar particle events of late 1992 were in partially ionized charge states, similar to those reported previously for energies near 1 MeV/nucleon. • Magnetospheric Physics — Discovery that magnetospheric electrons are globally accelerated in association with the impact of high-speed solar wind streams. — Evidence for deep dielectric charging as a likely cause of the January 1994 Anik spacecraft anomalies. — Discovery that remnants of relativistic electron belt generated by the March 24, 1991 interplanetary shock persisted until 1993. — Discovery of a radiation belt at L=1.2 composed of roughly equal amounts of 3He and 4He. — Discovery of high-energy (>50 MeV/nucleon) deuterium trapped in the magnetosphere. — Discovery that relativistic electron precipitation routinely has temporal structure at the bounce period.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Results	• Middle Atmosphere — Discovery that electron flux variations at SAMPEX altitudes are well correlated with solar wind variations, providing a solar-magnetosphere-middle atmosphere coupling. — Demonstration that the primary relativistic electron flux inputs into the middle atmosphere occur in the range 3.5<L. — Discovery that relativistic electron energy inputs into the middle atmosphere are asymmetric between the Northern and Southern Hemispheres, with the largest inputs occurring in the Southern Hemisphere. Within each hemisphere, there are preferred longitudes for the energy inputs. — Indication that relativistic precipitating electrons provide a significant source of odd nitrogen to the middle atmosphere and can impact middle atmospheric ozone. • Galactic Cosmic Rays — Improved demonstration that the isotopic composition galactic cosmic rays and anomalous component differ significantly.

[a] "Heavy Ion Large Telescope (HILT)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-038A&ex=2* (accessed April 26, 2006).

[b] "SAMPEX—Solar Anomalous and Magnetospheric Particle Explorer," *http://sunland.gsfc.nasa.gov/smex/sampex/mission/* (accessed May 11, 2006).

Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics

Launch Date/Launch Site	December 30, 1995 / Cape Canaveral Air Station
Date of Reentry	Still operating as of mid-2005
Launch Vehicle	Delta II
NASA Role	Mission management; provided spacecraft and PCA
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	To investigate the following:[a] • Periodic, transient, and burst phenomena in the x-ray emission from a wide variety of objects. • The characteristics of x-ray binaries, including the masses of the stars, their orbital properties, and the exchange of matter between them. • The inner structure of neutron stars and the properties of their magnetic fields. • The behavior of matter just before it falls into a black hole. • The effects of general relativity that can be seen only near a black hole. • The properties and effects of supermassive black holes in the centers of active galaxies. • The mechanisms causing the emission of x-rays in all these objects. By doing the following:[b] • Using the PCA to make detailed spectrophotometric observations of the brightest 800 x-ray sources in the sky over the 2-keV to 60-keV energy band with a temporal resolution of 1 microsecond energy resolution of <20 percent (6 keV), to a limiting sensitivity of 0.1 milliCrab. • Using the HEXTE to make detailed spectrophotometric observations of the brightest 400 x-ray sources in the sky over the 20-keV to 200-keV energy band with a temporal resolution of 10 microseconds, energy resolution of <20 percent (at 60 keV), to a limiting sensitivity of 0.5 milliCrab at 100 keV. • Using the ASM to monitor more than 75 percent of the sky every orbit over the 2-keV to 10-keV energy band to a limiting sensitivity of 20 milliCrab and a positional determination accuracy of 3 arc minutes by 5 arc minutes for bright sources. • Detecting and performing detailed studies with the PCA and HEXTE instruments within 8 hours of onset of five bright (flux>1 Crab) x-ray novae.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	580 km (360 mi)
Inclination (deg)	23

Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics (Continued)

Period (min)	100
Weight	33,200 kg (7.055 lb)
Dimensions[c]	5.4 m by 1.8 m by 1.8 m (18 ft by 6 ft by 6 ft)
Shape	Rectangular
Power Source	Solar panels
Prime Contractor	In-house project
Instruments and Experiments	• PCA PI: Jean Swank, Goddard Space Flight Center The PCA consisted of five large xenon gas detectors with a combined collecting area of two-thirds of a square meter to measure x-rays in the 2 keV to 60 keV region. The PCA collecting area was 6.250 cm^2. The PCA operated in tandem with the HEXTE, and its pointing area overlapped with the HEXTE pointing area, increasing the collecting area by an additional 1,600 cm^2. • HEXTE PI: Richard Rothschild, University of California, San Diego The HEXTE consisted of two clusters of four detectors each that covered the energy range from 20 keV to 200 keV. The HEXTE featured a large area and low background with a 1-degree FOV coaligned with the PCA FOV. The HEXTE operated in tandem with the PCA, and the two together operated as a high-resolution, sensitive x-ray detector.[d] • ASM PI: Alan Levine, Massachusetts Institute of Technology The rotating ASM consisted of three scanning shadow cameras that scanned 70 percent of the sky every 100 minutes at 2 keV to 10 keV and monitored the intensity and long-term behavior of the brightest x-ray sources. The ASM also provided an alert if a source changed state or brightened suddenly, allowing the spacecraft to be maneuvered within a few hours so the PCA and HEXTE could study the event. • Experiment Data System (EDS) PI: Alan Levine, Massachusetts Institute of Technology The EDS consisted of eight Event Analyzers (EAs), of which six were dedicated to the PCA and two to the ASM. Each EA contained an Intel 80286 processor and associated memory. The EAs could be programmed independently in a variety of modes to process incoming events from the instruments.

Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics (Continued)

Results	Performed a wide variety of x-ray observations to include: pulsars, neutron stars, black holes, and gamma-ray bursts. Among the mission's discoveries were: • Observed the reappearance of bursting pulsars. • Discovered neutron stars emitting streams of x-rays that pulsed more than 1,000 times a second. The pulses were not strictly periodic but varied slightly from cycle to cycle. Astronomers call them "quasi-periodic oscillations" or QPOs. • Data from the RXTE ASM confirmed the detection of a 77.7-day period from the low mass x-ray binary Cygnus X-2. • Astronomers used the RXTE to observe a black hole that appeared to drag space and time around itself as it rotated. This effect was called "frame dragging" and was predicted by Einstein's Theory of Relativity. This was the first time physical evidence supporting this aspect of Einstein's 1918 theory had been available. • Helped confirm the existence of magnetars as a class of neutron star. • Discovered that a star emitting rapid pulses of x- rays may be the long-sought "missing link" between old neutron stars that emit powerful flashes of x-rays, and older, rapidly spinning neutron stars that emit mainly radio waves. This star, designated SAX J1808.4-3658, was located 12,000 light years away toward the constellation Sagittarius. • The RXTE's PCA was flooded with an intense wave of gamma rays emanating from a magnetar 20,000 light years away, even though the PCA was not pointing at the source. The wave was so powerful that it blasted sensitive detectors on seven scientific spacecraft that were in Earth orbit, or elsewhere in the solar system, to maximum or off-scale levels.
Remarks	The RXTE was the first mission to provide 100 percent of the observing time to the broad scientific community.

[a] "About RXTE," *http://heasarc.gsfc.nasa.gov/docs/xte/learning_center/what_is_RXTE.html* (accessed October 20, 2005).

[b] Wesley T, Huntress, Jr., to multiple addresses, "XTE Mission Objectives," September 1, 1995 (NASA History Office Folder 11616).

[c] "The Rossi X-ray Timing Explorer," NASA Facts, *http://www.gsfc.nasa.gov/gsfc/spacesci/pictures/2003/0702pulsarspeed/Rossi_Fact_Sheet.pdf* (accessed October 20, 2005).

[d] "Taking the Pulse of the Universe," RXTE Brochure, *http://xte.mit.edu/xte_pulse.html* (accessed October 20, 2005). Also "About RXTE," *http://heasarc.gsfc.nasa.gov/docs/xte/learning_center/what_is_RXTE.html* (accessed August 9, 2005).

Table 4–41. Fast Auroral Snapshot Explorer Mission Characteristics

Launch Date/Launch Site	August 21, 1996 / Vandenberg Air Force Base
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Pegasus XL
NASA Role	Supplied spacecraft; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To study the microphysics of space plasma and the accelerated particles that cause the aurora. • To measure particles and fields with high temporal and spatial resolution in regions where electrons are energized to form the aurora and ions are accelerated out of the ionosphere into the magnetosphere.
Orbit Characteristics:	
Apogee	4,175 km (2,594 mi)
Perigee	351 km (218 mi)
Inclination (deg)	83
Period (min)	133
Weight	Total observatory: 191 kg (421 lb) Instruments: 51 kg (112 lb)
Dimensions	1.2 m (3.9 ft) diameter by 1.8 m (5.9 ft)
Shape	Octagonal cylinder
Power Source	Solar arrays and battery
Prime Contractor	Goddard Space Flight Center
Instruments and Experiments	• Electric Field Experiment: PI: Charles Carlson, University of California, Berkeley Composed of three orthogonal boom pairs. Spherical sensors deployed on radial wire and axial booms provided information on the plasma density and electron temperature. • Magnetic Field Experiment: PI: Charles W. Carlson, University of California, Berkeley Consisted of two magnetometers mounted 180 degrees apart on deployable graphite epoxy booms. The search coil magnetometer used a three-axis sensor system to provide magnetic field data over the frequency range of 10 Hz to 2.5 kHz. The flux gate magnetometer was a three-axis system using high, stable, low-noise, ring core sensors to provide magnetic field information from dc to 100 Hz.

Table 4–41. Fast Auroral Snapshot Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Time-of-Flight Energy Angle Mass Spectrograph (TEAMS) PI: Charles W. Carlson, University of California, Berkeley The TEAMS was a high-sensitivity, mass-resolving spectrometer measuring full three-dimension distribution functions of the major ion species with one spin of the spacecraft. The experiment covered the core of all plasma distributions of importance in the auroral region. • Electrostatic Analyzers PI: Charles W. Carlson, University of California, Berkeley Sixteen Electrostatic Analyzers configured in four stacks were used for both electron and ion measurements. The four stacks were placed around the spacecraft so that the entire package was provided a full 360 degree FOV. The analyzers provided a 64-step energy sweep, covering approximately 3 keV to 30 keV up to 16 times per second.
Results	This highly successful spacecraft helped scientists answer fundamental questions about the causes and makeup of the aurora.

[a] "Fast Auroral Snapshot Explorer (FAST)," Institute of Geophysics and Planetary Physics, UCLA, *http://www-ssc.igpp.ucla.edu/fast/* (accessed August 18, 2005).

Table 4–42. Advanced Composition Explorer Mission Characteristics

Launch Date/Launch Site	August 25, 1997 / Cape Canaveral Air Station
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Delta II
NASA Role	Project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	To determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, interplanetary medium, local interstellar medium, and galactic matter.
Orbit Characteristics	Orbits at Earth-Sun libration L1 point about 1.5 million km (1 million mi) from Earth
Weight	785 kg (1730.6 lb) (includes 195 kg (430 lb) of fuel at launch)
Dimensions	1.6 m (5.2 ft) by 1.0 m (3.3 ft)
Shape	Irregular octagon
Power Source	Four fixed solar arrays
Prime Contractor	The Johns Hopkins University Applied Physics Laboratory, California Institute of Technology Space Radiation Laboratory
Scientific Co-Investigators[a]	PI: Edward Stone, California Institute of Technology/ Jet Propulsion Laboratory Project Scientist: Tycho von Rosenvinge, Goddard Space Flight Center[b] Co-Investigators: Walter Binns, Washington University in St. Louis Peter Bochsler, University of Bern, Switzerland Leonard Burlaga, NASA Goddard Space Flight Center Alan Cummings, California Institute of Technology William Feldman, Los Alamos National Laboratory Thomas Gerrard, California Institute of Technology[c] Johannes Geiss, University of Bern, Switzerland George Gloeckler, University of Maryland Robert Gold, The Johns Hopkins University Applied Physics Laboratory Dieter Hovestadt, Max Planck Institute for Extraterrestrial Physics, Germany Berndt Klecker, Max Planck Institute for Extraterrestrial Physics, Germany Stamatios Krimigis, The Johns Hopkins University Applied Physics Laboratory Glenn Mason, University of Maryland David McComas, Los Alamos National Laboratory

Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Scientific Co-Investigators[d]	Richard Mewaldt, California Institute of Technology Eberhard Möbius, University of New Hampshire Norman Ness, University of Delaware John Simpson, University of Chicago[e] Mark Wiedenbeck, Jet Propulsion Laboratory
Instruments and Experiments	• Cosmic Ray Isotope Spectrometer (CRIS): Measured the abundances of galactic cosmic ray isotopes with energies from ~100 MeV/nucleon to ~600 MeV/nucleon in the element range from helium to zinc with a collecting power more than 50 times greater than similar previous instruments. Determined the nuclear charge, mass, and kinetic energy of incident cosmic rays that stop in one of four identical stacks of large-area silicon solid-state detectors. • Solar Isotope Spectrometer (SIS): Provided high-resolution measurements of the isotopic composition of energetic nuclei from helium to nickel (Z=2 to 28) in the energy range from ~10 MeV/nucleon to ~100 MeV/nucleon. • Ultra Low Energy Isotope Spectrometer (ULEIS): Measured ion fluxes in the charge range from helium through nickel from about 20 keV/nucleon to 10 MeV/nucleon, covering both suprathermal and energetic particle energy ranges. Performed exploratory measurements of ultra-heavy species (mass range above nickel) in a more limited energy range near 0.5 MeV/nucleon. Studied the elemental and isotopic composition of solar energetic particles and the mechanisms by which these particles were energized in the solar corona. Investigated mechanisms by which supersonic interplanetary shock waves energized ions. • Solar Energetic Particle Ionic Charge Analyzer (SEPICA): Detected the ionic charge state, kinetic energy, and nuclear charge of ions coming from the Sun to determine not only the type of ions present but also the history of those ions within the Sun. • Solar Wind Ion Mass Spectrometer (SWIMS): Provided solar wind composition data for all solar wind conditions. Determined the quantities of most of the elements and a wide range of isotopes in the solar wind. • Solar Wind Ionic Composition Spectrometer (SWICS): Determined the charge of ions and the temperature and speeds of all the major solar wind ions. Covered solar wind speeds from 145 km/s (90 mi/s) (protons) to 1,532 km/s (952 mi/s) (iron).

Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Magnetometer (MAG): Consisted of one electronics box mounted on the spacecraft top deck and two sensors mounted at the end of two booms. Measured the local interplanetary magnetic field direction and magnitude. Established the large-scale structure and fluctuation characteristics of the interplanetary magnetic field at 1 AU upstream of Earth as a function of time throughout the mission. • Real Time Solar Wind (RTSW) Data Experiment: The EPAM, MAG, SIS, and SWEPAM instruments on the ACE supplied data to NOAA's Space Environment Center (SEC) for RTSW processing. This data offered up to 1 hour's advance warning of unusual solar activity, such as solar flares and coronal mass ejections, which could cause geomagnetic storms. • Spacecraft Loads and Acoustic Measurements (SLAM): This engineering instrument directly measured the launch vibration environment on the spacecraft during the first 5 minutes of launch. The system consisted of nine low-frequency accelerometer channels covering a frequency range from dc to 100 Hz, six high-frequency accelerometer channels, and three microphone channels, each covering a frequency range from 5 Hz to 2,000 Hz.
Results[f]	As of July 2005, the ACE has been at the L1 point for eight years. Only the SEPICA has failed. The ACE provided new determinations of the composition of the Sun, which comprises more than 99 percent of the matter in the solar system. By measuring how many electrons remained attached to solar wind and higher-energy ions, the ACE measured the (several million degree) temperatures of regions from which these particles originate. Elemental and isotopic composition measurements reveal the composition of the solar atmosphere, as well as composition patterns that arise when some particles are accelerated more easily than others. The broad range of composition measurements that ACE provided made it possible to identify the origin of energetic particle populations observed in interplanetary space and understand the processes by which they are accelerated. Comparisons of the composition of solar wind and higher energy solar particles with that of meteorites, comets, the Moon, planetary atmospheres, and galactic material provided key information on the history of our solar system.

Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Results[g]	ACE's measurements of radioactive isotopes in the galactic cosmic rays have shown that cosmic rays must have been accelerated at least 100,000 years after they were synthesized in supernova explosions. Other isotope measurements show that cosmic rays typically spend about 15 million years in our galaxy before leaving, implying that they must be replenished continually. The relative abundances of the stable isotopes of magnesium, silicon, calcium, iron, and nickel in cosmic rays are found to be very similar to those in solar system material, indicating that the effects of galactic evolution since the creation of the solar system are not large. ACE's studies of solar wind, solar particles, and cosmic rays, in combination with other spacecraft such as Ulysses and Voyager, have provided new insight into the solar wind that envelops our solar system and the nature of its interactions with the galaxy. From its position at L1, the ACE directly measured Earth's ever-changing solar wind and solar particle environment, including interplanetary disturbances that disrupt Earth's magnetic field and cause the aurora. The combination of ACE data from L1 and magnetospheric data from the Polar, Geotail, SAMPEX, and IMAGE spacecraft made it possible to determine how the magnetosphere and upper atmosphere respond to solar variations.
Remarks	On January 21, 1998, NOAA and the ACE project opened the ACE Real Time Solar Wind monitoring capability to the public.

[a] As of February 2000. "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005). Also "Advanced Composition Explorer (ACE) Project Responsibilities and Key Personnel," *http://www.srl.caltech.edu/ACE/ace_personnel.html* (accessed May 4, 2006).

[b] Jonathan Ormes of Goddard Space Flight Center was the original ACE Project Scientist.

[c] Not included as of February 2000.

[d] As of February 2000. "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005). Also "Advanced Composition Explorer (ACE) Project Responsibilities and Key Personnel," *http://www.srl.caltech.edu/ACE/ace_personnel.html* (accessed May 4, 2006).

[e] Deceased as of February 2000.

[f] "Advanced Composition Explorer," 2nd ed., March 2002, p. 4, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

[g] "Advanced Composition Explorer," 2nd ed., March 2002, p. 4, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

Table 4–43. Student Nitric Oxide Explorer Mission Characteristics

Launch Date/Launch Site	February 26, 1998 / Vandenberg Air Force Base
Date of Reentry	December 13, 2003
Launch Vehicle	Pegasus XL
NASA Role	Funding, launch service management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Scientific objectives: • To determine how variations in the solar soft x-radiation produce changes in the density of nitric oxide in the lower thermosphere. • To determine how auroral activity produces increased nitric oxide in the polar regions.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	535 km (332 mi)
Inclination (deg)	97.75
Period (min)	95.8
Weight	254 lb (115 kg)
Dimensions	36 in (0.9 m) high, 39 in (1 m) wide
Shape	Hexagonal
Power Source	Solar panels, nickel cadmium battery packs
Prime Contractor	University of Colorado at Boulder, LASP
Instruments and Experiments[a]	Mission PI: Charles Barth, University of Colorado • Ultraviolet Spectrometer (UVS): Measured the density of nitric oxide between the altitudes of 100 km (62 mi) and 200 km (124 mi) in the terrestrial upper atmosphere by observing the (1,0) and (0,1) gamma bands. The spectrometer had a focal length of 125 mm (4.9 in). • Auroral Photometer (AP): Determined energy deposited in the upper atmosphere by energetic auroral electrons. It had two channels; both had a circular FOV of 11 degrees full-cone. The AP and UVS photomultiplier electronics were identical, resulting in significant economies in fabrication and operation. • Solar X-ray Photometer (SXP): Measured the solar irradiance at wavelengths from 0.1 nm to 35 nm in the soft x-ray to hard extreme UV portion of the solar spectrum. Each photometer channel consisted of a silicon photodiode. Five photodiodes were flown. Coatings were selected so overlapping bandpasses could isolate key parts of the solar spectrum at low resolution.

Table 4–43. Student Nitric Oxide Explorer Mission Characteristics (Continued)

Instruments and Experiments	The FOV was 70 degrees full cone. The SXP took 12 measurements per spin, centered on the zenith, with a 63-second integration time. Thus, it obtained an integrated solar measurement once per orbit, when the Sun was near the zenith. Data was stored in a buffer, which was emptied once per spin by the spacecraft microprocessor in the same manner as the UVS and AP.
Results	The SNOE remained fully functional until December 12, 2003. It reentered the atmosphere on December 13 after five years, 290 days on orbit. The SNOE determined the influence of the Sun on Earth's upper atmosphere by measuring the amount of nitric oxide in the atmosphere. SNOE observations confirmed previously held suspicions that the solar soft x-ray irradiance was stronger than prior sparsely available data and empirical models suggested. The SNOE demonstrated that solar soft x-ray irradiance and auroral energy deposition controlled the abundance of nitric oxide over the globe; it also provided the results that wintertime midlatitude nitric oxide was controlled by auroral energy while summertime polar nitric oxide was controlled by solar irradiance. The morphology of nitric oxide also provided clues to the processes in the magnetospheric, which led to the auroral energy deposition. Further, the mission's serendipitous observations of polar mesospheric clouds provided an excellent database for climatological studies of these clouds, showing a strong hemispheric asymmetry in their distribution and the strong influence of local dynamics.[b]

[a] "Scientific Instruments," *http://lasp.colorado.edu/snoe/lib/instruments.html* (accessed August 31, 2005).

[b] Scott Bailey and Charles Barth, letter written by SNOE investigators upon the occasion of SNOE's end of life. *http://snoe.gi.alaska.edu/bailey/SNOE_reentry.htm* (accessed August 31, 2005).

Table 4–44. Transition Region and Coronal Explorer Mission Characteristics

Launch Date/Launch Site	April 1, 1998 / Vandenberg Air Force Base
Date of Reentry	Operational as of mid-2005
Launch Vehicle	Pegasus XL
NASA Role	Project management, developed and built spacecraft
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To follow the evolution of magnetic field structures from the solar interior to the corona. • To investigate the mechanisms of the heating of the outer solar atmosphere. • To investigate the triggers and onset of solar flares and mass ejections. • To explore the three-dimensional magnetic structures that emerge through the visible surface of the Sun—the photosphere—and define both the geometry and dynamics of the upper solar atmosphere: the transition region and corona.
Orbit Characteristics:	
Apogee	600 km (373 mi)
Perigee	650 km (404 mi)
Inclination (deg)	97.8
Period (min)	95
Weight	250 kg (551 lb)
Dimensions	6 ft by 3.5 ft (1.9 m by 1.1 m)
Power Source	Solar cells and battery
Prime Contractor	Spacecraft: Goddard Space Flight Center Telescope: Lockheed Martin
Mission PI	Alan Title, Lockheed Palo Alto and team including 13 other scientists from the United States, Sweden, the United Kingdom, and the Netherlands.
Instruments and Experiments	The single TRACE telescope was of Cassegrain design, 1.6 m (5.2 ft) long with an aperture of 30 cm (11.8 in). The focal length was 8.66 m (28.4 ft). The telescope's FOV was 8.5 by 8.5 arc minutes with a spatial resolution of 1 arc second. The light was focused on a 1024-element by 1024-element CCD detector (0.5 arc second/pixel). The instrument's temporal resolution was less than 1 second, although the nominal temporal resolution was 5 seconds. Exposure times for observations ranged between 2 milliseconds and 260 seconds.

Table 4–44. Transition Region and Coronal Explorer Mission Characteristics (Continued)

Instruments and Experiments	The primary and secondary mirrors had normal-incidence coatings specially designed for EUV and UV observations that divided the mirrors into quadrants. These segmented coatings were designed to provide identically sized, perfectly coaligned images. Which mirror quadrant was used for an observation was determined by the position of a quadrant selector shutter mechanism positioned behind the entrance aperture. Three of the mirror coatings provided for observations in specific iron emission bands. The final mirror coating allowed broadband UV observations. Further selection of UV observations could be made through a filter wheel mounted in front of the CCD.[b]
Results	First light for the telescope occurred on April 20, 1998. Observations have been collected nearly 24 hours per day since then with no significant problems in any segment of the spacecraft, instrument, or mission operations. The telescope has operated successfully in conjunction with the SOHO.

[a] "Transition Region and Coronal Explorer," *http://sunland.gsfc.nasa.gov/smex/trace* (accessed September 2, 2005). Also "Transition Region and Coronal Explorer (TRACE)," ISD–The Information Systems Division 580, *http://isd.gsfc.nasa.gov/MSE/OnOrbit/TRACE.htm* (accessed September 2, 2005).

[b] "TRACE Imaging Telescope," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-020A&ex=** (accessed September 27, 2005).

Table 4–45. Submillimeter Wave Astronomy Satellite Mission Characteristics

Launch Date/Launch Site	December 5, 1998 / Vandenberg Air Force Base
Date of Reentry	Made observations until July 21, 2004; the spacecraft was reactivated in June 2005 for a three-month period to support the Deep Impact encounter with Comet 9P/Tempel-1
Launch Vehicle	Pegasus XL
NASA Role	Spacecraft; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	By observing spectral lines emanating from dense molecular clouds, the SWAS would: • Determine the composition of interstellar clouds. • Establish how dense molecular clouds cool as they collapse and form planets.
Orbit Characteristics:	
Apogee	600 km (373 mi)
Perigee	600 km (373 mi)
Inclination (deg)	70
Period (min)	97
Weight	Spacecraft: 285 kg (628 lb) Instrument: 102 kg (225 lb)
Dimensions	Spacecraft: 1.63 m by 1.02 m[a] (5.3 ft by 3.3 ft) Telescope: 55 cm by 71 cm[b] (1.8 ft by 2.3 ft)
Shape	Spacecraft: Roughly octagonal Telescope: Elliptical
Power Source	Solar arrays and battery
Prime Contractor	Goddard Space Flight Center, Harvard-Smithsonian Center for Astrophysics
Instruments and Experiments	Submillimeter Wave Telescope: PI: Gary J. Melnick, Harvard-Smithsonian Center for Astrophysics heading teams from the United States and Germany The SWAS had a 55-cm by 71-cm (1.8 ft by 2.3 ft) elliptical off-axis Cassegrain telescope with a beam width of 4 arc minutes at its operating frequencies. The telescope incorporated dual heterodyne radiometers. The outputs of the two SWAS receivers were combined to form a final intermediate frequency, which extended from 1.4 GHz to 2.8 GHz. An acousto-optical spectrometer provided by the University of Cologne recorded the spectra (taken every 2 seconds by the spacecraft) that were dispersed into 1,400 1-MHz channels by the spectrometer.

Table 4–45. Submillimeter Wave Astronomy Satellite Mission Characteristics (Continued)

Instruments and Experiments	The SWAS instrument consisted of seven major subsystems: 1. The signal detection subsystem consisting of two submillimeter heterodyne receivers built by Millitech Corporation 2. An acousto-optical spectrometer provided by the University of Cologne in Germany 3. The telescope assembly 4. The star tracker assembly 5. The instrument control electronics 6. The instrument structure 7. The thermal control subsystem [c]
Results	The SWAS had successful launch and early operations. Early SWAS results included the discovery that large amounts of water seemed to saturate the interstellar medium; by contrast, molecular oxygen could not be found.[d] "Hibernating" since July 21, 2004, the SWAS was reactivated to full science operations mode to support the 2005 Deep Impact mission.

[a] "Submillimeter Wave Astronomy Satellite (SWAS)," 1995 Flight Project Data Book, Space Science.

[b] "The Submillimeter Wave Astronomy Satellite (SWAS)," *http://cfa-www.harvard.edu/swas/instrument.html* (accessed August 11, 2005).

[c] "The SWAS Instrument," *http://cfa-www.harvard.edu/swas/instrument.html* (accessed August 11, 2005).

[d] "First Results from SWAS Include Some Surprises," Harvard-Smithsonian Center for Astrophysics Press Release, January 8, 1999, *http://cfa-www.harvard.edu/cfa/ep/pressrel/melnick.html* (accessed October 11, 2005).

Table 4–46. Roentgen Satellite Mission Characteristics

Launch Date/Launch Site	June 1, 1990 / Cape Canaveral
Date of Reentry	End of mission: February 12, 1999
Launch Vehicle	Delta II
NASA Role	High Resolution Imager, launch vehicle, launch services; site of U.S. ROSAT Science Data Center
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• To conduct an all-sky survey with imaging x-ray and EUV telescopes.[a] 1995 Flight Project Data Book:[b] • Study coronal x-ray emission from stars of all spectral types, • Detect and map x-ray emission from galactic supernova remnants. • Evaluate the overall spatial and source count distributions for various x-ray sources. • Perform detailed studies of various populations of active galaxy sources. • Perform morphological studies of the x-ray-emitting clusters of galaxies. • Perform detailed mapping of the local interstellar medium (EUV survey). Mission Operation Report:[c] • Measure the spatial, spectral, and temporal characteristics of discrete cosmic sources including normal stars, collapsed stellar objects, and active galactic nuclei. • Perform spectroscopic mapping of extended x-ray sources including supernova remnants, galaxies, and clusters of galaxies. • Conduct mission operation observations of cosmic sources with unprecedented sensitivity and spatial resolution over the 0.1 keV to 2.0 keV energy band.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	580 km (360 mi)
Inclination (deg)	53
Period (min)	96
Weight	2,424 kg (20,776 lb)
Dimensions	4.5 m by 3 m (14.8 ft by 9.9 ft)
Power Source	Solar panels and a rechargeable battery
Prime Contractor	Dornier

Table 4–46. Roentgen Satellite Mission Characteristics (Continued)

Instruments and Experiments[d]	• XRT PSPC PI: Joachim Trümper, Max Planck Institute, Germany HRI PI: Martin Zombeck, Smithsonian Astrophysical Observatory, Cambridge, MA Consisted of four nested Wolter-I mirrors; mirror assembly had a 2.40-m (7.9-ft) focal length. The focal plane instrumentation consisted of a carousel on which there were two PSPCs, each with a filter wheel carrying a boron filter and HRI. WFC PI: Kenneth Pounds, University of Leicester, UK Consisted of three nested Wolter-Schwarzschild mirrors (coaligned with the XRT); mirror assembly had a 0.525-m (1.7-ft) focal length. Focal plane instrumentation consisted of a curved microchannel plate (MCP), a carousel with eight filters, of which six were science filters.
Results	ROSAT's highlights included: • Detailed exploration of a million-degree, low-density halo of gas surrounding the Milky Way galaxy. • Detection of large gas halos glowing in x-rays from virtually all comets passing near the Sun, produced by the interaction of the comet's gas and fast-moving subatomic particles in the solar wind. • Detection of clusters of galaxies at a larger distance than expected, leading scientists to question how such massive objects could form so early in the history of the universe. • Detection of an isolated nearby neutron star, which, according to previous theories, had been large enough at one time to collapse into a black hole and therefore led scientists to question how massive a star can get without its lifecycle ending in a black hole stage. • Revolutionary discoveries about star formation, including the observation that a large fraction of young stars lie far away from "classical" star-forming regions, indicating that star formation is a more ubiquitous process than previously thought and x-ray emission from young stars plays a key role in the regulation of the star formation rate. • Measurement of the total amount and distribution of dark matter in assemblages of galaxies, with x-ray-emitting gas tracing the effect of gravity and showing that the distribution of dark matter differs from that of the galaxies as seen in visible light. [e]

Table 4–46. Roentgen Satellite Mission Characteristics (Continued)

Results	The ROSAT successfully completed its six-month all-sky survey phase and primary mission of 20 months, including the pointed observations of selected celestial targets. The ROSAT continued to collect data during its extended mission. The satellite was turned off on February 12, 1999 after failure of the telescope's last working detector.

[a] Max Planck Institut Für Extraterrestrische Physik, *ROSAT User's Handbook http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

[b] "Roentgen Satellite (ROSAT)," *1995 Flight Project Data Book* (NASA History Office Folder 6328).

[c] Mission Operation Report, "Roentgensatellit (ROSAT)," Report no. E-876-90-03 (NASA History Office Folder 30959).

[d] *ROSAT User's Handbook*, *http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

[e] "ROSAT Wrap-Up: ROSAT X-ray Telescope Mission Comes to an End," ROSAT Guest Observer Facility, *http://agile.gsfc.nasa.gov/docs/rosat/taps.html* (accessed August 9, 2005).

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics

Launch Date/Launch Site	July 25, 1990 / Cape Canaveral
Date of Reentry	Contact with the CRRES was lost on October 12, 1991, presumably due to on board battery failure.
Launch Vehicle	Atlas Centaur
NASA Role	Operations relating to spacecraft integrity; tracking and control; launch; on-orbit initialization/checkout of the spacecraft; and chemical release campaigns[a]
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives	• Launch of the spacecraft into a highly elliptical GTO with an initial perigee of 350 km (217 mi) altitude and an apogee at geosynchronous altitude of 35,780 km (22,233 mi) and inclined at near 18 degrees to the equator. • NASA performance of active chemical release experiments in the ionosphere and magnetosphere. • DOD studies of microelectronic components as the CRRES travels through the inner and outer radiation belts of Earth. • DOD low-altitude studies of ionospheric irregularities, performed in the ionosphere near the orbit perigee.
Orbit Characteristics:	
Apogee	33,786 km (20,994 mi); initial orbit was 350 km by 33,584 km (217.5 mi by 20,868 mi)
Perigee	350 km (217.5 mi)
Inclination (deg)	18.15
Period (min)	590
Weight	1,724 kg (3,800 lb)
Dimensions	2.6 m (8.5 ft) diameter, 1 m (3.3 ft) high, 3 m (9.8 ft) between opposite faces
Shape	Octagonal prism
Power Source	Solar arrays, batteries
Prime Contractor	Ball Aerospace Systems Group (spacecraft)

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments	• G-1 through G-4: Diamagnetic Cavity, Unstable Velocity Distributions, Plasma Coupling PIs: Robert Hoffman, Goddard Space Flight Center; Steven Mende, Lockheed Palo Alto Research Labs Magnetic and solar storms inject plasma into the magnetosphere. The reaction of the natural magnetosphere to these injections is important to understanding energy and particle transport. Injections of barium ions simulate natural plasma injections in a precisely controlled manner. These four injections were at different altitudes and magnetic field strengths to understand how different regions of space react to artificial cloud plasmas. • G-5: Stimulated Electron Precipitation to Produce Auroras PI: Gerhard Haerendel, Max Planck Institut; Paul Bernhardt, Naval Research Laboratory Neil Brice proposed in 1970 that injections of artificial ion clouds in the Van Allen radiation belts would cause the high-energy charged particles to "unstick" from the magnetic field and crash into the atmosphere. Injecting artificial lithium plasma in a region of high-energy, trapped electrons, tested this theory. To search for artificial auroras created by these particles, observers with optical instruments and radars closely monitored the magnetic field line footprint where it entered the atmosphere in Canada and South America. • G-6: Stimulation of Ion-Cyclotron Waves and Artificial Ion Precipitation PI: Steven Mende, Lockheed Palo Alto Research Lab High-energy protons dominate the premidnight sector of the high-altitude magnetosphere. Some of these protons "leak out" of stable trapped orbits and precipitate into the atmosphere to cause a weak aurora. This experiment injected an artificial lithium plasma cloud into this proton region and measured any increased proton precipitation. This experiment had the same objectives as the previous electron experiment, except that the particles of interest were protons. The enhanced precipitation was detected by optical instruments at the base of the magnetic field line as these protons produced light in the distinct wavelengths of the hydrogen atom. The CRRES instruments monitored the state of the magnetosphere and helped determine the best time for the release.

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments	• G-7: Ion Tracing and Acceleration PI: William Peterson, Lockheed Palo Alto Research Lab The release of tracer lithium ions were tracked by instruments aboard NASA's Dynamics Explorer 1, the CRRES, Spacecraft Charging at High Altitudes (SCATHA), and the Japanese Akebono satellites. The previous two lithium releases could be used for this experiment, but this release was made when the relative positions of the satellites were favorable for observing the artificial tracer ions. • G-8: Gravitational Instability, Field Equipotentiality, Ambipolar Acceleration PI: Gernard Haerendel, Max Planck Institut Space plasmas often become highly irregular and structured. Electric and magnetic fields are important to this process, but less is known about the effects of gravity. For the light protons in the magnetosphere, it is safe to assume that the effect of gravity is negligible compared to electric and magnetic forces. For the heavier ions, such as oxygen and nitrogen, this assumption about gravity is questionable. This release created a heavy barium plasma along a magnetic field line, and the distortions due to gravity were studied with optical instruments and the radar at Jicamarca, Peru. • G-9: Velocity Distribution Relaxation and Field Equipotentiality PIs: Morris Pongratz, Los Alamos National Laboratory; Gene Wescott, University of Alaska The CRRES satellite released gas at orbital velocity, and the ion clouds formed moved very rapidly (8 km to 10 km per second [5 miles to 6.2 miles per hour]) relative to the natural ionosphere. This state is common in nature, occurring when beams of electrons enter the auroral zone or when material is pulled into a star. The beams eventually slow down; they do not slow through physical collisions between particles, as is the case with neutral gases. Instead, the long-range electrical and magnetic forces that act on the charged particles dominate the physics of beam-plasma interactions. The exact mechanisms of these interactions are not well understood. In this experiment, barium was released over an extensive network of ground and aircraft observatories in the Caribbean while instruments on the CRRES measured the electric and magnetic fields resulting from the interactions.

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments[b]	• G-10: Stimulating a Magnetospheric Substorm PI: David Simons, Los Alamos National Laboratory Sometimes during a magnetospheric substorm, a very large number of charged particles reach the atmosphere together, causing a very bright aurora. This experiment attempted to create a substorm by injecting an artificial barium plasma at the precise moment that the magnetosphere was unstable, "pushing the magnetosphere over the edge." Since barium ions could be seen glowing in sunlight (the particles normally cannot be seen), scientists could obtain a clear visual picture of magnetic substorm creation and behavior. • G-11, G-12: Mirror Force, Field Equipotentiality, Ambipolar Acceleration PI: Gene Wescott, University of Alaska As the release of barium ions flows along magnetic field lines, it will be affected by electric fields. By tracking the details of the ions' motion, these electric fields can be measured. Such electric fields are important in controlling inter-hemispheric flows of electrons and ions. The releases over the Caribbean filled the entire magnetic field line from the equator the other end in South America. Observations from ground and aircraft observatories in the Caribbean and South America pinpointed ion motion details. • G-13, G-14: Critical Velocity Ionization PI: Gene Wescott, University of Alaska The objective of these releases was to investigate the critical ionization velocity phenomenon, first proposed to explain mass differentiation in planetary formation—why the inner planets are made of heavy material and the outer planets are mostly hydrogen. The critical ionization velocity model states that if the relative velocity of electrically neutral chemical species and magnetized plasma is large enough, ionization of the neutral gas will take place even though the energy available is less than that required for ionization. Barium, calcium, and strontium were released in these experiments. These materials had a range of critical ionization velocities, allowing study of the effect over a wide range of this parameter.
Results	Successful mission until battery failure on October 12, 1991.

[a] Mission Operation Report, Report no. S-145-90-02, "USAF/NASA Combined Release and Radiation Effects Satellite," (NASA History Office Folder 5700).

[b] "Combined Release and Radiation Effects Satellite (CRRES) Press Kit," (NASA History Office Folder 5700)

Table 4–48. Hubble Space Telescope Mission Characteristics

Launch Date/Launch Site	April 25, 1990 / Kennedy Space Center
Date of Reentry	Operating as of mid-2005.
Launch Vehicle	STS-31/*Discovery*
NASA Role	• Marshall Space Flight Center: Development, assembly, and test; launch and deployment; on-orbit verification of system and science instrument functions. • Goddard Space Flight Center: Overall management of daily on-orbit operations; overall operational and servicing mission preparations; development, integration, and test of replacement hardware, space support equipment, and crew aids and tools. • Johnson Space Center: Astronaut training, Shuttle operations, overall mission management, and crew aids and tools. • Kennedy Space Center: Launch services, overall management of launch and post-orbit operations for mission hardware.
Responsible (Lead) Center	Marshall Space Flight Center; transferred to Goddard Space Flight Center when the Orbital Verification phase was nearing completion (about six months after launch).
Mission Objectives	Original science objectives: • To determine the constitution, physical characteristics, and dynamics of celestial bodies; the nature of processes occurring in stellar objectives; the history and evolution of the universe; and whether the laws of nature are universal in the space-time continuum.[a] SM1 objectives: • To restore planned scientific capabilities. • To restore reliability of vehicle systems. • To validate the on-orbit servicing concept for the Hubble Space Telescope. SM2 objectives: • To improve the telescope's productivity. • To extend the telescope's wavelength range into the near infrared for imaging and spectroscopy. • To greatly increase the efficiency of spectrographic science. • To replace failed or degraded spacecraft components.
Orbit Characteristics:[b]	
Apogee	569 km (307 nmi, 353 mi)
Perigee	569 km (307 nmi, 353 mi)
Inclination (deg)	28.5
Period (min)	97
Weight	24,500 lb (11,110 kg)

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Dimensions	Length: 43.5 ft (13.3 m) Diameter: 14.0 ft (4.3 m) with solar arrays stowed; 40.0 ft (12.0 m) with solar arrays deployed Solar array: 7.9 ft by 39.9 ft (2.4 m by 12.1 m)
Main Mirror Characteristics[c]	Diameter: 94.5 in (2.4 m) Weight: 1,825 lb (821 kg) Coating: 0.075 micron aluminum covered with 0.025 micron magnesium fluoride over 70 percent at hydrogen Lyman-Alpha Reflectivity: 70 percent in the UV wavelengths and greater than 85 percent at visible wavelengths
Shape	Cylindrical
Power Source	Solar arrays and nickel hydrogen batteries
Prime Contractor	Lockheed Martin; Ball Aerospace: science instruments for SM1 and SM2
Instruments and Experiments	Original instruments: • WFPC PI: James A. Westphal, California Institute of Technology The WFPC, built by JPL, was used to obtain high resolution images of astronomical objects across a relatively wide FOV and a broad range of wavelengths (1,150 angstroms to 11,000 angstroms). The WFPC enabled scientists to investigate the age of the universe and search for new planetary systems around young stars. The WFPC compared near and far galaxies and observed comets such as Halley's comet, which previously could be viewed only every 75 years. The WFPC was used in two ways: in wide-field mode, the FOV allowed pictures of hundreds of distant galaxies at once; and in planetary mode, the camera provided close-ups of all the planets in our solar system except Mercury, which is too close to the Sun for safe pointing. The WFPC observed larger areas of the sky and more varied forms of light (from far UV to near infrared) than other science instruments. Although the FOV of the telescope's WFPC was greater than that of other telescope instruments, the "wide field" was less than typical ground-based wide-field cameras, which have a FOV of around 5 degrees. This camera's FOV was only 2.67 arc minutes. The camera would take about 100 "wide-field" images to get a picture of the full Moon. The narrower FOV allowed much better resolution of distant objects.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• FOC PI: F. Duccio Macchetto, ESA/STScI The FOC extended the reach of the Hubble Space Telescope and produced the telescope's sharpest images. The FOC photographed stars five times farther away than ground-based telescopes. Many faint stars and galaxies appeared as blazing sources of light to the FOC. The FOC's primary use was to obtain images in more detail than the WFPC. The FOC had two complete detector systems. Each used an image intensifier tube to produce an image on a phosphor screen 100,000 times brighter than the light received. This phosphor image was then scanned by a sensitive electron-bombarded silicon (EBS) television camera and stored in the camera's memory for transmission to the ground. This system was so sensitive that objects brighter than 21st magnitude had to be dimmed by the camera's filter systems to avoid saturating the detectors. Even with a broadband filter, the brightest object that could be accurately measured was 20th magnitude.[d] The FOC helped determine the distance scale of the universe, peered into the centers of globular star clusters, photographed phenomena so faint they could not be detected from the ground, and studied binary stars (two stars so close together they appeared to be one). It was part of the ESA's contribution to the Hubble Space Telescope program. The FOC offered three focal ratios: f/48, f/96, and f/288 on a standard television picture format. The f/48 image measured 22 arc seconds by 22 arc seconds and yielded a resolution (pixel size) of 0.043 arc second. The f/96 mode provided an image of 11 arc seconds by 11 arc seconds on each side and a resolution of 0.022 arc second. The f/288 FOV was 3.6 arc seconds by 3.6 arc seconds, with resolution down to 0.0072 arc second. The FOC weighed 700 lb (318 kg) and was 3 ft by 3 ft by 7 ft (0.9 m by 0.9 m by 2.2 m) in size. The ESA, Dornier Systems, and Matra-Espace Corporation built the instrument.[e]

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• FOS PI: R.J. Harms, Applied Research Corp. (formerly with University of California, San Diego) The FOS spread out the light gathered by a telescope so it could be analyzed to determine properties of celestial objects. Properties of these celestial objects included their chemical composition and abundances, temperature, radial velocity, rotational velocity, and magnetic fields. The FOC also analyzed the properties of extremely faint objects in both visible and UV light. It studied the chemical properties of comets before they approached close enough to the Sun for their chemistry to be altered, as well as probing to see the composition of quasars. This instrument compared galaxies relatively near Earth with those at great distances, helping researchers determine the history of galaxies and the rate at which the universe was expanding. The FOS examined fainter objects than the GHRS and studied these objects across a much wider spectral range—from the UV (1,150 angstroms) through the visible red and the near-infrared (8,000 angstroms)—than the GHRS. The FOS could isolate individual light sources from those surrounding them at very great distances. Two occulting devices blocked out light from the center of an object while allowing the light from just outside the center to pass through. This allowed analysis of the shells of gas around red giant stars of the faint galaxies around a quasar. This instrument used two 512-element Digicon sensors (light intensifiers). The “blue” tube was sensitive from 1,150 angstroms to 5,500 angstroms (UV to yellow). The “red” tube was sensitive from 1,800 angstroms to 8,000 angstroms (longer UV through red). Light entered the FOS through any of 11 different apertures from 0.1 arc seconds to about 1.0 arc seconds in diameter. The FOS had two modes of operation: at low resolution, it could reach 26th magnitude in 1 hour with a resolving power of 250; and at high resolution, the FOS could reach only 22nd magnitude in 1 hour (before the signal-to-noise ratio became a problem), but the resolving power was increased to 1,300.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• GHRS PI: John C. Brandt, Jr., University of Colorado, Boulder The GHRS was the only science instrument devoted entirely to UV spectroscopy. In contrast to the FOS, the spectrograph's detectors were designed to be insensitive to visible light, since the UV emissions from stars were often hidden by the much brighter visible emissions and traded the extremely faint objects detected by FOS for the ability to analyze very fine spectral detail. The GHRS separated incoming light into spectral components so the composition, temperature, motion, and other chemical and physical properties of the objects could be analyzed. Like the FOS, the GHRS used two 521-channel Digicon electronic light detectors; however, the GHRS detectors were blind to visible light. One tube was sensitive from 1,050 angstroms to 1,700 angstroms, while the other was sensitive from 1,150 angstroms to 3,200 angstroms. The "high resolution" in this instrument's name refers to high spectral resolution, or the ability to study the chemical fingerprints of objects in very great detail. The combination of this spectral resolution with the high spatial resolution of the cameras allows scientists to determine the chemical nature, temperature, and density of the gas between stars. The spectrograph's investigations range from peering into the center of far-away quasars to analyzing the atmospheres of planets in our own solar system. The GHRS had three resolution modes: low, medium, and high. Low resolution was 2,000—higher than the best resolution available on the FOS. Examining a feature at 1,200 angstroms, the GHRS could resolve detail of 0.6 angstroms and examine objects down to 19th magnitude. At medium resolution of 20,000, that same spectral feature at 1,200 angstroms could be seen in detail down to 0.06 angstroms; however, the object must be brighter than 16th magnitude. High resolution was 100,000, allowing a spectral line at 1,200 angstroms to be resolved down to 0.012 angstroms. High resolution could be applied only to objects of 14th magnitude or brighter. The GHRS also could discriminate between variations in light from objects as rapid as 100 milliseconds apart.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• HSP PI: Robert C. Bless, University of Wisconsin, Madison The HSP, a simple but precise light meter, measured the brightness of objects being studied, as well as any variations in that brightness with time, in both visible and UV ranges. The photometer studied the smallest astronomical objects of any of the telescope's instruments. One of the photometer's tasks was to look for clues that black holes existed in binary star systems. Variations in brightness would occur as one star revolved around the other. Irregularities in variation might indicate that matter was being lost to a black hole—an object so dense that nothing, not even light, could escape from it. The photometer also provided astronomers with an accurate map of the magnitude of stars. • Fine Guidance Sensors: PI: William H. Jefferys, University of Texas, Austin The fine guidance sensors, built by Perkin-Elmer Corporation, were one of five different types of sensors used by the Hubble Space Telescope's pointing control system to point the telescope at a target. The three fine guidance sensors served a dual purpose. Two of the sensors locked on to reference stars to point the telescope to a precise position in the sky, and then held at that position with an accuracy of 0.01 arc second. The guidance sensors locked on to a star and then measured any apparent motion to an accuracy of 0.0028 arc second. This gave the Hubble Space Telescope the ability to remain pointed at the target with no more than 0.007 arc second of deviation during long periods of time. This level of stability was comparable to being able to hold a laser beam focused on a dime 200 miles (322 km) away (about the distance from Washington, DC to New York City). This sensor, in addition to serving as a backup unit, was used for astrometry—the science of measuring the angles between astronomical objects and determining precise positions and motions of stars and other celestial objects. These measurements were combined with information from other instruments to prepare a more accurate distance scale of the universe.[f] The fine guidance sensors could provide star positions about 10 times more precisely than those observed from a ground-based telescope. When used for astrometric science, the fine guidance sensors let the Hubble Space Telescope do the following:

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	— Search for the wobble in the motion of nearby stars that could indicate the presence of a planetary companion. — Determine if certain stars were really double stars. — Measure the masses of stars. — Measure the angular diameter of stars, galaxies, etc. — Refine the positions and the absolute magnitude scale for stars. — Help determine the true distance scale for the universe.[g] First Servicing Mission: • WFPC2 PI: John T. Trauger, California Institute of Technology WFPC2, built by JPL, was a spare instrument developed in 1985 by JPL in Pasadena, California. The WFPC2 replaced the original WFPC. WFPC 2 had four CCD cameras arranged to record simultaneous images in four separate FOVs at two magnifications.[h] The relay mirrors in WFPC2 were spherically aberrated to correct for the spherically aberrated primary mirror of the observatory. It observed in a wavelength from 1,200 angstroms to 10,000 angstroms.[i] The "heart" of WFPC2 consisted of an L-shaped trio of wide-field sensors and a smaller, high-resolution ("planetary") camera in the square's remaining corner.[j] The instrument weighed 619 lb (280 kg). The camera was 3.3 ft by 5 ft by 1.7 ft (1 m by 1.3 m by 0.5 m), and the radiator was 2.6 ft by 7 ft (0.8 m by 2.2 m). • COSTAR: The COSTAR, built by Ball Electro-Optics & Cryogenics Division, was not a science instrument; it was a corrective optics package that displaced the HSP during the first servicing mission. The COSTAR was designed to optically correct the effects of the primary mirror's aberration on the FOC. (All other instruments installed on later servicing missions were designed with their own corrective optics. When the FOC was replaced by another instrument, the COSTAR was no longer needed.) The COSTAR weighed 640 lb (290 kg) and was 3 ft by 3 ft by 7 ft (0.9 m by 0.9 m by 2.2 m). Second Servicing Mission: • STIS PI: Bruce E. Woodgate, Goddard Space Flight Center

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	The STIS, built by Ball Aerospace Systems Group, spanned UV, visible, and near infrared wavelengths. It separated the light gathered by the telescope into component colors, allowing scientists to analyze the composition of celestial objects, their temperature and motion, and other chemical and physical properties. The STIS's main advance was the capability for two-dimensional rather than one-dimensional spectroscopy. The STIS's two-dimensional detectors allowed the instrument to gather 30 times more spectral data and 500 times more spatial data than existing spectrographs on the Hubble Space Telescope, which looked at one place at a time. This capability recorded many regions in a planet's atmosphere or many stars within a galaxy in one exposure, making the Hubble Space Telescope faster and more efficient. One of the greatest STIS advantages was in the study of supermassive black holes. The STIS contained a new generation electronic light sensor called a Multi-Anode Microchannel Array (MAMA), as well as a CCD. The STIS's coronograph allowed it to search the environment of bright stars for very faint companion objects (possible planets). The STIS could also take UV images like a camera. The STIS could do the following: — Search for massive black holes by studying the star and gas dynamics around galactic centers. — Measure matter distribution in the universe by studying quasar absorption lines. — Use high sensitivity and ability to detect fine detail to study stars forming in distant galaxies. — Perform spectroscopic mapping—measuring chemical composition, temperature, gas density, and motion across planets, nebulae, and galaxies.The STIS was 2.2 m by 0.89 m by 0.89 m (7.1 ft by 2.9 ft by 2.9 ft) and weighed 318 kg (700 lb). Following installation and calibration, the STScI managed STIS operation.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• NICMOS PI: Rodger I. Thompson, University of Arizona The NICMOS, built by Ball Aerospace Systems Group and Rockwell International, provided the capability for infrared imaging and spectroscopic observations of astronomical targets. The NICMOS detectors performed better than previous infrared detectors. The NICMOS gave astronomers their first clear view of the universe at near-infrared wavelengths between 0.8 micrometers and 2.5 micrometers—longer wavelengths than the human eye could see. The expansion of the universe shifted the light from very distant objects to longer red and infrared wavelengths. The NICMOS's near-infrared capabilities provided views of objects too distant for research by current Hubble Space Telescope instruments that were sensitive only to optical and UV wavelength light. The NICMOS could do the following: — Probe objects created near the beginning of the universe. — Look deeper into clouds of dust to view how stars and planets were formed. — Detect cold objects, such as brown dwarfs, that emit light most brightly at infrared wavelength. The NICMOS contained three cameras, each with a different spatial resolution. Camera 1 had the highest resolution for very fine detailed pictures at shorter near-infrared wavelengths. Camera 2 had the next highest resolution for detailed pictures at longer wavelengths. Camera 3 had a much wider FOV to encompass extended objects at slightly lower resolution. Each camera had wheels of filters and optical components. The cameras could operate independently while others were taking images. As well as a camera, the NICMOS was a spectrometer, a coronograph, and a polarimeter. Each of these operational modes was initiated by rotating the proper element in a wheel containing filters and optical components into the camera beam. A combination of grating and a prism called a "grism" provided spectroscopy for the NICMOS. Polarizers in the wheel were rotated into place when observers wanted to determine the degree of polarization of radiation from a celestial object. One of the cameras had a special set of masks, called a coronograph, to block light from a bright object to observe an adjacent faint object, such as a faint planet near a bright star. The sensitive infrared detectors in the NICMOS must operate at very cold temperatures, 58 K (minus 355°F), because any surrounding heat would create extra infrared signals that interfered with the actual signal from the object being studied.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	The NICMOS kept its detectors cold inside a cryogenic dewar (a thermally insulated container) containing frozen nitrogen. The dewar cooled the detectors for up to five years. The NICMOS was the Hubble Space Telescope's first cryogenic instrument. The NICMOS was 2.2 m by 0.88m by 0.88 m (7.1 ft. by 2.8 ft by 2.8 ft) and weighed 390 kg (861 lb).[k] After installation and calibration, STScI managed the NICMOS.
Results	The Hubble Space Telescope enormously improved our understanding of the cosmos, from the universe's size, age, and fate, to the meteorology of planets; it also improved our understanding of stellar births and deaths. More importantly, the Hubble Space Telescope established itself as a premier observatory making discoveries at the forefront of astronomy and becoming "the public's premier gateway to science."[l] See science results above.

[a] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Report no. X 458-61-93-02, November 1993, p. 10 (NASA History Office Folder 005989).

[b] "Quick Facts," HubbleSite, Space Telescope Science Institute, *http://hubblesite.org/reference_desk/facts_.and._figures/quick_facts/quick_facts_2.shtml* (accessed September 7, 2005); The NSSDC Database gives the Hubble Space Telescope's apogee at 610.44 km and perigee at 586.5 km, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1990-037B-traj.html* (accessed September 7, 2005); The "SM2 Media Reference Guide," p 1-6, puts Hubble's orbit at 320 nmi (593 km), *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[c] "STS-31 Press Kit," April 1990, p. 31, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_035_STS-031R_Press_Kit.pdf* (accessed September 12, 2005). Also Chaisson, *The Hubble Wars*, p. 153; "Hubble Amazing Optics," *http://hubblesite.org/sci.d.tech/nuts_.and._bolts/optics/* (accessed April 26, 2006).

[d] "Overview of the Hubble Space Telescope," Space Telescope Science Institute, *http://www.stsci.edu/hst/HST_overview/* (accessed September 5, 2005).

[e] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[f] "STS-31 Press Kit," pp. 9, 11.

[g] "STS-82 Press Kit, Second Hubble Servicing Mission," February 1997, pp. 14–18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_082_STS-082_Press_Kit.pdf* (accessed September 5, 2005).

[h] "SM2 Media Guide," p. 4-19, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[i] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[j] "Space Shuttle Mission STS-82 Press Kit," February 1997, p. 27, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_082_STS-082_Press_Kit.pdf* (accessed September 12, 2005).

[k] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005). The STS-82 Press Kit gives the weight of NICMOS as 347 kg (765 lb).

[l] "The Hubble Space Telescope: Science in the First Decade," *http://hubblesite.org/discoveries/10th/vault/in-depth/science.shtml* (accessed May 8, 2006).

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics

Launch Date/Launch Site	April 5, 1991 / Kennedy Space Center
Date of Reentry	June 4, 2000
Launch Vehicle	STS-37/*Atlantis*
NASA Role	Project management of the observatory and communications, tracking, and data systems; BATSE and EGRET instruments
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	Primary objective: • To obtain two years of gamma-ray measurements (10 KeV to 30 GeV) covering close to the entire celestial sphere, with instruments providing an order-of-magnitude greater sensitivity and accuracy than previously flown gamma-ray missions. Secondary objectives: • To provide a uniform full-sky gamma-ray survey using wide-field imaging instruments and make selected high-priority observations using the narrow aperture and independently oriented instruments. • To provide guest investigators 30 percent of the observation time at the completion of Phase I (first 15 months) and 50 percent of the observation time at the completion of Phase II (an additional 12 months). Specific objectives:[b] • To study gamma-ray sources emitting in our galaxy and beyond. • To investigate evolutionary forces in neutron stars and black holes. • To perform detailed studies of nucleosynthesis. • To search for primordial black hole emissions.
Orbit Characteristics:	
Apogee	453 km (281 mi)
Perigee	448 km (278 mi)
Inclination (deg)	28.5
Period (min)	90
Weight	Fueled: 15,876 kg (35,000 lb)[c]
Dimensions[d]	Launch configuration: 7.72 m by 5.03 m by 4.62 m (25.3 ft by 16.5 ft by 15.2 ft) Orbit configuration (solar arrays and high gain antenna deployed): 9.5 m by 21.52 m by 9.24 m (31.2 ft by 70.6 ft by 30.3 ft) Solar array wing span: 21.52 m (70.6 ft)
Power Source	Solar arrays, three nickel cadmium batteries
Prime Contractor	TRW Space & Electronics Group

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Instruments and Experiments	• BATSE PI: Gerald J. Fishman, Marshall Space Flight Center The BATSE was the all-sky monitor for the observatory, detecting and locating strong transient sources, called gamma-ray bursts, as well as outbursts from other sources across the entire sky. There were eight BATSE detectors, one facing outward from each satellite corner, which were sensitive to gamma-ray energies from 20 keV to more than 1,000 keV. Sodium iodide (NaI) crystals at the heart of the BATSE detectors produced a flash of visible light when struck by gamma rays. The flashes were recorded by light-sensitive detectors whose output signal was digitized and analyzed to determine the arrival time and energy of the gamma ray causing the flash. Each BATSE detector unit consisted of a large-area detector sensitive to faint transient events along with a smaller detector optimized for spectroscopic studies of bright events.[e] • OSSE PI: James Kurfess, Naval Research Laboratory The OSSE consisted of four NaI scintillation detectors sensitive to energies from 50 keV to 10 MeV. Each of these detectors could be individually pointed. This allowed observations of a gamma-ray source to be alternated with observations of nearby background regions. An accurate subtraction of background contamination could then be made. The OSSE observed the energy spectrum of nuclear lines in solar flares, the radioactive decay of nuclei in supernova remnants, and the signature of matter-antimatter (electron-positron) annihilation in the galactic center region.[f] • The EGRET used high-voltage, gas-filled spark chambers to produce images at these high energies. High-energy gamma rays entered the chambers and produced an electron-positron pair of particles causing sparks. The path of the particles was recorded, allowing determination of the direction of the original gamma ray. The particle energies were recorded by a NaI crystal beneath the spark chambers that provided a measure of the original gamma-ray energy.[g]

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Instruments and Experiments	• COMPTEL PI: Volker Schönfelder, Max Planck Institute for Extraterrestrial Physics, Germany The COMPTEL used the Compton Effect and two layers of gamma-ray detectors to reconstruct an image of a gamma-ray source in the energy range from 1 MeV to 30 MeV. Gamma rays from active galaxies, radioactive supernova remnants, and diffuse gamma rays from giant molecular clouds could be studied with this instrument. A liquid scintillator that scattered an incoming gamma-ray photon according to the Compton Effect filled the COMPTEL's upper layer of detectors. This photon was then absorbed by NaI crystals in the lower detectors. The instrument recorded the time, location, and energy of the events in each layer of detectors, making it possible to determine the direction and energy of the original gamma-ray photon and reconstruct an image and energy spectrum of the source.[h] • EGRET PI: Carl E. Fichtel, Goddard Space Flight Center; R. Hofstadter, Stanford University; and K. Pinkau, Max Planck Institute for Extraterrestrial Physics, Germany The EGRET provided the highest energy gamma-ray window for the CGRO. The EGRET's energy range was from 20 million to 30 billion eV. The EGRET was 10 to 20 times larger and more sensitive than previous detectors operating at these high energies. The telescope observed high-energy processes associated with diffuse gamma-ray emissions; gamma-ray bursts; cosmic rays; pulsars; and active galaxies known as blazars.

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Results	The instruments on the CGRO made many discoveries, some expected and some surprising. Some of these discoveries were the following: • The discovery that a second class of gamma-ray-emitting active galactic nuclei, known as Seyfert galaxies, emitted most of their gamma rays at lower energies than previously thought was evidence that such objects might be the source of diffuse gamma rays. • The first detection of the presence and nuclear decay of cobalt 57, an isotope of cobalt thought to have been created during the explosion of a star known as Supernova 1987A, helped confirm the nucleosynthesis theory of how elements heavier than hydrogen and helium were formed and distributed in our galaxy through the evolution of stars. • The all-sky map produced by the EGRET was dominated by emission from interactions between cosmic rays and the interstellar gas along the plane of the Milky Way. Some point sources in this map were pulsars along the plane. Seven pulsars were known to emit in the gamma-ray portion of the spectrum, and five of these gamma-ray pulsars were discovered since CGRO launch. The Crab and Geminga pulsars were found near the galactic anticenter. One of the major EGRET discoveries was the class of objects known as blazars—quasars emitting the majority of their electromagnetic energy in the 30 MeV to 30 GeV portion of the spectrum. These objects, which were at cosmological distances, sometimes appeared to vary on timescales of days. • An all-sky map made by the COMPTEL illustrated the power of imaging in a narrow band of gamma-ray energy, in the light of radioactive aluminum 26. This map revealed unexpectedly high concentrations of radioactive aluminum 26 in small regions. In a COMPTEL image of the galactic anticenter, several interesting objects were visible, including two pulsars, a flaring black hole candidate, and a gamma-ray blazar. • In another map of the galactic center region, scanning observations made by the OSSE revealed gamma-ray radiation from the annihilation of positrons and electrons in the interstellar medium, another line emission. The OSSE recorded the spectrum of a solar flare, yielding direct evidence of accelerated particles smashing into material on the Sun’s surface, exciting nuclei then radiating in gamma rays.

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Results	• One of the BATSE's primary objectives was to study the phenomenon of gamma-ray bursts, brief flashes of gamma rays that occurred at unpredictable locations in the sky. The BATSE's all sky map of burst positions showed that, unlike galactic objects clustering near the plane or center of the galaxy, these bursts came from all directions. A cosmological origin (i.e., well beyond our galaxy) was now established. Burst light curves suggested a chaotic phenomenon was at work; no two have ever appeared exactly the same. An average light curve for bright and dim bursts was consistent with the explanation that bursts were at cosmological distances: the dim ones, which presumably were farther away, were stretched more in cosmic time than the bright ones, as the events participated in the general expansion of the universe. The BATSE also could image the sky, using Earth as an occulting disk, using a technique called Radon transforms.[i]

[a] "Gamma Ray Observatory Mission Operations Report," NASA Office of Space Science and Applications, Report no. E-S-458-31-91-01, p. 4 (NASA History Office Folder 30780).

[b] "GRO, Compton Gamma Ray Observatory Quicklook," JPL Mission and Spacecraft Library, *http://msl.jpl.nasa.gov/QuickLooks/groQL.html* (accessed August 11, 2005).

[c] "Compton Gamma-Ray Observatory," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-027B* (accessed August 31, 2005).

[d] Bob Soufl, GRO Description, May 21, 1991, via Martin Davis, Goddard Space Flight Center, e-mail received September 6, 2005.

[e] "The Burst And Transient Source Experiment (BATSE)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/batse.html* (accessed August 31, 2005).

[f] "The Oriented Scintillation Spectrometer Experiment (OSSE)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/osse.html* (accessed August 31, 2005).

[g] "The Energetic Gamma Ray Experiment Telescope (EGRET)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/egret.html* (accessed August 31, 2005).

[h] "The Imaging Compton Telescope (COMPTEL)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/comptel.html* (accessed August 31, 2005).

[i] "About the Compton Gamma Ray Observatory," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/cgro* (accessed August 31, 2005). Also Donna Drelick, "Compton Gamma Ray Observatory On Orbit Five Years," *Goddard News* 45 (April 1996): 3.

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics

Launch Date/Launch Site	July 23, 1999 / Kennedy Space Center
Date of Reentry	Currently operating
Launch Vehicle	STS-93/*Columbia*
NASA Role	Mission management
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives[a]	Science objectives:[b] • To determine the nature of celestial objects from normal stars to quasars. • To understand the nature of physical processes that take place in and between astronomical objects. • To understand the history and evolution of the universe. Program objective:[c] To address some of the most fundamental and pressing questions in present-day astrophysics through observations of matter at the extremes of temperature, density, and energy content. The Chandra mission scientific objectives are the following: • Determine the nature of celestial objects, from normal stars to quasars. • Understand the nature of physical processes that take place in and between astronomical objects. • Understand the history and evolution of the universe. The AXAF program objectives and philosophy are the following:[d] The objective of the AXAF program is to make fundamental scientific discoveries and contribute to our understanding of the universe through rigorous analysis and distribution of unique scientific data. The AXAF program will accomplish this objective by extending the range of astrophysical observations significantly beyond that of previous x-ray observatories through increases in sensitivity and resolution.
Orbit Characteristics:	
Apogee	140,161 km (86,900 mi)
Perigee	10,000 km (6,213 mi)
Inclination (deg)	28.5
Period	64 hours, 18 minutes
Weight	Dry: 4,800 kg (10,560 lb); total at launch: 12,930 lb
Dimensions	13.8 m by 19.5 m (45.3 ft by 64.0 ft) (solar arrays deployed)
Power Source	Solar arrays and nickel hydrogen batteries
Prime Contractor	TRW, Inc. (Northrop Grumman)

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• ACIS PI: Gordon Garmire, Pennsylvania State University One of two focal plane instruments, the ACIS is an array of charged coupled devices. This instrument can make x-ray images and, at the same time, measure the energy of each incoming x-ray. Thus, scientists can make pictures of objects using only x-rays produced by a single chemical element and compare, for example, the appearance of a supernova remnant in light produced by oxygen ions to that of neon or iron ions. The ACIS is the instrument of choice for studying temperature variations across x-ray sources such as vast clouds of hot gas in intergalactic space or chemical variations across clouds left by supernova explosions. • HRC PI: Stephen Murray, Harvard-Smithsonian Center for Astrophysics The HRC is one of two instruments used at the focus of the Chandra where it detects x-rays reflected from an assembly of eight mirrors. The camera's unique capabilities stem from the close match of its imaging capability to the focusing power of the mirrors. When used with the Chandra mirrors, the HRC can make images that reveal details as small as one-half an arc second. The HRC is especially useful for imaging hot matter in remnants of exploded stars, distant galaxies, and clusters of galaxies. The camera also is useful for identifying very faint sources. • The High Energy Transmission Grating Spectrometer and the Low Energy Transmission Grating Spectrometer

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• These spectrometers are dedicated to high-resolution spectroscopy. Each spectrometer is activated by swinging an assembly into position behind the mirrors. The assembly holds hundreds of gold transmission gratings; when in place behind the mirrors, the gratings intercept the x-rays reflected from the mirrors. These gratings diffract the intercepted x-rays, changing their direction by amounts that depend sensitively on the x-ray energy, much like a prism separates light into its component colors. One of the focal plane cameras, either the HRC or ACIS, detects the location of the diffracted x-ray, enabling a precise determination of its energy. The gratings exploit the Chandra's sharp mirror focus and matching detector resolution to produce high resolution x-ray spectroscopy. Since the grating spectrometers can measure energy to an accuracy of up to one part in a thousand, they are used to study detailed energy spectra, distinguishing individual x-ray lines. This enables the temperature, ionization, and chemical composition to be explored. • LETG PI: (Development) A.C. Brinkman, University of Utrecht; (Operations) Mariano Mendez, Netherlands Institute for Space Research The LETG is a freestanding gold grating made of fine wires or bars with a regular spacing, or period, of 1µm. The fine gold wires are held by two different support structures, a linear grid with 25.4-µm spacing and a coarse triangular mesh with 2-mm (0.08-in) spacing. The gratings are mounted on a toroidal ring structure matched to the Chandra mirrors. The LETG gratings are designed to cover an energy range from 0.08 keV to 2 keV. However, their diffraction can also be seen in visible light.

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• HETG PI: Claude R. Canizares, MIT Center for Space Research The HETGs have much finer periods, as follows: 0.2 μm or 2,000 angstroms for the high-energy gratings, and 0.4μm or 4,000 angstroms for the medium energy gratings. To distinguish between them, the two types of gratings are oriented at slightly different angles so that the x-rays are diffracted in an "X" pattern at the focal plane. Since the size of the gold grating bars is smaller than a wavelength of visible light, special fabrication techniques were required to make them. The gratings take advantage of the fact that the gold bars are partially transparent to x-rays, so that the diffraction is more efficient, and more x-rays are captured in the high-resolution spectrum. The HETG gratings are designed to cover an energy range from 0.4 to 10 keV.
Results	Successful launch in 1999 after more than 20 years of development.
Remarks	The Chandra is the world's most powerful x-ray telescope. With its inertial upper stage and support equipment, the Chandra was the largest and heaviest payload ever launched by the Space Shuttle. The Chandra's operating orbit is 200 times higher than the Hubble Space Telescope's orbit. On each orbit, the Chandra observatory travels one-third of the way to the Moon.

[a] E-mail from David Hood, NASA Marshall Space Flight Center, October 7, 2005.

[b] "Program Plan for Advanced X-ray Astrophysics Facility Design, Development, and Operations," April 17, 1997.

[c] "Program Commitment Agreement," Chandra X-ray Observatory, February 2003.

[d] "Advanced X-ray Astrophysics Facility Program Policy and Requirements Document, Level I," April 20, 1994.

Table 4–51. Ulysses Mission Milestones[a]

Date	Event
October 6, 1990	Launch on the Space Shuttle *Discovery*
December 30, 1990	1st opposition[b]
August 21, 1991	1st conjunction[c]
February 8, 1992	Jupiter closest approach
February 15, 1992	1st aphelion
February 27, 1992	2nd opposition
August 26, 1992	Maximum Earth range
September 2, 1992	2nd conjunction
March 1, 1993	3rd opposition
September 4, 1993	3rd conjunction
June 26, 1994	Start of first south polar pass
September 13, 1994	Maximum south solar latitude
November 5, 1994	End of first south polar pass
March 4, 1995	4th conjunction
March 12, 1995	1st perihelion
March 13, 1995	Ecliptic crossing
June 9, 1995	Minimum Earth range
June 19, 1995	Start of first north polar pass
July 31, 1995	Maximum north solar latitude
September 29, 1995	End of first north polar pass
February 24, 1997	4th opposition
August 30, 1997	5th conjunction
February 26, 1998	5th opposition
April 17, 1998	2nd aphelion
May 9, 1998	Ecliptic crossing
August 28, 1998	Maximum Earth range
September 1, 1998	6th conjunction

[a] "Ulysses Mission Milestones," *http://ulysses-ops.jpl.esa.int/ulsfct/milestones1.html* (accessed August 25, 2005).

[b] The term *opposition* describes an alignment of Earth, the Sun, and spacecraft with Earth in the middle.

[c] The term *conjunction* as used in the Ulysses mission refers to a "superior conjunction," an alignment of Earth, the Sun, and spacecraft with the Sun in the middle and Earth and spacecraft on opposite sides of it.

Table 4–52. Ulysses Mission Characteristics

Launch Date/Launch Site	October 6, 1990 / Kennedy Space Center
Date of Reentry	Mission ended July 1, 2008.
Launch Vehicle	STS-41/*Discovery*
NASA Role	Launch vehicle and launch support, inertial upper stage, payload assist module
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Primary mission objective: • To investigate for the first time, as a function of solar latitude, the properties of the solar wind; the structure of the Sun/wind interface; the heliospheric magnetic field; solar radio bursts and plasma waves; solar x-rays; solar and galactic cosmic rays; and interstellar interplanetary neutral gas and dust. Secondary objectives: • To conduct interplanetary-physics investigations during the in-ecliptic Earth-Jupiter phase; measure the Jovian magnetosphere during the Jupiter flyby phase; detect cosmic gamma-ray bursts; and search for gravitational waves from cataclysmic cosmic events. Science objectives: • To provide an accurate assessment of the global three-dimensional properties of the interplanetary magnetic field and the solar wind. • To improve our knowledge of the composition of the solar atmosphere and the origin and acceleration of the solar wind by systematically studying the composition of the solar-wind plasma and solar energetic particles at different heliographic latitudes. • To provide new insight into the acceleration of energetic particles in solar flares and into the storage and transport of these particles in the corona by observing the x-ray and particle emission from solar active regions and from other magnetic configurations that are more accessible for study from out-of-the-ecliptic. • To further our knowledge of the internal dynamics of the solar wind; our knowledge of the waves, shocks, and other discontinuities; and our knowledge of the heliospheric propagation and acceleration of energetic particles by sampling plasma conditions expected to differ from those available for study near the ecliptic. • To improve our understanding of the spectra and composition of galactic cosmic rays in interstellar space by measuring the solar modulation of these particles as a function of heliographic latitude and by sampling these particles over the solar poles, where low-energy cosmic rays may have easier access to the inner solar system than near the ecliptic plane.

Table 4–52. Ulysses Mission Characteristics (Continued)

Mission Objectives[a]	• To advance our knowledge of the neutral component of interstellar gas by measuring, as a function of heliographic latitude, the properties and distribution of neutral gas entering the heliosphere. • To improve our knowledge of interplanetary dust by measuring its properties and distribution as a function of heliographic latitude. • To search for gamma-ray burst sources and, in conjunction with other spacecraft observations, identify these sourced with known celestial objects or phenomena. • To search for low-frequency gravitational waves by recording very precise two-way Doppler tracking data at the ground stations.
Orbit Characteristics	Solar orbit inclined at 80 degrees to the ecliptic plane
Period	6.2 years around the Sun[b]
Weight	366.7 kg (808.4 lb) total at launch; scientific payload: 55.1 kg (121.5 lb)[c]
Dimensions	Length: 3.2 m (10.5 ft), width: 3.3 m (10.8 ft) (booms stowed), height: 2.1 m (6.9 ft)
Power Source	Radioisotope thermoelectric generator
Prime Contractor	Dornier Systems
Instruments and Experiments	• Magnetic Fields Experiment (VHM/FGM) PI: Andrew Balogh, Imperial College, the United Kingdom This experiment determined the large-scale features and gradients of the field, as well as the heliolatitude dependence of interplanetary phenomena so far only observed near the ecliptic plane. The magnetometer used two sensors, a Vector Helium Magnetometer and a Fluxgate Magnetometer. On-board data processing yielded measurements of the magnetic field vector with a time resolution up to two vectors per second and a sensitivity of about l0 pT. • Solar Wind Plasma (SWOOPS) Experiment PI: D.J. McComas, Los Alamos National Laboratory This experiment detected and analyzed particles in the solar wind to determine variations in the particles from the equator to the poles. It determined how the solar wind changed as a function of distance from the Sun and distance from the ecliptic plane. While traveling along its flight path, the SWOOPS Experiment also measured local changes in the number and energy of particles as the solar wind blew past Ulysses. The instrument measured how the properties of the solar wind differed between low and high latitudes. The instrument traced the solar wind back to its place of origin more easily at the poles than at the equator. It observed particles in the energy range from 1 eV to 35,000 eV.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• SWICS PIs: George Sloeckler, University of Maryland and Johannes Geiss, Universitt, Switzerland The SWICS determined the elemental and ionic-charge composition and the temperatures and mean speeds of all major solar-wind ions, from hydrogen through iron, at solar wind speeds ranging from 175 km/s to 1,280 km/s (109 mi/s to 795 mi/s). The instrument, which covered an energy-per-charge range from 0.16 keV/e to 59.6 keV/e in approximately 13 minutes, combined an electrostatic analyzer with post-acceleration, followed by a time-of-flight and energy measurement. • Unified Radio and Plasma Wave (URAP) Investigation: PI: R.J. MacDowall Goddard Space Flight Center The URAP Investigation determined the direction, angular size, and polarization of radio sources for remote sensing of the heliosphere and the Jovian magnetosphere. The investigation also conducted a detailed study of local wave phenomena, which determine the transport coefficients of the ambient plasma. The URAP Investigation sensors consisted of a 72.5-m (237.9-ft) electric field antenna in the spin plane, a 7.5-m (24.6-ft) electric field monopole along the spin axis, and a pair of orthogonal search coil magnetic antennae. The various receivers, designed to encompass specific needs of the investigation, covered the frequency range from dc to l MHz. A relaxation sounder provided very accurate electron density measurements. • Energetic Particle Composition and Neutral Gas Experiment (EPAC)[d] PI: Erhardt Keppler, Max Planck Institut für Aeronomie, Germany The EPAC provided information on the relative abundances; energies; direction of travel; and chemical composition of medium-energy charged particles in interplanetary space. The EPAC consisted of four identical telescopes inclined at angles of 22.5°, 67.5°, 112.5°, and 157.5° with respect to the spacecraft spin axis. Each telescope's FOV was 35° full angle. A separate instrument detected neutral helium atoms entering the solar system from interstellar space and determined their speed; direction of arrival; temperature; and density.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies (HI-SCALE) PI: Louis J. Lanzerotti, Bell Laboratories, Lucent Technologies The HI-SCALE measured interplanetary ions and electrons during the entire mission. Ions and electrons were identified uniquely and detected by five separate solid-state detector telescopes oriented to give nearly complete pitch-angle coverage from the spinning spacecraft. Ion elemental abundances were determined by a delta E vs. E telescope using a thin (5-micron) front-facing solid state detector element in a three-element telescope. A microprocessor-based data system controlled experiment operation. Inflight calibration was provided by radioactive sources mounted on telescope covers that could be closed for calibration purposes and for radiation protection during the mission. Ion and electron spectral information was determined using both broad-energy-range rate channels and a 32-channel pulse-height analyzer for more detailed spectra. The instrument weighed 5.775 kg (12.7 lb) and used 4.0 W of power. • Cosmic Ray and Solar Particle Investigation (COSPIN) PI: R.B. McKibben, University of Chicago The COSPIN consisted of a group of six charged-particle telescopes to measure the energy, composition, intensity, and anisotropy of nucleons in the energy range from ~0.5 MeV/nucleon to ~600 MeV/nucleon for elements in the range H to Ni. Isotopic abundances for nuclei H to Ni were obtained over a more limited energy range. Electron measurements extended from 2.5 MeV to 6,000 MeV. One set of telescopes measured the three-dimensional anisotropies of protons and helium at low energies. A special high-flux telescope provided measurements of protons and heavier particles ~0.2 MeV to ~36 MeV with high azimuthal resolution. An international consortium prepared these instruments to address a wide range of scientific objectives.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Solar X-rays and Cosmic Gamma Ray Bursts PI: Kevin Hurley, University of California, Berkeley This experiment detected x-rays emitted sporadically from the vicinity of solar active regions. Although solar x-rays were observed for many years by spacecraft above Earth's atmosphere, the altitude in the solar atmosphere at which the radiation was emitted and its directivity, which would help identify the source mechanism, were unknown. As Ulysses traveled poleward, the Sun blocked radiation at low altitudes and affected how the intensity varied with direction to the source. Cosmic gamma-ray bursts were detected about 20 years ago, but their origin remained obscure. By accurately timing their arrival at Ulysses and at Earth, their source location could be pinpointed to see what astrophysical objects or bodies gave rise to them. • Dust Experiment (DUST) PI: Eberhard Grün, Max Planck Institut für Kernphysik, Germany The DUST directly observed dust grains with masses between 10^{-16} g and 10^{-6} g in interplanetary space to investigate their physical and dynamical properties as functions of heliocentric distance and ecliptic latitude. Of special interest was the question of what portion was provided by comets, asteroids, and interstellar particles. The investigation was performed with an instrument measuring the mass, speed, flight direction, and electric charge of individual dust particles. The instrument was a multicoincidence detector with a mass sensitivity 10^6 times higher than that of previous *in situ* experiments that measured dust in the outer solar system. The instrument weighed 3.8 kg (8.4 lb), consumed 2.2 W, and had a normal data transmission rate of 8 bits/s in nominal spacecraft tracking mode. • Coronal-Sounding Experiment (SCE) PI: M.K. Bird, University of Bonn, Germany The SCE used established coronal-sounding techniques to derive the plasma parameters of the solar atmosphere. Applying appropriate model assumptions, the three-dimensional electron density distribution was determined from dual-frequency ranging and Doppler measurements recorded at the NASA Deep Space Network (DSN) during solar conjunctions. Multistation observations were used to derive the plasma bulk velocity at solar distances where the solar wind was expected to undergo its greatest acceleration. As a secondary objective profiting from the favorable geometry during the Jupiter encounter, radio-sounding measurements yielded a unique cross-scan of electron density in the Io Plasma Torus.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Gravitational Waves Experiment (GWE) PI: Bruno Bertotti, Universita di Pavia, Italy The GWE used the Ulysses radio transmitter for scientific purposes. According to Einstein's theory of relativity, the motion of large masses in the universe—such as those associated with the formation of black holes—should cause the radiation of gravitational waves. Though such waves had yet to be detected, they could be observed through their effect on the spacecraft, which was expected to undergo a slight perturbation that might be detected as a shift in frequency of the Ulysses radio signal. Interdisciplinary topics:[e] • Directional Discontinuities Team Leader: Joseph Lemaire, Institut d'Aeronomie Spatiale de Belgique, Belgium This experiment compared Ulysses measurements of solar-wind plasma and magnetic field regions to theoretical models. • Mass Loss and Ion Composition Team Leader: Giancarlo Noci, Istituto de Astronomia, Italy This experiment combined measurements of the solar wind and magnetic field to study the mass and angular momentum lost by the Sun in the equatorial and polar regions. The experiment also studied the dependence of the solar wind composition on solar latitude.
Results	Ulysses explored the solar wind from all angles, producing the first three-dimensional picture of the heliosphere. The mission found that the wind from the cooler regions close to the Sun's poles fans out to fill two-thirds of the heliosphere and blows at a uniform speed of 750 km/s (466 mi/s), much faster than the 350 km/s (217 mi/s) wind that emerges from the Sun's equatorial zone. Ulysses was the first spacecraft to survey the Sun's southern and northern polar regions.[f] See the narrative above for further mission results.

[a] "Ulysses Mission Operation Report," Report no. S-448-41-90-01, October 4, 1990 (NASA History Office Electronic Document, Record no. 30797).

[b] "Ulysses Orbit/Navigation," European Space Agency, *http://helio.estec.esa.nl/ulysses/resources_galleryorbit.html* (accessed August 25, 2005).

[c] "Ulysses Datasheet," *http://ulysses-ops.jpl.esa.int/ulsfct/datasheet.html* (accessed August 25, 2005).

[d] Title of experiment as given in "Space Shuttle Mission STS-41 Press Kit," October 1990, p. 15. Title of experiment is given as "Energetic Particle Composition and Interstellar Gas" in the "Ulysses Mission Operation Report," Office of Space Science and Applications, Report no. S-448-41-90-01, October 4, 1990.

[e] "STS-41 Press Kit," p. 17.

[f] "Ulysses Overview," *http://www.esa.int/esaSC/120395_index_0_m.html* (accessed October 20, 2005).

Table 4–53. ASCA/Astro-D Mission Characteristics

Launch Date/Launch Site	February 20, 1993 / Kagoshima Space Center, Japan
Date of Reentry	March 2, 2001; lost attitude control on July 14, 2000, during a geomagnetic storm, ending scientific observations.
Launch Vehicle	ISAS M-3S-II
NASA Role	Provided four telescope mirrors and two x-ray CCD solid state detectors; telemetry tracking support via the DSN; pre-mission test support and mission support
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To examine a variety of x-ray sources with moderate spatial and spectral resolution at energies from 1 keV to 12 keV, with particular emphasis on the iron K band near 6 keV. • To study the structure of extended sources such as clusters of galaxies and supernova remnants. • To determine temperatures and elemental abundances in astrophysical sources through the measurement of spectral features.
Orbit Characteristics:	
Apogee	500 km (311 mi)
Perigee	600 km (373 mi)
Inclination (deg)	31.5
Period (min)	95
Weight	417 kg (919 lb)
Dimensions	4.7 m (15.4 ft) along the telescope axis, 3.5 m (11.5 ft) across the solar paddles
Power Source	Solar panels and batteries
Prime Contractor	NEC under contract to the ISAS
Instruments and Experiments	• XRT (4) PI: Peter Serlemitsos, Goddard Space Flight Center The ASCA XRTs were lightweight versions of similar mirrors flown earlier on the Broad Band X-ray Telescope (BBXRT) experiment aboard NASA's Astro-1 Shuttle mission.[b] Two identical XRTs worked in conjunction with GISs and two worked with SISs. The XRTs were developed by the ISAS and used four sets of multi-nested thin-foil conical reflectors provided by NASA.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Instruments and Experiments	Each conical foil, x-ray mirror on the ASCA consisted of 120 nested, gold-coated, aluminum foil surfaces. The conical geometry approximated of the more precise Wolter type I geometry for grazing incidence mirrors; this was crucial because it allowed the mirrors to be constructed of thin foil. The mirror technology provided a large throughput through high energies. The effective area was greater than 1,000 cm^2 below 2 keV and greater than 500 cm^2 around 6 keV to 7 keV.[c] The mirrors were equipped with heating elements to elevate their mean temperature in orbit; this ensured that the reflecting surfaces remained free of any condensable materials that might escape from the rest of the spacecraft and guarded against large thermal gradients across the mirror structure that could defocus the mirror. Additionally, very thin (0.22 m (0.7 ft) and 0.54 m (1.8 ft) for the SIS and GIS detectors, respectively) aluminized mylar thermal covers were fastened over the entire mirror aperture. The mirrors were mounted on an extendable optical bench that was commanded to extend 1,200 mm (47 in) after launch to increase the mirror-to-detector distance to the nominal 3,500 mm (138 in) focal length. During integration at the spacecraft, the fields of view of the four telescopes were co-aligned to within less than 1 arc minute.[d] • GIS (2)[e] PI: Kazuo Makishima, University of Tokyo The two GISs were imaging gas scintillation proportional counters, each with a gas cell and a photon-sensitive phototube. They were based on the gas scintillation proportional counter that flew on Japan's second x-ray astronomy mission TENMA. The gas cell was filled with a mixture of 90 percent xenon and 10 percent helium, and it had a front window made of beryllium 10 microns thick. The phototube had a quartz window 7.5 cm (2.9 in) thick and 10-stage dynodes. The area sensitive to x-rays was 50 mm (2 in) in diameter. It had an energy range from 0.7 keV to 10 keV, energy resolution of 8 percent at 5.8 keV, and a circular FOV with a diameter of 50 arc minutes. Scientists and engineers at Tokyo University built the GIS.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Instruments and Experiments	• SIS (2) PI: George Ricker, Massachusetts Institute of Technology The two SISs were identical independent CCD camera systems provided by a hardware team from MIT, Osaka University, and the ISAS. Each module had a hybrid CCD at the focus of a grazing incidence thin-foil telescope. Each camera was based around four 420-pixel by 422-pixel CCD chips, abutted side-by-side, front-side illuminated, and operated in frame-store configuration. The SIS had an energy range of 0.4 keV to 10 keV; its energy resolution was 2 percent at 5.9 keV. The SIS had a 22-arc minute by 22-arc minute square FOV.[f]
Results	The ASCA scientists made significant discoveries relating to magnetars, black holes, and cosmic rays. • The discovery of a neutron star, located 40,000 light years from Earth, confirmed the existence of a special class of neutron stars called “magnetars,” objects with magnetic fields estimated to be one thousand trillion times the strength of Earth’s magnetic field. The finding should help astronomers better calculate the rate at which stars die and create the heavier elements that later become planets and other stars.[g] • Measurements made with the ASCA, as well as with other satellites, contributed to evidence that some recently discovered black holes “vacuum up” energy from their surroundings through their “event horizons,” the one-way membrane around black holes predicted by Einstein’s theory of relativity. Analysis of a particular x-ray nova called V404 Cyg indicated that the star seemed to be swallowing nearly a hundred times more energy than it radiated, and the only way this could happen was if the star was a true black hole. This was the most real, direct evidence of black holes that scientists have had.[h] Astronomers working with ASCA data found an indicator of the rate at which giant black holes at the centers of distant galaxies were swallowing matter from their surroundings. The indicator consisted of x-ray emissions from very energetic iron atoms swirling in toward the edge of the black hole.[i]

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Results	• Physicists from Japan and the United States used ASCA data to discover a possible solution to the puzzle of the origin of high-energy cosmic rays that bombard Earth from all directions in space. They found what they termed "the first strong observational evidence" for the production of these particles in the shock wave of a supernova remnant, the expanding fireball produced by the explosion of a star. The investigators used the satellite to determine that cosmic rays were generated at a high rate in the remains of the supernova discovered in the year 1006 AD, which appeared to medieval viewers to be as bright as the Moon. They determined that the cosmic rays were accelerated to high velocities by a process first suggested by the nuclear physicist Enrico Fermi in 1949.[j] Scientific discoveries were made in the following areas:[k] • Origin of the diffuse x-ray background. • Active galactic nuclei including the first direct detection of relativistic line broadening of an x-ray emission line in an active galactic nucleus, indicating that the observed iron K line radiation emanated from within tens of Schwarzschild radii of the massive central object. Also detected x-ray emissions from the radio lobes of Fornax A and Centaurus B. • Clusters of galaxies including highly robust determinations of the mass of clusters of galaxies and the demonstration that most of the intracluster gas in rich clusters had been processed by Type II supernovae at early epochs. • Galaxies (and galactic center) including the discovery that metal abundances in the gas haloes of elliptical galaxies were sub-solar with, in the few cases measured so far, a decrease in abundance with radius. Also evidence that the center of the Milky Way was filled with ionized hot gas whose heating mechanism remains unknown. • Supernova remnants including the measurement, using images in prominent x-ray emission lines, of significant variation in supernova remnants of both ionization and chemical composition as a function of position, as well as coherent velocity features directly measuring the expansion of the ejecta; the identification of a site of cosmic ray acceleration in the supernova remnant SN1006. • Stars including measurements of abundances in the coronae of active stars suggesting metal deficiencies when compared to photospheric abundances. Also the unexpected discovery of hard x-ray emissions, including a flare, from class I protostellar candidates.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Results	• X-ray binaries including the discovery of a ~30 msec period in Cen X-4, demonstrating the theoretically predicted link between low-mass x-ray binaries and radio millisecond pulsars. • Cataclysmic variables and supersoft sources. • Gamma-ray bursts including the identification of a soft gamma-ray repeater with a neutron star in a supernova remnant.

[a] "ASTRO-D Mission Operation Report," Report no. S-689-93-01 (NASA History Office Folder 5670).

[b] Peter J. Serlemitsos and Hideyo Kunieda, "The ASCA Mirrors," *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mirrors1.html* (accessed August 29, 2005).

[c] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, pp. 6–7 (NASA History Office Folder 5670).

[d] Peter J. Serlemitsos and Hiedyo Kunieda, "The ASCA Mirrors," *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mirrors1.html* (accessed May 4, 2006).

[e] "ASCA's Gas Imaging Spectrometers," *http://agile.gsfc.nasa.gov/docs/asca/asca_gis.html* (accessed August 29, 2005). PIs provided by Nicholas White, ASCA Project Scientist, in an e-mail, May 3, 2006.

[f] "ASCA's Solid-state Imaging Spectrometers," *http://agile.gsfc.nasa.gov/docs/asca/asca_sis.html* (accessed September 26, 2005).

[g] "Strongest Stellar Magnetic Field Yet Observed Confirms Existence of Magnetars," *NASA News* Release 98-87, May 20, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-087.txt* (accessed May 4, 2006).

[h] "Astronomers Closing in on Black Holes," Harvard–Smithsonian Center for Astrophysics, (no date), *http://sao-www.harvard.edu/blackhole/index.html* (accessed September 25, 2005).

[i] "Astronomers Discover Indicator That Reveals Rate of Matter Consumption by Enormous Black Holes," ASCA Guest Observer Facility, Release no. 97-141, October 27, 1997, *http://heasarc.gsfc.nasa.gov/docs/asca/science/nandra.html* (accessed September 26, 2005).

[j] "Cosmic Ray Mystery May Be Solved," *NASA News* Release 95-208, November 21, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-208.txt* (accessed September 25, 2005).

[k] K.A. Arnaud et al, "ASCA Science Highlights," *http://legacy.gsfc.nasa.gov/docs/asca/science/science.html* (accessed August 29, 2005).

Table 4–54. BeppoSAX Mission Characteristics

Launch Date/Launch Site	April 30, 1996 / Cape Canaveral
Date of Reentry	Reentered April 29, 2003, based on American Space Surveillance Network assessment; switched off April 11, 2002.[a]
Launch Vehicle	Atlas-Centaur
NASA Role	Launch vehicle and launch site, data archive
Mission Objectives	Scientific objectives:[b] • To observe x-ray sources in the range from 0.1 keV to 300 keV over a relatively large area. • To monitor large regions of the sky with a resolution of 5 arc minutes in the range from 2 keV to 30 keV to study long-term variability of sources down to 1 mCrab; also to detect x-ray transient phenomena.
Orbit Characteristics:	
Apogee	594 km (369 mi)
Perigee	575 km (357 mi)
Inclination (deg)	3.9
Period (min)	96.4
Weight	900 kg (1,984 lb) (on-orbit dry mass), 1,400 kg (3,086 lb) total
Dimensions	Diameter: 2.7 m (8.9 ft) (solar panels closed); height: 3.6 m (11.8 ft)
Power Source	Solar panels
Prime Contractor	Alena Spazio (space segment) Telespazio (ground segment)
Instruments and Experiments	• Narrow Field Instruments: Four x-ray imaging concentrators sensitive from 1 keV to 10 keV (one extending down to 0.1 keV). The instrumentation consisted of the following: — Medium Energy Concentrator Spectrometer (MECS): Medium-energy set (from 1.3 keV to 10 keV) of three identical grazing-incidence telescopes with double cone geometry. The effective area was a total of 150 cm^2 (23 sq in) at 6 keV; the FOV was 56 arc minutes in diameter, and the angular resolution for 50 percent total signal radius was 75 arc seconds at 6 keV. — Low Energy Concentrator Spectrometer (LECS): Low-energy (from 0.1 keV to 10 keV) telescope, identical to the other three but with a thin window position sensitive gas scintillation proportional counter in its focal plane; the effective area was 22 cm^2 (3.4 sq in) at 0.28 keV; the FOV was 37 arc minutes diameter, and the angular resolution was 9.7 arc minutes at 0.28 keV.

Table 4–54. BeppoSAX Mission Characteristics (Continued)

Instruments and Experiments	— High Pressure Gas Scintillator Proportional Counter: Energy from 4 keV to 120 keV; the effective area was 240 cm^2 (37 sq in) at 30 keV. • Phoswich Detection System (PDS): Had a range of 15 keV to 300 keV. The lateral shields of the PDS were used as a gamma-ray burst monitor in the range from 60 keV to 600 keV. The effective area was 600 cm^2 (93 sq in) at 80 keV • WFCs: Two cameras ranged from 2 keV to 30 keV with FOVs of 20 degrees by 20 degrees. The WFCs were perpendicular to the axis of the narrow field instruments and pointed in opposite directions to each other. The effective area was 140 cm^2 (22 sq in).
Results	During its six years of active life, BeppoSAX made 30,720 contacts with the ESA's Malindi ground station in Kenya and performed nearly 1,500 observations of most types of cosmic sources, discovering more than 50 gamma-ray bursts.

[a] "BeppoSAX Status," *http://heasarc.gsfc.nasa.gov/docs/sax/email/sax_status.html#11apr2002* (accessed August 3, 2005).

[b] "BeppoSAX Mission Outline," The BeppoSAX Science Data Center, *http://bepposax.gsfc.nasa.gov/bepposax/scientificase.html* (accessed August 3, 2005).

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics

Launch Date/Launch Site	October 24, 1998 / Cape Canaveral Air Station
Date of Reentry	Deep Space 1 mission ended December 18, 2001, when transmitter was turned off.
Launch Vehicle	Delta II 7326 (first use of this model)
NASA Role	Project management
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Deep Space 1: To test 12 advanced technologies in deep space; to lower the cost and risk to future science-driven missions using the technologies for the first time.
Orbit Characteristics	Deep space orbit
Weight	Deep Space 1: Total: 486.3 kg (1,072.1 lb), spacecraft: 373.4 kg (823.2 lb), hydrazine: 31.1 kg (68.6 lb), xenon: 81.5 kg (179.7 lb)
Dimensions	Deep Space 1: Bus: 1.1 m by 1.1 m by 1.5 m (3.6 ft by 3.6 ft by 4.9 ft) With instruments and systems attached: 2.5 m (8.2 ft) high, 2.1 m (6.9 ft) deep, 1.7 m (5.5 ft) wide Solar panels: 11.75 m (38.5 ft) deployed
Shape	Octagonal
Power Source	Solar panels and batteries
Prime Contractor	Spacecraft: Spectrum Astro, Inc. Engine: Hughes Electron Dynamics Division, Spectrum Astro, Inc.
Instruments and Experiments	Advanced Technologies: • Solar Electric Ion Propulsion System Developed by Hughes Electron Dynamics Division, Spectrum Astro, Inc., Moog, Inc., and Physical Science, Inc. Unlike chemical rocket engines, ion engines accelerate nearly continuously, giving each ion a tremendous burst of speed. The Deep Space 1 Ion Propulsion System engine provided about 10 times the specific impulse (ratio of thrust to propellant used) of chemical propulsion. — Diagnostic Subsystem PI: Karl-Heinz Glassmeier The primary objective was to monitor and characterize the induced environment around the spacecraft created by the Ion Propulsion System and its interaction with the space environment.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments	• Solar Concentrator Arrays Developed by AEC-Able Engineering, Inc., Entech, Lewis Research Center, and JPL The arrays provided power to the ion engine more efficiently than conventional arrays and costed and weighed less. The array had to work correctly immediately after launch for the mission to proceed because stored battery energy was sufficient only for a few hours. Autonomy • Autonomous Optical Navigation Developed by JPL This navigation system computed and corrected the spacecraft's course using images of asteroids and stars collected by the on-board camera system. Earlier spacecraft navigation systems relied on human controllers on Earth. • Beacon Monitor Operations Developed by JPL This technology will eventually reduce the need for mission controllers on Earth to monitor the health of the spacecraft at all times. The spacecraft's beacon monitor could beam one of four signals to Earth summarizing its status and indicating the urgency of need for human intervention. • Autonomous Operations System (Remote Agent) Developed by Ames Research Center, JPL, and Carnegie Mellon University This system was composed of an "agent" that could plan, make decisions, and operate by itself. Sophisticated software was programmed into the spacecraft's computer to allow it to think and act on its own without human intervention or guidance. The agent also knew when a failure had occurred, what to do about it, and when to call for help. Science Instruments • Miniature Camera and Imaging Spectrometer PI: Lawrence A. Soderblom, U.S. Geological Survey This instrument was about 10 times less in mass, cost, and power consumption than conventional instruments performing similar tasks. Comparative imaging was done with a standard CCD and a new active pixel sensor, which integrated the electronics and detector on a fingernail-sized chip. The mass of this instrument, which was considered a space physics package, was less than 25 percent of currently used comparable instruments. The instrument required about 50 percent less power than conventional instruments.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments	• Plasma Experiment for Planetary Exploration (PEPE) PI: David T. Young, Southwest Research Institute This multiple-instrument package measured the three-dimensional mass-resolved plasma distribution. The PEPE collected scientific data during cruise and asteroid encounter; measured the effects induced by the ion propulsion system on the space environment, including interactions with the solar wind and on spacecraft surfaces and instruments; and validated new plasma sensor technologies for use on future flights. The PEPE was mounted on the edge of the octagonal top of Deep Space 1. Telecommunications • Small Deep-Space Transponder Developed by Motorola Government Space System This was a miniaturized 3.2-kg (7-lb) transponder combining receiver, command detector, telemetry modulation exciters, beacon tone generation, and control functions. The transponder received and transmitted in the microwave X-band and transmitted in the higher-frequency Ka-band. The transponder's small size and low mass was enabled by the use of advanced gallium arsenide monolithic microwave integrated-circuit chips, high-density packaging techniques, and silicon application-specific integrated-circuit chips. • Ka-Band Solid-State Power Amplifier Developed by Lockheed Martin This high-frequency, solid-state amplifier amplified the transponder radio signal and allowed the spacecraft's transponder to transmit in the microwave Ka band. A system with similar capability using current technology would be more than twice as heavy and three times more expensive. Microelectronics • Low-Power Electronics Developed by Lincoln Laboratory, Massachusetts Institute of Technology This experiment involved sophisticated low-voltage technologies, low-activity logic, low-energy architectures, and micro-power management. It tested a ring oscillator, transistors, and a multiplier designed to consume very little electrical power.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments[a]	• Multifunctional Spacecraft Structure Developed by the U.S. Air Force Phillips Laboratory and Lockheed Martin This multifunctional structure integrated electronics with the spacecraft and demonstrated futuristic technologies for making the spacecraft smaller, lighter, and more efficient. It combined thermal management and electronics in one load-bearing structural element consisting of a composite panel with copper polyimide patches bonded to one side and embedded heat-transferring devices. The panel's outer surface acted as a thermal radiator. Electrical circuitry was designed in the copper polyimide layer; flex jumpers served as electrical interconnects for power distribution and data transmission. • Power Activation and Switching Module Developed by Lockheed Martin, the Boeing Company, and JPL The module was a "smart" power switch consisting of eight power switches grouped in redundant pairs; it could monitor four electrical loads. The switches sensed voltage and current and could limit current if necessary. Secondary Payload • The SEDSAT, an amateur radio satellite conducting remote sensing. The SEDSAT detached from the rocket about 90 minutes later to begin orbiting Earth.
Results	Deep Space 1 successfully tested 12 new technologies for future space use.
Remarks	• First use of ion propulsion as primary propulsion source. • First use of autonomous navigation in deep space. • First New Millennium Program technology validation mission.

[a] "Testing Technologies," *http://nmp.jpl.nasa.gov/ds1/gen/gen2.html* (accessed August 11, 2005). Also "Plasma Experiment for Planetary Exploration (PEPE)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-061A&ex=2* (accessed August 18, 2005). Also "Deep Space 1 Launch Press Kit," October 1998 (NASA History Office Electronic File 30203).

Table 4–56. High Energy Transient Experiment, Satelite de Aplicaciones Cientificas-B Dual Mission Characteristics

Launch Date/Launch Site	November 4, 1996 / Wallops Island, Virginia
Date of Reentry	April 2, 2002
Launch Vehicle	Pegasus XL
NASA Role	HETE: Collaboration between NASA and MIT. Managed by NASA as a University Explorer mission of opportunity. SAC-B: Provided one scientific instrument, launch services, support for initial orbit operations and emergency backup through mission life.
Responsible (Lead) Center	Goddard Space Flight Center (Wallops Flight Facility)
Mission Objectives	HETE: To carry out the first multiwavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments. SAC-B: To study solar physics and astrophysics through the examination of solar flares, gamma-ray burst sources, and the diffuse soft x-ray cosmic background.
Orbit Characteristics	Did not reach orbit
Weight	SAC-B: 181 kg (399 lb) HETE: 128 kg (282 lb)
Dimensions	SAC-B: Body: 62 cm by 62 cm (2 ft by 2 ft) wide by 80 cm (2.6 ft) high; four solar panels 62 cm (2 ft) wide by 76 cm (2.5 ft) long when extended HETE: Body fit within a cylinder 89-cm high by 66-cm diameter
Power Source	Solar arrays and batteries
Prime Contractor	HETE: AeroAstro, L.L.C. SAC-B: INVAP S.W.
Instruments and Experiments	SAC-B: • Hard X-Ray Spectrometer (HXRS) Instrument Manager: Ana Maria Hernandez, Argentinean National Commission of Space Activities The instrument was provided by the Argentine Institute of Astronomy and Space Physics. The instrument was to search the hard x-ray spectrum between 20 keV and 320 keV for rapidly varying events on timescales as short as tens of milliseconds.

Table 4–56. High Energy Transient Experiment, Satelite de Aplicaciones Cientificas-B Dual Mission Characteristics

Instruments and Experiments	• Goddard X-Ray Experiment (GXRE) PI: Brian Dennis, Goddard Space Flight Center The instrument had two detectors: the Soft X-Ray Spectrometer (SOXS) was to perform coordinated observations with the HXRS by observing soft x-ray emissions from solar flares. The Gamma Ray Burst Spectrometer (GRaBS) was to provide time profiles of the x-ray emission from non-solar gamma-ray bursts in the energy range from ~20 keV to >300 keV. • Cosmic Unresolved X-Ray Background Instrument Using CCDs (CUBIC) PI: Gordon Garmire, Pennsylvania State University The instrument was to measure the spectrum of the diffuse x-ray background with unprecedented sensitivity and spectral resolution between 0.1 keV and 10.0 keV in selected areas of the sky. • Imaging Particle Spectrometer for Energetic Neutral Atoms (ISENA) PI: Stefano Orsini, Franscati, Italy Provided by the Italian Istituto di Fisica dello Spazio Interplanetario (Institute for Interplanetary Space Physics), the ISENA was to measure neutral atoms at spacecraft altitudes HETE: • French Gamma Telescope (FREGATE) PI: Gilbert Vedrenne, Centre d'Etude Spatiale des Rayonnements (CESR), France The FREGATE consisted of four wide-field gamma-ray detectors, supplied by the CESR of Toulouse, France, to handle the detection and spectroscopy of gamma-ray bursts and monitor variable x-ray sources. • Wide-Field X-ray Monitor (WXM) PI: Masuaru Majsuoka, RIKEN, Japan The WXM was supplied by a collaboration of the Los Alamos National Laboratory and the Institute of Chemistry and Physics (RIKEN) of Tokyo, Japan. The WXM was the prime instrument for detecting x-ray sources. • Ultraviolet CCD cameras (4) PI: George Ricker, Massachusetts Institute of Technology The cameras were built by MIT's Center for Space Research; three cameras were identical; one had an optical filter. The cameras were to provide the most accurate directional information about transient events and assist with spacecraft attitude determination.
Results	Failed to reach orbit.

Table 4–57. Geotail Mission Characteristics

Launch Date/Launch Site	July 24, 1992/Cape Canaveral Air Force Station
Date of Reentry	Still operating in mid-2005.[a]
Launch Vehicle	Delta II
NASA Role	Project management, two scientific instruments, two other scientific instruments jointly with the ISAS, launch vehicle and launch support
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Acquire in situ data defining the field and particle environments of the geomagnetic tail region of the magnetosphere. Science objectives: • Determine the overall plasma electric and magnetic field characteristics of the distant and near geomagnetic tail. • Help determine the role of the distant and near-Earth tail in substorm phenomena and in the overall magnetospheric energy balance. Also relate these phenomena to external triggering mechanisms. • Study the processes that initiate reconnection in the near-Earth tail and observe the microscopic nature of the energy conversion mechanism in this reconnection region. • Determine the composition and charge state of plasma in the geomagnetic tail at various energies during quiet and dynamic periods and distinguish between the ionosphere and solar wind as sources of this plasma. • Study plasma entry, energization, and transport processes in interaction regions such as the inner edge of the plasma sheet, the magnetopause, and the bow shock, and investigate boundary layer regions.
Orbit Characteristics	Two orbits: approximately 220 Earth radii (1,401,620 km) and 8 Earth radii (51,024 km) by 30 Earth radii (191,340 km)
Weight	1,009 kg (2,220 lb) including 360 kg (792 lb) of hydrazine fuel
Dimensions	Diameter: 2.2 m (7.2 ft); height: 1.6 m (5.2 ft)
Shape	Cylindrical
Power Source	Body-mounted solar cell panel, nickel cadmium batteries
Prime Contractor	Institute of Space and Astronautical Science, Japan

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments	• Comprehensive Plasma Investigation (CPI) PI: Louis A. Frank, University of Iowa The CPI made comprehensive observations of the three-dimensional velocity distribution functions of electrons and positive ions, with identification of ion species. The instrument contained three sets of quadrispherical analyzers with channel electron multipliers that obtained three-dimensional measurements for hot plasma and solar wind electrons, solar wind ions, and positive-ion composition measurements. • Energetic Particle and Ion Composition (EPIC) Investigation PI: Richard McEntire, The Johns Hopkins University Applied Physics Laboratory The EPIC investigation explored the distant magnetotail region and obtained information on the origin, transport, storage, acceleration, and dynamics of suprathermal and nonthermal particle populations. The investigation was composed of two separate sensor and processing assemblies. The Supra-Thermal Ion Composition Spectrometer assembly measured charge state, mass, and energy of ions with energies from 30 keV to 230 keV per charge. The Ion Composition Subsystem assembly measured mass and energy properties of energetic ions with energies of less than 50 keV to 3 MeV. • Plasma Wave Investigation (PWI) PI: Hiroshi Matsumoto, Radio Atmospheric Science Center, Kyoto University This investigation determined the dynamic behavior of the plasma trapped in Earth's magnetosphere by measuring electric fields over the range from 0.5 Hz to 400 kHz and magnetic fields over the range from 1 Hz to 10 kHz. Triaxial magnetic search coils were used in addition to a pair of electric dipole antennae. The instrument contained two sweep-frequency receivers (12 Hz to 400 kHz and 12 Hz to 6.25 kHz), a multichannel analyzer (5.6 Hz to 311 kHz for the electric antenna and 5.6 Hz to 1.0 kHz for the magnetic coils), a low-frequency waveform receiver (0.01 Hz to 10 Hz), and a wideband waveform receiver (10 Hz to 16 kHz).

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments	• Electric Fields Detector (EFD) Investigation PI: Koichiro Tsuruda, Institute of Space and Astronautical Science, Japan The EFD investigated: — The large-scale configuration of the electric field in the magnetotail. — Magnetotail electric field variations during substorms. — The electric field in the plasma sheet. — The electric field near the magnetopause and in the plasma mantle at locations tailward of those covered by similar measurements on the International Sun Earth Explorer (ISEE) 1. — Micropulsation and low-frequency wave measurements at frequencies covering the local gyrofrequency (<1 Hz) and lower hybrid frequency (<10 Hz) in the magnetotail. — Plasma density as deduced from measurement of the floating potential of the spacecraft. — Electric field comparisons (with the aid of the other spacecraft in the ISTP program) at different points along the same magnetic field line, at different points along a common boundary, or in different regions of the magnetosphere. • The instrument consisted of two orthogonal double probes, each a pair of separated spheres on wire booms located in the satellite spin plane. The difference of potential between the spheres was measured. • High-Energy Particles (HEP) Investigation PI: Tadayoshi Doke, Waseda University, Japan The HEP investigation studied the following: 1) plasma dynamics in the geomagnetic tail, 2) solar flare particle acceleration and propagation, and 3) the origin, lifetime, and propagation of cosmic ray particles. Five instruments made up this investigation: a low-energy particle detector (LD), a burst detector (BD), medium-energy isotope detectors (MI-1 and MI-2), and a high energy Isotope detector (HI). LD and BD were mainly dedicated to magnetospheric studies. MI and HI concentrated on solar flare and cosmic-ray studies. • Low-Energy Particles (LEP) Experiment PI: Toshifumi Mukai, Institute of Space and Astronautical Science, Japan

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments[b]	The LEP experiment observed plasma and energetic electrons and ions in the terrestrial magnetosphere and interplanetary medium. The experiment consisted of three sensors sharing common electronics. LEP-electrostatic analyzers (EA) measured three-dimensional velocity distributions of hot plasma in the magnetosphere. The LEP-solar wind measured three-dimensional velocity distributions of solar wind ions in the energy range from 0.1 keV/Q to 8 keV/Q. The LEP-mass spectrometer was an energetic ion mass spectrometer that provided three-dimensional determinations of the ion composition in 32 steps in the energy range from 0 keV/Q to 25 keV/Q. All sensors operated continuously as long as spacecraft power allowed except during the orbit/attitude maneuvering operation. Although this experiment ceased operation soon after launch, the LEP-EA and LEP-SW portions of the experiment resumed operation in late 1993 and have worked ever since. • Magnetic Fields Measurement (MGF) PI: Tsugunobu Nagai, Tokyo Institute of Technology, Earth and Planetary Sciences, Japan This experiment measured the magnetic field variation of the magnetotail in the frequency below 50 Hz. The experiment consisted of dual three-axis fluxgate magnetometers and a three-axis search coil magnetometer. Triad fluxgate sensors were installed at the end and middle of a 6-m (20-ft) deployable mast. Three search coils were mounted approximately one-half of the way out on another 6-m (20-ft) boom.
Results[c]	In the area of magnetotail structure, dynamics, and plasma population, Geotail observations demonstrated that the structure and dynamics of the magnetotail were basically determined by magnetic reconnection under both southward and northward interplanetary magnetic field (IMF) conditions, except possibly when IMF was almost due northward. Relating to the role of magnetic reconnection in the magnetospheric substorm, Geotail observations significantly advanced our understanding of magnetic reconnection in the near-Earth tail for the magnetospheric substorm. Relating to characteristic plasma waves in the magnetotail, Geotail made a thorough survey of plasma waves in the magnetotail and clarified its relation to the macroscopic structure.

[a] "Geotail," *http://directory.eoportal.org/pres_GEOTAIL.html* (accessed September 2, 2005).

[b] "Geotail, Instrument Descriptions," *http://www-spof.gsfc.nasa.gov/istp/geotail/geotail_inst.html* (accessed September 2, 2005).

[c] "Typical Important Results," Institute of Space and Astronautical Science, *http://www.isas.jaxa.jp/e/enterp/missions/geotail/achiev/typical.shtml* (accessed September 2, 2005).

Table 4–58. Wind Mission Characteristics

Launch Date/Launch Site	November 1, 1994 / Cape Canaveral Air Station
Date of Reentry	None
Launch Vehicle	Delta II 7925
NASA Role	Project management, PIs for four U.S. instrument and Russian KONUS instrument
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Science objectives (Wind Project Overview)[a] • Provide complete plasma, energetic particle, and magnetic field input for magnetospheric and ionospheric studies. • Determine the magnetospheric output to interplanetary space in the up-stream region. • Investigate basic plasma processes occurring in the near-Earth solar wind. • Provide baseline ecliptic plane observations to be used in heliospheric latitudes from Ulysses. Science objectives (Mission Operation Report)[b] • Measure the mass, momentum, and energy flows through geospace and understand their time variability. • Obtain detailed knowledge of plasma physical processes important in controlling the behavior of the major components of the geospace system. • Determine the importance of changes in energy input to Earth's atmosphere caused by geospace processes.
Orbit Characteristics	Two orbits: apogee from 80 Earth radii to 250 Earth radii and perigee between 5 Earth radii and 10 Earth radii (31,890 km and 63,780 km) followed by a halo orbit about the sunward Sun-Earth gravitational equilibrium point (L1) varying from 235 Earth radii to 265 Earth radii (864,330 km to 1,690,170 km).
Weight	Launch weight: 1,250 kg (2,756 lb), spacecraft weight: 884 kg (1,949 lb)
Dimensions	Diameter: 2.4 m (7.87 ft), height: 1.8 m (5.91 ft)[c]
Shape	Cylindrical
Power Source	Solar panels and battery
Prime Contractor	Spacecraft: Martin Marietta[d]

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	• Radio and Plasma Wave Experiment (WAVES) PI: J.L. Bougeret, Laboratoire de Recherche Spatiale, France The WAVES measured the intensity and arrival direction for both propagating and *in situ* waves originating in the solar wind near Earth. These waves depict the state of the solar wind impinging on Earth's magnetosphere. The instrument contained five subsystems within the main electronics box, plus the antenna subsystems that included a spin-axis and two spin-plane electric antennae and a triaxial search coil. The WAVES had on-board interconnects with the 3-D Plasma investigation (3D PLASMA) and the Solar Wind Experiment (SWE). • Energetic Particle Acceleration, Composition and Transport (EPACT) PI: T. von Rosenvinge, Goddard Space Flight Center The EPACT instrument provided a comprehensive study of energetic particle acceleration and transport processes in solar flares, the interplanetary medium, and planetary magnetospheres, as well as the galactic cosmic rays and the anomalous cosmic ray component. The instrument consisted of three integrated telescope/electronics boxes mounted on the body of the spacecraft. The extensive dynamic range of particles to be measured was divided among three Low Energy Matrix Telescopes (LEMTs), two Alpha-Proton-Electron (APE) telescopes, an Isotope Telescope (IT), and a Supra Thermal Energetic Particle (STEP) telescope. An on-board recorder allowed continuous observations to be made. • SWE PI: K. Ogilvie, Goddard Space Flight Center The SWE provided complete, accurate specification of solar wind flow parameters in real time. The instrument was a six-axis ion-electron spectrometer that provided three-dimensional velocity distribution functions for ions and electrons, with high time resolution.

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	• Solar Wind and Suprathermal Ion Composition Experiment (SMS) PI: G. Gloeckler, Institute of Physical Sciences and Technology, University of Maryland This experiment consisted of three major instruments: 1) the SWICS, 2) the High Mass Resolution Spectrometer (MASS), and 3) the Suprathermal Ion Composition Spectrometer (STICS). This experiment determined the abundance, composition, and differential energy spectra of solar wind ions, as well as the composition, charge state and three-dimensional distribution functions of suprathermal ions. These ions, and their abundance fluctuations, provided information about events on the solar surface and the formation of the solar wind, complementing the EPACT and 3D PLASMA investigations. • Magnetic Field Investigation (MFI) PI: R. Lepping, Goddard Space Flight Center The MFI investigated the large-scale structure and fluctuation characteristics of the interplanetary magnetic field, which influenced the transport of energy and the acceleration of particles in the solar wind and dynamic processes in Earth's magnetosphere. The MFI consisted of dual triaxial fluxgate magnetometers mounted on a 12-m (40-ft) radial boom and a data processing and control unit within the spacecraft body. Mounting the magnetometers at the outboard end and at an inboard location on the boom helped reduce contamination of the measurements by spacecraft-generated magnetic fields. • 3D PLASMA PI: R. Lin, Space Sciences Laboratory, University of California, Berkeley The 3D PLASMA investigation measured ions and electrons in the interplanetary medium with energies including that of the solar wind and the energetic particle range. The experiment studied the particles upstream of the bow shock in the foreshock region and the transient particles emitted by the Sun during solar particle events following solar flares. This experiment covered the gap between the energy ranges covered by the SWE and EPACT.

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	The 3D PLASMA investigation consisted of two sensor packages mounted on small radial booms and an electronics package mounted inside the spacecraft. One boom-mounted sensor package contained an array of six double-ended semiconductor telescopes, each with two or three closely sandwiched silicon detectors to measure electrons and ions above 20 keV. The first sensor package also contained two ion electrostatic analyzers for measuring ion fluxes from approximately 3 keV to 40 keV. The second sensor package contained two electron electrostatic analyzers for measuring electron fluxes from about 3 keV to 30 keV and for making input to a fast particle correlator (FPC). The FPC, using plasma wave data from the WAVES, measured perturbations to the electron distribution function and studied other wave-particle interactions. • Transient Gamma Ray Spectrometer (TGRS) PI: B.J. Teegarden, Goddard Space Flight Center The TGRS detected several gamma-ray bursts and solar flares per week, with typical durations between 1 second and several minutes. Between bursts, the instrument remained in a waiting mode, measuring background counting rates and energy spectra. When a burst or flare occurred, the instrument switched to a burst mode, where each event in the detector was pulse-height analyzed and time tagged in a burst memory. Then the instrument switched to a dump mode for reading out the burst memory. The TGRS consisted of four assemblies: detector cooler assembly, pre-amp, analog processing unit (all mounted on a tower on the +Z end of the spacecraft), and a digital processing unit mounted in the body of the spacecraft.
Instruments and Experiments[e]	• Russian Gamma-Ray Spectrometer (KONUS) PIs: T.L. Cline, Goddard Space Flight Center; E. Mazets, IOFFE Physical Technical Institute, Russia The KONUS performed gamma-ray burst studies similar to the TGRS studies. It performed event detection and measured time history and energy spectra. Although KONUS had a lower resolution than the TGRS, the spectrometer had broader area coverage to complement that of the TGRS; the combined KONUS and TGRS data provided coverage of the full sky. The KONUS was the first Russian experiment on a NASA science mission. The KONUS consisted of two Russian sensors mounted on the top and bottom of the spacecraft aligned with the spin axis, a U.S. interface box, and a Russian electronics package mounted in the spacecraft body. The sensors (copies of sensors successfully flown on the Soviet Cosmos, Venera, and *Mir* missions) were identical and interchangeable.

Table 4–58. Wind Mission Characteristics (Continued)

Results	In addition to being an essential part of the ISTP program, Wind provided new results in heliospheric science and astrophysics, and it provided further investigations of the Sun-Earth connection.[f]

[a] "Wind Project Overview," *http://pwg.gsfc.nasa.gov/istp/wind/wind.html* (accessed September 2, 2005).

[b] Wind Mission Operations Report," Report no. S-417-94-01 (NASA History Office Folder 30999 Electronic Document).

[c] Finneran, "Wind Spacecraft Scheduled To Launch Nov. 1 at the Cape," *Goddard News* 41 (October 1994): 1–2. (NASA History Office Folder 5910). This figure is very close to the figures cited in the Wind Mission Operations Report. The NSSDC database master catalog *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-071A* (accessed July 18, 2006) states the diameter as 2.8 m and height as 1.25 m.

[d] Jim Elliot, "Launches of Wind and STS-66 Successful," *Goddard News* 41 (November 1994): 1 (NASA History Office Folder 5910).

[e] "Wind Instrument Descriptions," *http://pwg.gsfc.nasa.gov/wind_inst.shtml* (accessed May 16, 2006).

[f] K.W. Ogilvie and M.D. Desch, "The WIND Spacecraft and Its Early Scientific Results," *http://www-ssc.igpp.ucla.edu/IASTP/04* (accessed October 25, 2005).

Table 4–59. Polar Mission Characteristics

Launch Date/Launch Site	February 24, 1996 / Vandenberg Air Force Base
Date of Reentry	Operational as of mid-2005.
Launch Vehicle	Delta II
NASA Role	Program management and operation of the spacecraft; PI for TIDE/PSI
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• Determine the role of the ionosphere in the substorm phenomena and in the overall magnetospheric energy balance. • Measure plasma energy input through the dayside cusp. • Determine the characteristics of ionospheric plasma outflow and energized plasma inflow to the atmosphere. • Study characteristics of the auroral plasma acceleration regions. • Provide multispectral auroral images of the footprint of the magnetospheric energy deposition into the ionosphere and upper atmosphere.
Orbit Characteristics:	
Apogee	51,000 km (31,690 mi)
Perigee	5,100 km (3,169 mi)
Inclination (deg)	86
Period (min)	1,050
Weight	Total weight: 2,860 lb (1,300 kg); fuel weight: 662 lb (301 kg); dry weight: 2,198 lb (999 kg)
Dimensions[a]	Height: 2.28 m (7.5 ft) (including despun platform); diameter: 2.49 m (8.2 ft)
Shape	Cylindrical
Power Source	Solar array, three batteries
Prime Contractor	Lockheed Martin Corp.
Instruments and Experiments	• Magnetic Fields Experiment (MFE) PI: Christopher T. Russell, University of California, Los Angeles The MFE was a high-precision instrument designed to measure the magnetic fields in the high and low altitude polar magnetosphere. The MFE was used to investigate the behavior of field-aligned current systems and the role they played in the acceleration of particles and dynamics of the fields in the polar cusp, magnetosphere, and magnetosheath.

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments	• Electric Fields Instrument (EFI) PI: Forrest S. Mozer, Space Sciences Laboratory, University of California, Berkeley The EFI measured the three components of the ambient vector electric field and the thermal electron density. The results were used to study the following: — Parallel and perpendicular electric fields and density variations in double layers, electrostatic shocks, and other time domain structures found in the auroral acceleration region and at other locations in the Polar orbit. — The high latitude convection electric field. — The electric field and plasma density structure on field lines connected to the high-latitude magnetopause, polar cusp, and plasma mantle. — Correlations of electric fields with those measured by other ISTP program spacecraft at different points along the same magnetic field line or along a common boundary, or in different regions of the magnetosphere. — Modes, phase velocities, and wavelengths of propagating waves and spatial structures. • Plasma Waves Investigation (PWI) PI: Donald A. Gurnett, University of Iowa The PWI provided comprehensive measurements of plasma wave phenomena in the high-latitude auroral zones, dayside magnetic cusp regions, and plasmasphere and plasma sheet. The investigation used seven distinct sensors to detect the electric and magnetic fields of plasma waves. • Hot Plasma Analyzer (HYDRA) PI: Jack D. Scudder, University of Iowa The HYDRA consisted of a collection of electrostatic analyzers designed for high-resolution observations of electron and ion velocity distributions in Earth's polar magnetosphere. The scientific objectives were the following: — To observe the velocity space signatures identifying the sources of particles detected in the polar magnetosphere. — To improve understanding of the coupling of the plasma to the magnetic field in the polar magnetosphere where ideal magnetohydrodynamics ordering breaks down. — To elucidate time-dependent processes occurring in the auroral zone.[b]

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments[c]	• Thermal Ion Dynamics Experiment (TIDE)/Plasma Source Instrument (PSI) PI: Thomas E. Moore, Goddard Space Flight Center This experiment and instrument were developed to meet the requirements for three-dimensional plasma composition measurements capable of tracking the outflow of ionospheric plasma throughout the magnetosphere. • Toroidal Imaging Mass Angle Spectrograph (TIMAS): PI: William K. Peterson, Space Physics Laboratory, Lockheed Martin Advanced Technology Center The TIMAS measured the full three-dimensional velocity distribution functions of all major magnetospheric ion species with one-half spin period time resolution. • Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) PI: Theodore A. Fritz, Center for Space Physics, Boston University The CAMMICE's objective was to determine unambiguously the composition of the energetic particle populations of Earth's magnetosphere in the range from 6 keV/Q to 60 MeV per ion to identify mechanisms by which these charged particles were energized and transported from their parent source populations to the magnetosphere. • CEPPAD/SEPS PI: J. Bernard Blake, Space Sciences Department, The Aerospace Corporation Consisted of three packages: two were spacecraft body-mounted and the third was located on the despun platform. The first body-mounted package consisted of the Imaging Proton Sensor (IPS) and the Digital Processing Unit (DPU). The second consisted of the Imaging Electron Sensor (IES) and the High Sensitivity Telescope. The single despun platform package was the SEPS. • UVI PI: George K. Parks, University of Washington The UVI was a two-dimensional imager sensitive to far UV wavelengths. With its 8-degree circular FOV, the UVI imaged the sunlit and nightside polar regions of Earth in the far UV wavelengths. The UVI detected and provided images of very dim emissions with a wavelength resolution never achievable before. The resulting images helped quantify the overall effects of solar energy input to Earth's polar regions.

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments	• VIS PI: L.A. Frank, University of Iowa The VIS was a set of three low-light-level cameras. Two cameras shared primary and some secondary optics, and they were designed to provide images of the nighttime auroral oval at altitudes from about 1 Earth radii to 8 Earth radii (6,378 km to 51,024 km) as viewed from the eccentric, polar orbit of the spacecraft. A third camera monitored the directions of the FOVs of the auroral cameras with respect to the sunlit Earth. • PIXIE PI: David L. Chenette, Space Physics Laboratory, Lockheed Martin Advanced Technology Center The PIXIE measured the spatial distribution and temporal variation of x-ray emissions in the energy range from 3 keV to 60 keV from Earth's atmosphere. The morphology and spectra of energetic electron precipitation and its effects upon the atmosphere were derived from these x-ray measurements.
Results	This was a successful mission performing multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere.

[a] John B. Sigwarth, Polar Project Scientist, e-mail, August 11, 2005.
[b] "HYDRA Instrument Page," *http://www-st.physics.uiowa.edu/www/html/instrument.html* (accessed October 25, 2005).
[c] "Polar Instrument Descriptions," *http://www-spof.gsfc.nasa.gov/istp/polar/polar_inst.html* (accessed August 10, 2005).

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics

Launch Date/Launch Site	December 2, 1995/Cape Canaveral Air Station
Date of Reentry	Still in orbit as of mid-2005.
Launch Vehicle	Atlas IIAS
NASA Role	Launch vehicle; instrument interface hardware; mission and science operations; DSN support; data processing and archive
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To study and understand the solar corona—in particular, its heating mechanism and its expansion into the solar wind—both by remote sensing of the solar atmosphere with high-resolution spectrometers and by *in situ* measurements of the composition of the resulting particles in the solar wind. • To study the solar structure and interior dynamics from the Sun's core to the photosphere by helioseismological methods and the measurement of the solar irradiance variations.
Orbit Characteristics	Orbits around first Lagrangian point (L1) approximately 1.5 million km (1 million mi) from Earth in the direction of the Sun. Circles the L1 point once every six months.
Weight	1,850 kg (4,079 lb) at launch
Dimensions	4.3 m by 2.7 m by 3.7 m (14.1 ft by 8.9 ft by 12.1 ft); 9.5 m (31.2 ft) with solar arrays deployed
Power Source	Solar array and batteries
Prime Contractor	Matra Marconi under contract to the ESA
Instruments and Experiments	Solar Corona • Coronal Diagnostic Spectrometer (CDS) PI: Richard Harrison, Rutherford Appleton Laboratory, U.K. The CDS detected emission lines from ions and atoms in the solar corona and transition region, providing diagnostic information on the solar atmosphere, especially of the plasma in the temperature range from 10,000°C (18,032°F) to more than 1,000,000°C (1,800,032°F).

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments	• Large Angle and Spectrometric Coronograph (LASCO) PI: Guenter Brueckner, Naval Research Laboratory The LASCO observed the outer solar atmosphere (corona) from near the solar limb to a distance of 21 million km (13 million mi), that is, about one-seventh of the distance between the Sun and Earth. The LASCO blocked direct light from the surface of the Sun with an occulter, creating an artificial eclipse, 24 hours a day, seven days a week. The LASCO became the SOHO's principal comet finder. • Solar Wind Anisotropies (SWAN) PI: Jean Loup Bertaux, National Center for Scientific Research (CNRS), Verrièrres-Le-Buisson, France The SWAN was the SOHO's only remote sensing instrument that did not look at the Sun. The SWAN watched the rest of the sky, measuring hydrogen "blowing" into the solar system from interstellar space. By studying the interaction between the solar wind and this hydrogen, the SWAN determined how the solar wind was distributed. The SWAN could be characterized as the SOHO's solar wind "mapper." • Ultraviolet Coronograph Spectrometer (UVCS) PI: John Kohl, Smithsonian Astrophysical Observatory, Cambridge, MA The UVCS made measurements in UV light of the solar corona (between about 1.3 solar radii and 12 solar radii from the center) by creating an artificial solar eclipse. The spectrometer blocked the bright light from the solar disc and allowed observation of the less intense emission from the extended corona. The UVCS provided valuable information about the microscopic and macroscopic behavior of the highly ionized coronal plasma. • Solar Ultraviolet Measurements of Emitted Radiation (SUMER) PI: Klaus Wilhelm, Max Planck Institute, Germany This instrument performed detailed spectroscopic plasma diagnostics (flows, temperature, density, and dynamics) of the solar atmosphere, from the chromosphere through the transition region to the inner corona, over a temperature range from 10,000°C (18,032°F) to 2,000,000°C (3,600,032°F) and above.

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments	• Extreme Ultraviolet Imaging Telescope (EIT) PI: Jean Pierre Delaboudinière, Laboratory for Stellar and Planetary Physics, Orsay, France The EIT provided full disc images of the Sun at four selected colors in the EUV, mapping the plasma in the low corona and transition region at temperatures between 80,000°C (144,034°F) and 2,500,000°C (4,500,032°F). Solar Wind • Charge, Element, and Isotope Analysis System (CELIAS) PI: Dietrich Hovestadt, Max Planck Institute, Germany The CELIAS continuously sampled the solar wind and energetic ions of solar, interplanetary, and interstellar origin as they swept past the SOHO. The CELIAS analyzed the density and composition of particles present in this solar wind and warned of incoming solar storms that could damage satellites in Earth orbit. • Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) PI: Horst Kunow, University of Kiel, Germany The COSTEP detected and classified very energetic particle populations of solar, interplanetary, and galactic origin. It was a complementary instrument to the Energetic and Relativistic Nuclei and Electron (ERNE) experiment. • ERNE experiment PI: Jarmo Torsti, University of Turku, Finland The ERNE experiment measured high-energy particles originating from the Sun and Milky Way. The ERNE experiment was a complementary instrument to the COSTEP. Solar Interior • Global Oscillations at Low Frequencies (GOLF) PI: Alan Gabriel, Laboratory for Stellar and Planetary Physics, France This instrument measured velocity oscillations over the entire solar disc to study the internal structure of the Sun.

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments[b]	• Michelson Doppler Imager/Solar Oscillations Investigation (MDI/SOI) PI: Philip Scherrer, Stanford University The MDI/SOI recorded the vertical motion ("tides") of the Sun's surface at a million different points for each minute. By measuring the acoustic waves inside the Sun as they perturbed the photosphere, scientists could study the structure and dynamics of the Sun's interior. The MDI also measured the longitudinal component of the Sun's magnetic field. • Variability of Solar Irradiance and Gravity Oscillations (VIRGO) PI: Claus Fröhlich, Physical-Meteorological Observatory, Davos, Switzerland This instrument characterized solar intensity oscillations and measured the total solar irradiance (known as the "solar constant") to quantify its variability spanning periods of days to the duration of the mission.
Results	The SOHO revolutionized solar science by its special ability to observe simultaneously the interior and atmosphere of the Sun and particles in the solar wind and heliosphere. The SOHO made remarkable discoveries about flows of gas inside the Sun, giant "tornadoes" of hot, electrically charged gas, and clashing magnetic field-lines. The observatory also gave early warnings of solar eruptions that could affect Earth.
Remarks	Extending the mission past its April 1998 prime mission enabled the SOHO to observe intense solar activity in 2000 and compare the activity to the Sun's behavior during low dark sunspot activity in 1996.

[a] "Solar and Heliospheric Observatory (SOHO): International Solar Terrestrial Physics Program," *1995 Flight Project Data Book*, p. 82 (NASA History Office Folder 14567).

[b] "SOHO," Factsheet, ESA Media Centre, Space Science, June 1, 2003, *http://www.esa.int/esaSC/SEMJFH374OD_0_spk.html* (accessed August 8, 2005). Also "Solar and Heliospheric Observatory (SOHO)," NASA and ESA (NASA History Office Folder 14567).

Table 4–61. Solar-A/Yohkoh Mission Characteristics

Launch Date/Launch Site	August 30, 1991 / Kagoshima Space Center, Japan
Date of Reentry	Mission ended in December 2001 after a spacecraft failure.
Launch Vehicle	M-3S2
NASA Role	Managed SXT development; provided tracking support using DSN ground stations
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives	To study the high-energy radiations from solar flares (hard and soft x-rays and energetic neutrons), as well as study quiet structures and pre-flare conditions. NASA objectives: • To obtain simultaneous images of solar flares with high time and spatial resolutions in both the hard and soft x-rays so that the full morphology of the flare can be observed with sufficient precision to reveal the underlying physical processes. • To image the solar corona in soft x-rays, with both high time and spatial resolution, to reveal properties of the global coronal magnetic fields. • To measure variations of photospheric brightness with modest spatial resolution for studies of solar irradiance and global oscillations.
Orbit Characteristics:	
Apogee	Initial orbit: 792.6 km (492.5 mi)
Perigee	Initial orbit: 517.9 km (321.8 mi)
Inclination (deg)	31
Period (min)	90
Weight	420 kg (926 lb)
Dimensions	4 m by 4 m by 2 m (13.1 ft by 13.1 ft by 6.6 ft)
Shape	Rectangular
Power Source	Solar panels and batteries
Prime Contractor	Lockheed Martin

Table 4–61. Solar-A/Yohkoh Mission Characteristics (Continued)

Instruments and Experiments	• SXT PI: Tadashi Hirayama, National Astronomical Observatory of Japan The SXT formed x-ray images in the range from 0.25-keV to 4.0-keV on a 1024-pixel by 1024-pixel CCD using grazing-incidence optics. It used thin metallic filters to acquire images in restricted portions of this energy range. The SXT could resolve features down to 2.5 arc seconds in size. Information about the temperature and density of the plasma emitting the observed x-rays was obtained by comparing images acquired with the different filters. Flare images could be obtained every 2 seconds. Smaller images with a single filter could be obtained as frequently as once every 0.5 second. This instrument was made of two highly polished cylindrical surfaces ground to high-precision hyperbolas. X-rays entered the front of the mirror cylinders nearly parallel to the mirror surfaces. They grazed off the two surfaces to the focal point where an x-ray detector was located. The x-ray pictures were sent to the ground where scientists analyzed the data.[a] • HXT PI: Kazuo Makishima, University of Tokyo The HXT was a multigrid synthesis-type imager with a spatial resolution of 7 arc seconds, operating in the range from 20-keV to 80-keV. It observed hard x-rays in four energy bands through 64 pairs of grids. These grid pairs provided information about 32 spatial scales of the x-ray emission. This information was combined on the ground to construct an image of the source in each of the four energy bands. Structures with angular sizes down to about 5 arc seconds could be resolved. The instrument could obtain images as frequently as once every 0.5 seconds. • BCS PI: George A. Doschek, Naval Research Laboratory The BCS consisted of four bent crystal spectrometers. Each was designed to observe a limited range of soft x-ray wavelengths containing spectral lines sensitive to the hot plasma produced during a solar flare. The observations of these spectral lines provided information about the temperature and density of the hot plasma and about motions of the plasma along the line of sight. Images were not obtained, but this was offset by enhanced sensitivity to the line emission, high spectral resolution, and time resolution on the order of 1 second.

Table 4–61. Solar-A/Yohkoh Mission Characteristics (Continued)

Instruments and Experiments	• WBS PI: Jun Nishimura, Institute of Space and Astronomical Science, Japan The WBS consisted of three subinstruments that together spanned the entire energy range from soft x-rays to gamma rays, 2 keV to 100 MeV, with a time resolution on the order of 1 second or better. The detectors were: 1) the soft x-ray spectrometer, a gas proportional counter filled with xenon and carbon dioxide that covered the 2-keV to 30-keV band; 2) the hard x-ray spectrometer, a NaI scintillator covering the energy range from 20-keV to 600-keV; and 3) the gamma-ray spectrometer, a pair of identical BGO scintillators ($Bi_4 Ge_3 O_{12}$) (bismuth germinate) covering the 0.2-MeV to 100-MeV band.[b] Images were not obtained.
Results[c]	Yohkoh made discoveries about: • The Sun's corona, including information about how and where this outer layer of the Sun's atmosphere was heated to temperatures up to hundreds of times greater than the solar surface. Yohkoh also tracked the dramatic year-to-year evolution of the corona. • The physics of solar flares, titanic explosions in the atmosphere of the Sun caused by the violent release of magnetic energy. In less than 1 hour, a typical solar flare can release as much as 10,000 times the annual energy consumption of the United States. Yohkoh observations helped astronomers understand how the Sun's magnetic fields were deformed and twisted; broken and reconnected during flares; and how the electrified gas (plasma) of the Sun's corona was heated to millions of degrees during flares. • The structures that produce ejections of material from the Sun, helping astronomers understand and begin to predict "space weather." Although the prediction tools were still rudimentary, the discovery that certain structures on the Sun, namely sigmoids and transequatorial interconnecting loops (TIL), were more likely to be the sites of solar eruptions was noteworthy. The sigmoids—S-shaped regions seen in coronal imagery—were found to be more likely to erupt than non-S-shaped regions. The TILs received attention as another possible source of mass ejections.

[a] "The Yohkoh Satellite," *http://hesperia.gsfc.nasa.gov/sftheory/yohkoh.htm* (accessed August 29, 2005).
[b] "Wide Band Spectrometer," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-062A&ex=3* (accessed September 25, 2005).
[c] "Yohkoh Mission Celebrates a Decade of Solar Discovery," Goddard Space Flight Center, September 10, 2001, *http://www.gsfc.nasa.gov/topstory/20010917yohkoh.html* (accessed September 22, 2005).

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a])

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.045 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	January 9, 1989	White Sands Missile Range	Mission unsuccessful, vehicle unsuccessful
36.047 GU	Mentall/ Goddard Space Flight Center	Upper Atmosphere	January 17, 1989	White Sands Missile Range	Successful
AAF-XB-02	Kintner/Cornell University, James/Canadian Research Council	Upper Atmosphere	January 30, 1989	Andoya, Norway	Successful
21.100 GE	Pfaff/ Goddard Space Flight Center	Geospace Sciences	March 3, 1989	Kiruna, Sweden	Successful
21.096 GE	Pfaff/ Goddard Space Flight Center	Geospace Sciences	March 4, 1989	Kiruna, Sweden	Successful
33.057 UL	Barth/University of Colorado	Solar System Exploration	March 7, 1989	Poker Flat Research Range	Successful
31.073 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 18, 1989	Fort Churchill, Canada	Successful
31.074 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 22, 1989	Fort Churchill, Canada	Successful
29.027 UE	Mendillo/Boston University	Geospace Sciences	April 3, 1989	Wallops Island, Virginia	Vehicle successful, mission unsuccessful
35.022 GE	Hoffman/ Goddard Space Flight Center	Geospace Sciences	April 9, 1989	Fort Churchill, Canada	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
350.021 GE	Hoffman/Goddard Space Flight Center	Geospace Sciences	April 11, 1989	Fort Churchill, Canada	Successful
35.019 UE	Torbert/University of Alabama, Huntsville	Geospace Sciences	May 4, 1989	Wallops Island, Virginia	Successful
36.025 GS	Neupert/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 5, 1989	White Sands Missile Range	Successful
36.054 US	Rottman/University of Colorado	Solar and Heliospheric Sciences	June 20, 1989	White Sands Missile Range	Successful
36.043 GG	Smith/Goddard Space Flight Center	UV/Optical Astrophysics	June 27, 1989	White Sands Missile Range	Successful
27.122 UE	Sharp/University of Michigan	Geospace Sciences	July 17, 1989	White Sands Missile Range	Successful
36.059 UL	Judge/University of Southern California	Solar System Exploration	August 23, 1989	White Sands Missile Range	Successful
36.052 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	September 11, 1989	White Sands Missile Range	Successful
36.037 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	October 23, 1989	Wallops Island, Virginia	Successful
27.123 UG	Cash/University of Colorado	UV/Optical Astrophysics	November 20, 1989	White Sands Missile Range	Successful
12.042 WT	Flowers/Wallops Flight Facility	Test and Support	December 5, 1989	Wallops Island, Virginia	Successful
12.043 WT	Flowers/Wallops Flight Facility	Test and Support	December 21, 1989	Wallops Island, Virginia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.033 UL	Zipf/University of Pittsburgh	Solar System Exploration	January 23, 1990	White Sands Missile Range	Successful
39.002 UE	Kellogg/University of Minnesota	Geospace Sciences	February 1, 1990	Poker Flat Research Range	Successful vehicle, unsuccessful mission
35.020 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 23, 1990	Poker Flat Research Range	Successful
36.066 GU	Mentall/Goddard Space Flight Center	Upper Atmosphere	March 9, 1990	White Sands Missile Range	Successful
36.034 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	March 17, 1990	White Sands Missile Range	Successful
40.002 UE	Carlson/University of California, Berkeley	Geospace Sciences	March 22, 1990	Poker Flat Research Range	Successful
31.070 UE	Bering/University of Houston	Geospace Sciences	March 22, 1990	Poker Flat Research Range	Successful vehicle, unsuccessful mission
36.053 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 30, 1990	White Sands Missile Range	Successful
35.028 CE	Taylor/TRW	Geospace Sciences	April 5, 1990	Wallops Island, Virginia	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.067 UG	Cash/University of Colorado	UV/Optical Astrophysics	April 9, 1990	White Sands Missile Range	Successful
36.063 UG	Boyer/University of California, Berkeley	UV/Optical Astrophysics	April 17, 1990	White Sands Missile Range	Successful
36.073 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 21, 1990	White Sands Missile Range	Successful
36.074 UG	Cash/University of Colorado	UV/Optical Astrophysics	April 28, 1990	White Sands Missile Range	Successful
33.059 GE	Baker/Goddard Space Flight Center	Geospace Sciences	May 13, 1990	Poker Flat Research Range	Successful
30.035 UE	Hale/Pennsylvania State University	Geospace Sciences	May 13, 1990	Poker Flat Research Range	Successful
33.060 GE	Baker/Goddard Space Flight Center	Geospace Sciences	May 14, 1990	Poker Flat Research Range	Successful
36.069 UL	Barth/University of Colorado	Solar System Exploration	June 1, 1990	White Sands Missile Range	Successful vehicle, unsuccessful mission
27.124 UG	Martin/Columbia University	UV/Optical Astrophysics	July 16, 1990	White Sands Missile Range	Successful
29.028 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	July 30, 1990	Kwajalein, Marshall Islands	Successful
29.029 UE	Kelley/Cornell University	Geospace Sciences	August 2, 1990	Kwajalein, Marshall Islands	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
238.017 UE	Mendillo/Boston University	Geospace Sciences	August 11, 1990	Kwajalein, Marshall Islands	Successful vehicle, unsuccessful mission
38.015 UE	Mendillo/Boston University	Geospace Sciences	August 15, 1990	Kwajalein, Marshall Islands	Successful
38.016 UE	Mendillo/Boston University	Geospace Sciences	August 15, 1990	Kwajalein, Marshall Islands	Successful
36.056 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	August 22, 1990	Kwajalein, Marshall Islands	Successful
38.018 UE	Mendillo/Boston University	Geospace Sciences	August 22, 1990	Kwajalein, Marshall Islands	Successful
36.072 UL	Judge/University of Southern California	Solar System Exploration	September 4, 1990	White Sands Missile Range	Successful
21.102 IE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 11, 1990	Andoya, Norway	Successful
36.058 DS	Moses/Naval Research Laboratory	Solar and Heliospheric Sciences	November 21, 1990	White Sands Missile Range	Successful
36.060 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	November 21, 1990	White Sands Missile Range	Successful
36.057 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	January 26, 1991	White Sands Missile Range	Successful
40.001 UE	Kintner/Cornell University	Geospace Sciences	February 12, 1991	Poker Flat Research Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.070 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	February 22, 1991	White Sands Missile Range	Successful
12.044 WT	Kotsifakis/Wallops Flight Facility	Test and Support	March 5, 1991	Wallops Island, Virginia	Successful
36.077 UH	Cash/University of Colorado	High Energy Astrophysics	March 18, 1991	White Sands Missile Range	Successful
36.068 GG	Smith/Goddard Space Flight Center	UV/Optical Astrophysics	March 23, 1991	White Sands Missile Range	Successful
36.078 UL	Barth/University of Colorado	Solar System Exploration	March 30, 1991	White Sands Missile Range	Successful
31.079 UU	Zipf/University of Pittsburgh	Upper Atmosphere	April 25, 1991	Poker Flat Research Range	Successful
31.080 UU	Zipf/University of Pittsburgh	Upper Atmosphere	April 30, 1991	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.062 UL	Clarke/University of Michigan	Solar System Exploration	May 4, 1991	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.086 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 7, 1991	White Sands Missile Range	Successful
36.049 US	Walker/Stanford University	Solar and Heliospheric Sciences	May 13, 1991	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
24.011 CH	Catura/Lockheed Martin Space Corp.	High Energy Astrophysics	May 20, 1991	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.087 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	July 11, 1991	White Sands Missile Range	Successful
15.249 UE	Ulwick/Utah State University	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
21.103 GE	Goldberg/Goddard Space Flight Center/National Science Foundation	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
31.077 UE	Mitchell/Pennsylvania State University	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
15.250 UE	Ulwick/Utah State University	Geospace Sciences	August 5, 1991	Kiruna, Sweden	Successful
15.251 UE	Ulwick/Utah State University	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
21.104 GE	Goldberg/Goddard Space Flight Center/National Science Foundation	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
31.078 UE	Mitchell/Pennsylvania State University	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
27.129 UE	Sharp/University of Michigan	Geospace Sciences	September 6, 1991	White Sands Missile Range	Successful
38.019 UE	Mendillo/Boston University	Geospace Sciences	December 6, 1991	Wallops Island, Virginia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
38.020 UE	Mendillo/Boston University	Geospace Sciences	December 6, 1991	Wallops Island, Virginia	Successful
36.079 UG	Green/University of Colorado	UV/Optical Astrophysics	January 11, 1992	White Sands Missile Range	Successful
36.075 UE	Zipf/University of Pittsburgh	Geospace Sciences	January 23, 1992	White Sands Missile Range	Successful
36.096 UH	Cash/University of Colorado	High Energy Astrophysics	January 31, 1992	White Sands Missile Range	Successful
36.089 UG	Green/University of Colorado	UV/Optical Astrophysics	February 22, 1992	White Sands Missile Range	Successful
18.221 UE	Larsen/Clemson University	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful
27.130 CE	Kayser/Aerospace	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful
18.222 UE	Larsen/Clemson University	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful vehicle, unsuccessful mission
18.223 UE	Larsen/Clemson University	Geospace Sciences	March 6, 1992	Poker Flat Research Range	Successful
31.083 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 12, 1992	White Sands Missile Range	Successful
31.082 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 15, 1992	White Sands Missile Range	Successful
36.088 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 19, 1992	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
39.003 UE	Raitt/Utah State University	Geospace Sciences	March 29, 1992	Poker Flat Research Range	Successful
36.048 CS	Bruner/Lockheed Martin Space Corp.	Solar and Heliospheric Sciences	May 12, 1992	White Sands Missile Range	Successful
31.084 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 22, 1992	White Sands Missile Range	Successful
18.224 UE	Duncan/Clemson University	Geospace Sciences	May 25, 1992	Camp Tortuguero, Puerto Rico	Successful
31.085 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 27, 1992	White Sands Missile Range	Successful
36.065 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	May 30, 1992	Camp Tortuguero, Puerto Rico	Successful
36.064 CE	Szusczewicz/Science Applications International Corporation (SAIC)	Geospace Sciences	June 6, 1992	Camp Tortuguero, Puerto Rico	Successful
36.071 UE	Kelley/Cornell University	Geospace Sciences	June 9, 1992	Camp Tortuguero, Puerto Rico	Successful
21.105 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	June 23, 1992	Camp Tortuguero, Puerto Rico	Successful
36.082 DE	Weber/Air Force Geophysical Laboratory	Geospace Sciences	July 2, 1992	Camp Tortuguero, Puerto Rico	Successful
36.083 DE	Weber/Air Force Geophysical Laboratory	Geospace Sciences	July 4, 1992	Camp Tortuguero, Puerto Rico	Successful
36.081 CD	Djuth/Geospace Corp.	Geospace Sciences	July 12, 1992	Camp Tortuguero, Puerto Rico	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
27.133 UE	Sharp/University of Michigan	Geospace Sciences	July 24, 1992	Poker Flat Research Range	Successful
31.081 UU	Sheldon/University of Houston	Upper Atmosphere	August 21, 1992	Wallops Island, Virginia	Successful
36.090 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	August 24, 1992	White Sands Missile Range	Successful
31.093 UU	Zipf/University of Pittsburgh	Upper Atmosphere	August 26, 1992	White Sands Missile Range	Successful
12.045 WT	Balance/Wallops Flight Facility	Test and Support	August 27, 1992	Wallops Island, Virginia	Successful
31.092 UU	Zipf/University of Pittsburgh	Upper Atmosphere	September 1, 1992	White Sands Missile Range	Successful
30.040 UP	Johnson/University of Colorado	Special Projects	September 21, 1992	Wallops Island, Virginia	Successful
36.098 UE	Woods/University of Colorado	Geospace Sciences	October 27, 1992	White Sands Missile Range	Successful
31.094 UU	Zipf/University of Pittsburgh	Upper Atmosphere	December 6, 1992	White Sands Missile Range	Successful
31.095 UU	Zipf/University of Pittsburgh	Upper Atmosphere	December 11, 1992	White Sands Missile Range	Successful
36.085 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	December 15, 1992	White Sands Missile Range	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
40.003 UE	Arnoldy/University of New Hampshire	Geospace Sciences	January 1, 1993	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.100 NS	Davis/Marshall Space Flight Center	Solar and Heliospheric Sciences	February 8, 1993	White Sands Missile Range	Successful vehicle, unsuccessful mission
31.097 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 8, 1993	White Sands Missile Range	Successful
31.096 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 10, 1993	White Sands Missile Range	Successful
40.004 UE	Carlson/University of California, Berkeley	Geospace Sciences	April 2, 1993	Poker Flat Research Range	Successful
36.099 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	April 12, 1993	White Sands Missile Range	Successful
36.095 UN	Cash/University of Colorado	High Energy Astrophysics	April 17, 1993	White Sands Missile Range	Successful
27.136 UE	Parks/University of Washington	Geospace Sciences	May 6, 1993	Poker Flat Research Range	Successful
31.099 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 14, 1993	White Sands Missile Range	Successful
31.098 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 19, 1993	White Sands Missile Range	Successful
36.101 UL	Clarke/University of Michigan	Solar System Exploration	June 16, 1993	White Sands Missile Range	Successful
35.029 UE	Kintner/Cornell University	Geospace Sciences	July 22, 1993	Wallops Island, Virginia	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.105 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	August 17, 1993	White Sands Missile Range	Successful
24.017 CH	Catura/Lockheed Martin Space Corp.	High Energy Astrophysics	August 28, 1993	White Sands Missile Range	Unsuccessful vehicle, unsuccessful mission
31.100 UU	Zipf/University of Pittsburgh	Upper Atmosphere	September 10, 1993	White Sands Missile Range	Successful
31.101 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 13, 1993	White Sands Missile Range	Successful
36.107 UE	Woods/University of Colorado	Geospace Sciences	October 4, 1993	White Sands Missile Range	Successful
33.062 UE	Barth/University of Colorado	Geospace Sciences	October 4, 1993	White Sands Missile Range	Successful vehicle, unsuccessful mission
27.137 UE	Sharp/University of Michigan	Geospace Sciences	January 30, 1994	Poker Flat Research Range	Successful
36.110 IE	Pfaff/Goddard Space Flight Center	Geospace Sciences	February 9, 1994	Andoya, Norway	Successful
36.097 IE	Harris/Naval Research Center	Geospace Sciences	February 10, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
18.233 UE	Larsen/Clemson University	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
18.232 UE	Larsen/Clemson University	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
27.131 CE	Christensen/Aerospace Corp.	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
40.005 UE	Tolbert/University of New Hampshire	Geospace Sciences	March 5, 1994	Poker Flat Research Range	Successful vehicle, unsuccessful mission
31.071 UE	Bering/University of Houston	Geospace Sciences	March 7, 1994	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.114 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 11, 1994	Poker Flat Research Range	Successful
12.046 WT	Balance/Wallops Flight Facility	Test and Support	April 4, 1994	Wallops Island, Virginia	Successful
36.109 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 18, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.123 CS	Bruner/Lockheed Martin Missiles & Space	Solar and Heliospheric Sciences	April 25, 1994	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
31.087 UE	Croskey/Pennsylvania State University	Geospace Sciences	June 22, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
33.063 UE	Barth/University of Colorado	Geospace Sciences	June 27, 1994	Poker Flat Research Range	Successful
31.086 UE	Croskey/Pennsylvania State University	Geospace Sciences	July 15, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
30.039 UE	Croskey/Pennsylvania State University	Geospace Sciences	July 16, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
36.121. CL	Stern/Southwest Research Institute	Solar System Exploration	July 20, 1994	White Sands Missile Range	Successful
36.117 CL	Stern/Southwest Research Institute	Solar System Exploration	August 16, 1994	White Sands Missile Range	Successful
31.102 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 19, 1994	Alcantara, Brazil	Successful
31.103 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 20, 1994	Alcantara, Brazil	Successful
30.041 UP	Riddle/Colorado Space Grant	Special Projects	August 22, 1994	Wallops Island	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
31.105 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 24, 1994	Alcantara, Brazil	Successful
31.104 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 25, 1994	Alcantara, Brazil	Successful
21.110 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	September 9, 1994	Alcantara, Brazil	Successful
31.107 UU	Zipf/University of Pittsburgh	Geospace Sciences	September 12, 1994	White Sands Missile Range	Successful
31.108 UU	Zipf/University of Pittsburgh	Geospace Sciences	September 15, 1994	White Sands Missile Range	Successful
21.111 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	September 21, 1994	Alcantara, Brazil	Successful
18.226 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.225 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.228 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.227 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
36.084 UE	Zipf/University of Pittsburgh	Geospace Sciences	October 4, 1994	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
21.112 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 6, 1994	Alcantara, Brazil	Successful vehicle, unsuccessful mission
35.030 IE	Labelle/Dartmouth University	Geospace Sciences	October 14, 1994	Alcantara, Brazil	Successful
21.113 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 15, 1994	Alcantara, Brazil	Successful
36.124 AE	Woods/National Center for Atmospheric Research	Geospace Sciences	November 3, 1994	White Sands Missile Range	Successful
36.091 US	Walker/Stanford University	Solar and Heliospheric Sciences	November 3, 1994	White Sands Missile Range	Successful
36.013 NP	Ross/Lewis Research Center	Special Projects	November 22, 1994	White Sands Missile Range	Successful
36.050 UG	Nordsieck/University of Wisconsin	UV/Optical Astrophysics	December 3, 1994	White Sands Missile Range	Successful
36.102 UG	Green/University of Colorado	UV/Optical Astrophysics	December 17, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission
40.006 IE	Kintner/Cornell University	Geospace Sciences	January 25, 1995	Andoya, Norway	Successful
27.138 CE	Christensen/Aero Corp.	Geospace Sciences	February 2, 1995	Poker Flat Research Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
18.230 UE	Larsen/Clemson University	Geospace Sciences	February 2, 1995	Poker Flat Research Range	Successful
40.007 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 24, 1995	Poker Flat Research Range	Successful
31.106 NP	Schulze/NASA Headquarters	Special Projects	March 15, 1995	Wallops Island, Virginia	Successful
36.120 UE	Zipf/University of Pittsburgh	Geospace Sciences	March 21, 1995	White Sands Missile Range	Successful
31.112 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 21, 1995	White Sands Missile Range	Successful
35.031 UE	Westcott/University of Alaska	Geospace Sciences	March 26, 1995	Poker Flat Research Range	Successful vehicle, unsuccessful mission
36.104 UL	Clarke/University of Michigan	Solar System Exploration	April 1, 1995	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.137 CL	Stern/Southwest Research Institute	Solar System Exploration	April 15, 1995	White Sands Missile Range	Successful
36.108 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	April 18, 1995	White Sands Missile Range	Successful
36.125 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 15, 1995	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.092 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	May 22, 1995	White Sands Missile Range	Successful
33.064 UE	Barth/University of Colorado	Geospace Sciences	June 6, 1995	Poker Flat Research Range	Successful
12.047 WT	Maxfield/Wallops Flight Facility	Test and Support	June 30, 1995	White Sands Missile Range	Successful
31.109 UE	Espy/Utah State University	Geospace Sciences	July 26, 1995	Poker Flat Research Range	Successful vehicle, unsuccessful mission
31.110 UE	Espy/Utah State University	Geospace Sciences	August 9, 1995	Poker Flat Research Range	Successful
36.138 NP	Ross/Lewis Research Center	Special Projects	August 28, 1995	White Sands Missile Range	Successful
36.111 UE	Kelley/Cornell University	Geospace Sciences	September 2, 1995	Wallops Island, Virginia	Successful
36.131 US	Judge/University of Southern California	Solar and Heliospheric Sciences	September 12, 1995	White Sands Missile Range	Successful
36.106 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	October 25, 1995	Woomera, Australia	Successful
36.132 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	October 28, 1995	Woomera, Australia	Successful vehicle, unsuccessful mission
36.116 UG	Green/University of Colorado	UV/Optical Astrophysics	November 5, 1995	Woomera, Australia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
40.009 IE	James/Communications Research Centre of Canada	Geospace Sciences	November 7, 1995	Poker Flat Research Range	Successful
36.127 UG	Green/University of Colorado	UV/Optical Astrophysics	November 14, 1995	Woomera, Australia	Successful vehicle, unsuccessful mission
36.128 UG	Nordsieck/University of Wisconsin	UV/Optical Astrophysics	November 19, 1995	Woomera, Australia	Successful
36.126 UG	Green/University of Colorado	UV/Optical Astrophysics	November 20, 1995	Woomera, Australia	Successful
18.231 UE	Larsen/Clemson University	Geospace Sciences	November 24, 1995	Poker Flat Research Range	Successful
18.229 UE	Larsen/Clemson University	Geospace Sciences	November 27, 1995	Poker Flat Research Range	Successful
27.139 CE	Christensen/Aerospace Corp.	Geospace Sciences	November 27, 1995	Poker Flat Research Range	Successful
27.132 UH	McCammon/University of Wisconsin	High Energy Astrophysics	December 4, 1995	White Sands Missile Range	Successful vehicle/ unsuccessful mission
36.143 UE	Zipf/University of Pittsburgh	Geospace Sciences	February 23, 1996	White Sands Missile Range	Successful
36.145 NP	Ross/Lewis Research Center	Special Projects	February 23, 1996	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.122 UG	Green/University of Colorado	UV/Optical Astrophysics	March 6, 1996	White Sands Missile Range	Successful
27.140 UH	McCammon/University of Wisconsin	High Energy Astrophysics	June 4, 1996	White Sands Missile Range	Successful
36.134 UR	Lange/California Institute of Technology	Upper Atmosphere	June 17, 1996	White Sands Missile Range	Successful
36.118 NP	Olson/Lewis Research Center	Special Projects	June 20, 1996	White Sands Missile Range	Successful
36.147 NP	Judge/University of Southern California	Solar and Heliospheric Sciences	June 26, 1996	White Sands Missile Range	Successful
36.113 UG	Martin/Columbia University	UV/Optical Astrophysics	July 14, 1996	White Sands Missile Range	Successful
36.148 CL	Stern/Southwest Research Center	Solar System Exploration	July 26, 1996	White Sands Missile Range	Successful
31.114 UP	Riddle/University of Colorado	Special Projects	August 12, 1996	Wallops Island, Virginia	Successful
36.130 NS	Davis/Marshall Space Flight Center	Solar and Heliospheric Sciences	August 20, 1996	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.154 NP	Olson/Lewis Research Center	Special Projects	October 16, 1996	White Sands Missile Range	Successful
36.115 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	October 21, 1996	White Sands Missile Range	Successful
36.149 UL	Clare/University of Michigan	Solar System Exploration	October 29, 1996	White Sands Missile Range	Successful
36.142 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	November 13, 1996	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
41.005 GP	Deily/Goddard Space Flight Center	Special Projects	November 17, 1996	White Sands Missile Range	Successful
40.010 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 10, 1997	Poker Flat Research Range	Successful
40.011 UE	Torbert/University of New Hampshire	Geospace Sciences	February 11, 1997	Poker Flat Research Range	Successful
36.161 NP	Olson/Lewis Research Center	Special Projects	February 26, 1997	White Sands Missile Range	Successful
36.139 UE	Parks/University of Washington	Geospace Sciences	March 13, 1997	Poker Flat Research Range	Successful
36.158 UL	Green/University of Colorado	Solar System Exploration	March 25, 1997	White Sands Missile Range	Successful
36.155 CL	Stern/Southwest Research Institute	Solar System Exploration	March 30, 1997	White Sands Missile Range	Successful
36.156 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 6, 1997	White Sands Missile Range	Successful
36.157 UL	Harris/University of Wisconsin	Solar System Exploration	April 8, 1997	White Sands Missile Range	Successful
36.093 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	May 2, 1997	White Sands Missile Range	Successful
36.133 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	May 8, 1997	White Sands Missile Range	Successful
36.135 AE	Woods/National Center for Atmospheric Research	Geospace Sciences	May 15, 1997	White Sands Missile Range	Successful
41.013 DT	Bowman/Department of the Army	Test and Support	May 23, 1997	Wallops Island, Virginia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.163 UR	Lange/California Institute of Technology	Upper Atmosphere	May 29, 1997	White Sands Missile Range	Successful
41.011 UE	Ulwick/Utah State University	Geospace Sciences	August 8, 1997	Wallops Island, Virginia	Unsuccessful
21.120 NE	Mlynczak/Langley Research Center	Geospace Sciences	August 8, 1997	White Sands Missile Range	Successful
36.164 US	Judge/University of Southern California	Solar and Heliospheric Sciences	August 11, 1997	White Sands Missile Range	Successful
41.014 DT	Bowman/Department of the Army	Test and Support	September 2, 1997	Woomera, Australia	Successful
41.015 DT	Bowman/Department of the Army	Test and Support	September 5, 1997	Woomera, Australia	Successful
41.016 DT	Bowman/Department of the Army	Test and Support	September 10, 1997	Woomera, Australia	Successful
36.169 NM	Olson/Lewis Research Center	Microgravity Research	September 10, 1997	White Sands Missile Range	Successful
36.165 NP	Ross/Lewis Research Center	Special Projects	September 10, 1997	White Sands Missile Range	Successful
41.017 DT	Bowman/Department of the Army	Test and Support	September 11, 1997	Woomera, Australia	Successful
36.144 UE	Zipf/University of Pittsburgh	Geospace Sciences	September 19, 1997	White Sands Missile Range	Successful
36.140 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	September 30, 1997	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.129 DS	Moses/Naval Research Laboratory	Solar and Heliospheric Sciences	October 16, 1997	White Sands Missile Range	Successful
41.004 IE	Kane/Pennsylvania State University	Geospace Sciences	November 5, 1997	Andoya, Norway	Successful
36.080 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	November 14, 1997	White Sands Missile Range	Successful
36.167 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	November 18, 1997	White Sands Missile Range	Successful
36.153 IE	Maynard/Mission Research Corp.	Geospace Sciences	December 2, 1997	Svalbard, Norway	Successful
36.152	Pfaff/Goddard Space Flight Center	Geospace Sciences	December 3, 1997	Svalbard, Norway	Successful
21.117	Kelley/Cornell University	Geospace Sciences	February 20, 1998	Camp Tortuguero, Puerto Rico	Successful
21.119 UE	Larsen/Clemson University	Geospace Sciences	February 20, 1998	Camp Tortuguero, Puerto Rico	Successful
21.118 UE	Larsen/Clemson University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
33.067 UE	Larsen/Clemson University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
41.008 UE	Ulwick/Utah State University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
21.114 UE	Earle/University of Texas at Dallas	Geospace Sciences	March 7, 1998	Camp Tortuguero, Puerto Rico	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.159 UE	Kelley/Cornell University	Geospace Sciences	March 11, 1998	Camp Tortuguero, Puerto Rico	Successful
21.115 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	March 25, 1998	Camp Tortuguero, Puerto Rico	Successful
36.177 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	April 18, 1998	White Sands Missile Range	Successful
36.160 UG	Green/University of Colorado	UV/Optical Astrophysics	April 18, 1998	White Sands Missile Range	Successful
30.042 NP	Koehler/NASA Wallops Flight Facility	Special Projects	May 6, 1998	Wallops Island, Virginia	Successful
36.175 UR	Lange/California Institute of Technology	Upper Atmosphere	May 22, 1998	White Sands Missile Range	Successful
31.111 UP	Basciano/University of Cincinnati	Special Projects	June 17, 1998	Wallops Island, Virginia	Successful
36.176 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	August 15, 1998	White Sands Missile Range	Successful
36.150 NP	Murbach/Ames Research Center	Special Projects	September 18, 1998	White Sands Missile Range	Successful
36.171 CS	Hassler/Southwest Research Institute	Solar and Heliospheric Sciences	November 2, 1998	White Sands Missile Range	Successful
36.178 NM	Ross/Lewis Research Center	Microgravity Research	November 18, 1998	White Sands Missile Range	Successful vehicle, unsuccessful mission

[a] Goddard Space Flight Center, Wallops Flight Facility, "NASA Research Carriers Program Sounding Rocket and Balloon Projects Schedule," October 2001.

Table 4–63. NASA Balloon Flights (1989–1998[a])

Experimenter/Organization	Discipline	Date	Site	Results
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	April 3, 1989	Alice Springs, Australia	Successful
Sofia/Yale University	Solar and Heliospheric Physics	April 18, 1989	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	April 19, 1989	Ft. Sumner, New Mexico	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	May 8, 1989	Alice Springs, Australia	Successful
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	May 15, 1989	Palestine, Texas	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	May 21, 1989	Alice Springs, Australia	Successful
Waters/Jet Propulsion Laboratory	Upper Atmosphere Research	May 27, 1989	Palestine, Texas	Successful
Heaps/Goddard Space Flight Center	Upper Atmosphere Research	June 6, 1989	Palestine, Texas	Balloon successful, mission unsuccessful
Diagnostic, Anderson/National Scientific Balloon Facility, Harvard University	Test Flight	July 28, 1989	Palestine, Texas	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	July 31, 1989	Palestine, Texas	Successful
Diagnostic, Anderson/National Scientific Balloon Facility, Harvard University	Test Flight	August 25, 1989	Palestine, Texas	Successful
Zander/University of Liege	Upper Atmosphere Research	August 28, 1989	Palestine, Texas	Successful
Beatty/Boston University	Cosmic Ray Astrophysics	September 1, 1989	Prince Albert, Canada	Successful
Golden, Streitmatter/New Mexico State University, Goddard Space Flight Center	Cosmic Ray Astrophysics	September 5, 1989	Prince Albert, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Traub, Waters/Smithsonian Astrophysical Observatory, Jet Propulsion Laboratory	Upper Atmosphere Research	September 26, 1989	Ft. Sumner, New Mexico	Successful
White/University of California, Riverside	Gamma Ray/X-Ray Astrophysics	September 29, 1989	Ft. Sumner, New Mexico	Successful
Meyer/Massachusetts Institute of Technology	Upper Atmosphere Research	October 6, 1989	Ft. Sumner, New Mexico	Successful
Farmer/Jet Propulsion Laboratory	Upper Atmosphere Research	October 8, 1989	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	October 13, 1989	Ft. Sumner, New Mexico	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	October 24, 1989	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	November 2, 1989	Ft. Sumner, New Mexico	Successful
Richards/University of California, Berkeley	Upper Atmosphere Research	November 15, 1989	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Upper Atmosphere Research	November 19, 1989	Ft. Sumner, New Mexico	Successful
Stuchlik, LDB Subsystems Test/Goddard Space Flight Center–Wallops Flight Facility	Test Flight	January 1, 1990	McMurdo Station, Antarctica	Balloon successful, mission unsuccessful
Stuchlik, LDB Subsystems Test/Goddard Space Flight Center–Wallops Flight Facility	Test Flight	January 8, 1990	McMurdo Station, Antarctica	Balloon successful, mission unsuccessful
Sofia/Yale University	Solar and Heliospheric Physics	May 4, 1990	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	May 5, 1990	Ft. Sumner, New Mexico	Successful
Stachnik-Traub/Jet Propulsion Laboratory	Upper Atmosphere Research	May 12, 1990	Ft. Sumner, New Mexico	Balloon and mission unsuccessful
Meyer/Massachusetts Institute of Technology	UV/Optical Astrophysics	May 31, 1990	Ft. Sumner, New Mexico	Successful
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	May 31, 1990	Ft. Sumner, New Mexico	Successful
Stachnik-Traub/Jet Propulsion Laboratory, Smithsonian Astrophysical Observatory	Upper Atmosphere Research	June 4, 1990	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	June 4, 1990	Palestine, Texas	Successful
Lubin/University of California, Santa Barbara	UV/Optical Astrophysics	July 2, 1990	Palestine, Texas	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	July 10, 1990	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	July 28, 1990	Ft. Sumner, New Mexico	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 9, 1990	Lynn Lake, Canada	Balloon successful, mission unsuccessful
Simpson, Diagnostic/Wallops Flight Facility	Test Flight	August 16, 1990	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 26, 1990	Lynn Lake, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Zander/University of Liege	Upper Atmosphere Research	August 29, 1990	Palestine, Texas	Successful
Stuchlik/LDB Subsystems	Test Flight	September 2, 1990	Palestine, Texas	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 19, 1990	Ft. Sumner, New Mexico	Balloon and mission unsuccessful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 26, 1990	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 27, 1990	Ft. Sumner, New Mexico	Successful
Russell/Langley Research Center	Upper Atmosphere Research	October 9, 1990	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 11, 1990	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	October 23, 1990	Ft. Sumner, New Mexico	Successful
Bawcom/National Scientific Balloon Facility	Test Flight	October 28, 1990	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Geospace Sciences	October 30, 1990	Ft. Sumner, New Mexico	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	December 20, 1990	Antarctica	Balloon successful, mission unsuccessful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	January 30, 1991	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Holzworth/University of Washington	Geospace Sciences	February 20, 1991	New Zealand	Balloon successful, mission unsuccessful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	February 23, 1991	Palestine, Texas	Successful
Bawcom/ Diagnostic/National Scientific Balloon Facility	Test Flight	March 29, 1991	Ft. Sumner, New Mexico	Successful
Anderson/Harvard University	Upper Atmosphere Research	March 31, 1991	Ft. Sumner, New Mexico	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	April 9, 1991	Daggett, California	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	May 5, 1991	Ft. Sumner, New Mexico	Successful
Bawcom/ Diagnostic/National Scientific Balloon Facility	Test Flight	May 8, 1991	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	May 26, 1991	Palestine, Texas	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 26, 1991	Palestine, Texas	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	June 4, 1991	Palestine, Texas	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	June 12, 1991	Palestine, Texas	Successful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	June 16, 1991	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	June 17, 1991	Palestine, Texas	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Simpson/NSP/Wallops Flight Facility	Test Flight	June 18, 1991	Ft. Sumner, New Mexico	Balloon failed, mission successful
Hays/University of Michigan	Upper Atmosphere Research	June 19, 1991	Palestine, Texas	Successful
Beatty/Boston University	Cosmic Ray Astrophysics	July 25, 1991	Lynn Lake, Canada	Successful
Klarmann/Washington University	Cosmic Ray Astrophysics	August 9, 1991	Lynn Lake, Canada	Successful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	September 10, 1991	Palestine, Texas	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	September 17, 1991	Ft. Sumner, New Mexico	Successful
Golden/New Mexico State University	Cosmic Ray Astrophysics	September 23, 1991	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	September 25, 1991	Ft. Sumner, New Mexico	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	October 1, 1991	Ft. Sumner, New Mexico	Successful
Bawcom/Diagnostic/National Scientific Balloon Facility	Test Flight	November 2, 1991	Palestine, Texas	Successful
Holzworth, Diagnostics/University of Washington	Test Flight	November 8, 1991	Ft. Sumner, New Mexico	Successful
Salamon/University of Utah	Cosmic Ray Astrophysics	December 16, 1991	Antarctica	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	January 10, 1992	Antarctica	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	February 20, 1992	Daggett, California	Successful
Anderson/Harvard University	Upper Atmosphere Research	February 22, 1992	Sondre Stronfjord, Greenland	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Anderson/Harvard University	Upper Atmosphere Research	March 1, 1992	Sondre Stronfjord, Greenland	Successful
Simpson, OZP/NWallops Flight Facility	Test Flight	March 9, 1992	Daggett, California	Successful
Anderson/Harvard University	Upper Atmosphere Research	March 11, 1992	Sondre Stronfjord, Greenland	Successful
Simpson, NSP/Wallops Flight Facility	Test Flight	April 12, 1992	Palestine, Texas	Mission successful, balloon unsuccessful,
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	April 26, 1992	Alice Springs, Australia	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	April 27, 1992	Alice Springs, Australia	Balloon successful, mission unsuccessful
Nolt/Langley Research Center	Upper Atmosphere Research	May 4, 1992	Ft. Sumner, New Mexico	Successful
Zander/University of Liege	Upper Atmosphere Research	May 4, 1992	Ft. Sumner, New Mexico	Successful
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	May 7, 1992	Alice Springs, Australia	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 8, 1992	Alice Springs, Australia	Balloon successful, mission failed
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 24, 1992	Alice Springs, Australia	Successful
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	May 29, 1992	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	June 1, 1992	Alice Springs, Australia	Successful
Silverberg/Goddard Space Flight Center	Infrared/Submillimeter Astrophysics	June 5, 1992	Palestine, Texas	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 17, 1992	Lynn Lake, Canada	Successful
Holzworth/University of Washington	Upper Atmosphere Research	July 24, 1992	Wallops Island, VA	Balloon succeeded, mission unsuccessful
Murcray/University of Denver	Upper Atmosphere Research	July 24, 1992	Palestine, Texas	Successful
Holzworth/University of Washington	Upper Atmosphere Research	July 31, 1992	Wallops Island, VA	Balloon and mission unsuccessful
Meyer/University of Chicago	Cosmic Ray Astrophysics	August 2, 1992	Lynn Lake, Canada	Balloon and mission unsuccessful
Holzworth/University of Washington	Upper Atmosphere Research	August 11, 1992	Wallops Island, VA	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 25, 1992	Lynn Lake, Canada	Successful
Webster/Jet Propulsion Laboratory	Upper Atmosphere Research	August 26, 1992	Palestine, Texas	Successful
Gregory, LDB/National Scientific Balloon Facility	Test Flight	August 29, 1992	Palestine, Texas	Successful
Simpson, OZP/Wallops Flight Facility	Test Flight	September 6, 1992	Lynn Lake, Canada	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 14, 1992	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Stachnik, Traub/Jet Propulsion Laboratory, Smithsonian Astrophysical Observatory	Upper Atmosphere Research	September 29, 1992	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	September 30, 1992	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 16, 1992	Ft. Sumner, New Mexico	Successful
Robbins/Wallops Flight Facility	Test Flight	November 5, 1992	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 10, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 19, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 21, 1992	New Zealand	Mission successful, balloon unsuccessful
Holzworth/University of Washington	Upper Atmosphere Research	November 30, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	December 6, 1992	New Zealand	Successful
Trombka/Goddard Space Flight Center	Solar and Heliospheric Physics	December 12, 1992	Antarctica	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	December 31, 1992	Antarctica	Balloon successful, mission failed
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	March 23, 1993	Daggett, California	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	April 3, 1993	Daggett, California	Successful
Murcray/University of Denver	Upper Atmosphere Research	April 7, 1993	Daggett, California	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Parks/University of Washington	Geospace Sciences	May 1, 1993	Fairbanks, Alaska	Balloon successful, mission failed
Bell/Wallops Flight Facility	Test Flight	May 3, 1993	Ft. Sumner, New Mexico	Successful
Parks/University of Washington	Geospace Sciences	May 6, 1993	Fairbanks, Alaska	Successful
Lubin, Seiffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	May 21, 1993	Palestine, Texas	Successful
Murcray/University of Denver	Upper Atmosphere Research	May 25, 1993	Palestine, Texas	Balloon successful, mission failed
Nolt/Langley Research Center	Upper Atmosphere Research	May 31, 1993	Ft. Sumner, New Mexico	Successful
Zander/University of Liege	Upper Atmosphere Research	June 11, 1993	Ft. Sumner, New Mexico	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	June 13, 1993	Palestine, Texas	Successful
Lubin, Meinhold/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 16, 1993	Palestine, Texas	Successful
Crannell/Goddard Space Flight Center	Solar and Heliospheric Physics	June 22, 1993	Palestine, Texas	Successful
Murcray/University of Denver	Upper Atmosphere Research	July 19, 1993	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 26, 1993	Lynn Lake, Canada	Successful
Lubin, Koch/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	August 12, 1993	Palestine, Texas	Balloon succeeded, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Weidenbeck/Jet Propulsion Laboratory	Cosmic Ray Astrophysics	August 13, 1993	Lynn Lake, Canada	Balloon succeeded, mission unsuccessful
LDBV, Simpson/Wallops Flight Facility	Test Flight	August 17, 1993	Lynn Lake, Canada	Successful
Holzworth/University of Washington	Geospace Sciences	August 18, 1993	Wallops Flight Facility	Successful
LDB, Kubara/Wallops Flight Facility	Test Flight	September 2, 1993	Lynn Lake, Canada	Balloon and mission unsuccessful
Golden/New Mexico State University	Cosmic Ray Astrophysics	September 9, 1993	Ft. Sumner, New Mexico	Successful
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	September 14, 1993	Ft. Sumner, New Mexico	Successful
Tueller/Goddard SpaceFlight Center	Gamma Ray/X-Ray Astrophysics	September 23, 1993	Ft. Sumner, New Mexico	Successful
Toon, Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	September 25, 1993	Ft. Sumner, New Mexico	Successful
Gregory/University of Alabama	Cosmic Ray Astrophysics	September 29, 1993	Ft. Sumner, New Mexico	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	October 27, 1993	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 14, 1993	Antarctica	Balloon successful, mission unsuccessful
Wilkes/University of Washington	Cosmic Ray Astrophysics	January 2, 1994	Antarctica	Successful
Rust/Applied Physics Lab	Solar and Heliospheric Physics	January 23, 1994	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Muller/University of Chicago	Cosmic Ray Astrophysics	May 30, 1994	Ft. Sumner, New Mexico	Successful
Nolt/Langley Research Center	Upper Atmosphere Research	May 15, 1994	Ft. Sumner, New Mexico	Successful
Traub, Toon/Smithsonian Astrophysical Observatory, Jet Propulsion Laboratory	Upper Atmosphere Research	May 22, 1994	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Geospace Sciences	May 26, 1994	Wallops Flight Facility	Balloon succeeded, mission unsuccessful
Holzworth/University of Washington	Geospace Sciences	May 26, 1994	Wallops Flight Facility	Successful
Silverberg/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 2, 1994	Palestine, Texas	Successful
Lubin, Seiffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 7, 1994	Palestine, Texas	Successful
Lubin, Sieffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 20, 1994	Palestine, Texas	Successful
Holzworth/University of Washington	Geospace Sciences	June 22, 1994	Wallops Flight Facility	Successful
Murcray/University of Denver	Upper Atmosphere Research	July 10, 1994	Palestine, Texas	Balloon succeeded, mission unsuccessful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 1, 1994	Lynn Lake, Canada	Successful
Golden/New Mexico State University	Cosmic Ray Astrophysics	August 8, 1994	Lynn Lake, Canada	Successful
Cooper, LDB/Wallops Flight Facility	Test Flight	August 17, 1994	Lynn Lake, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Lubin, Koch/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	August 27, 1994	Palestine, Texas	Balloon succeeded, mission unsuccessful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 28, 1994	Lynn Lake, Canada	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	September 2, 1994	Palestine, Texas	Balloon and mission unsuccessful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	September 10, 1994	Palestine, Texas	Successful
Sofia/Yale University	Solar and Heliospheric Physics	September 26, 1994	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 9, 1994	Ft. Sumner, New Mexico	Successful
Klein/National Scientific Balloon Facility	Test Flight	October 19, 1994	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 21, 1994	Antarctica	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	January 8, 1995	Antarctica	Successful
Raque/Wallops Flight Facility	Test Flight	April 1, 1995	Ft. Sumner, New Mexico	Successful
Parsons/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	June 1, 1995	Palestine, Texas	Successful
Silverberg/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 1, 1995	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 26, 1995	Lynn Lake, Canada	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	August 23, 1995	Lynn Lake, Canada	Successful
Sandy/Virginia Space Grant Consortium	Special Projects	August 23, 1995	Wallops Flight Facility	Successful
Lande/University of Pennsylvania	Special Projects	August 23, 1995	Wallops Flight Facility	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Binns/Washington University	Cosmic Ray Astrophysics	August 26, 1995	Lynn Lake, Canada	Balloon and mission unsuccessful
Richards/University of California, Berkeley	IR/Submillimeter Astrophysics	September 3, 1995	Palestine, Texas	Successful
Sood/University of New South Wales	Special Projects	September 26, 1995	Alice Springs, Australia	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 27, 1995	Ft. Sumner, New Mexico	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 28, 1995	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 1, 1995	Ft. Sumner, New Mexico	Successful
Tueller/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	October 4, 1995	Alice Springs, Australia	Balloon and mission unsuccessful
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	October 6, 1995	Alice Springs, Australia	Successful
Frontera/Instituto Di Tecnologie e Studio Delle Radiaziioni Extraterrestri (TESRE)	Gamma Ray/X-Ray Astrophysics	October 6, 1995	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 10, 1995	Ft. Sumner, New Mexico	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	October 14, 1995	Ft. Sumner, New Mexico	Successful
Hailey/Lawrence Livermore National Laboratory	Gamma Ray/X-Ray Astrophysics	October 16, 1995	Alice Springs, Australia	Successful
Tueller/ Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	October 24, 1995	Alice Springs, Australia	Successful
Tueller/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	November 14, 1995	Alice Springs, Australia	Successful
Meyer/University of Chicago	IR/Submillimeter Astrophysics	December 9, 1995	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 19, 1995	Antarctica	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Rust/Applied Physics Laboratory	Solar and Heliospheric Physics	January 7, 1996	Antarctica	Successful
Lubin/University of California, Santa Barbara	IR/Submillimeter Astrophysics	February 11, 1996	Ft. Sumner, New Mexico	Successful
Lubin, Meinhold/University of California, Santa Barbara	IR/Submillimeter Astrophysics	June 2, 1996	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	June 10, 1996	Ft. Sumner, New Mexico	Successful
Wilkinson/Princeton University	IR/Submillimeter Astrophysics	June 17, 1996	Palestine, Texas	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	June 30, 1996	Palestine, Texas	Successful
Rotter/National Scientific Balloon Facility	Test Flight	July 3, 1996	Palestine, Texas	Successful
Adams/Naval Research Laboratory	Cosmic Ray Astrophysics	July 4, 1996	Fairbanks, Alaska	Balloon and mission unsuccessful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	July 24, 1996	Lynn Lake, Canada	Balloon successful, mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 8, 1996	Palestine, Texas	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	September 21, 1996	Ft. Sumner, New Mexico	Successful
Buisson/Centre National d'Etudes Spatiales (CNES)	Gamma Ray/X-Ray Astrophysics	September 22, 1996	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 28, 1996	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 10, 1996	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	October 13, 1996	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Anspaugh/Jet Propulsion Laboratory	Special Projects	October 23, 1996	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful
Wilkinson/Princeton University	IR/Submillimeter Astrophysics	November 9, 1996	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	February 14, 1997	Brazil	Successful
Orr, Simpson/National Scientific Balloon Facility, Wallops Flight Facility	Test Flight	March 30, 1997	Ft. Sumner, New Mexico	Successful
Traub/Jet Propulsion Laboratory	Upper Atmosphere Research	April 30, 1997	Fairbanks, Alaska	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	May 7, 1997	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	May 8, 1997	Fairbanks, Alaska	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	May 20, 1997	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 24, 1997	Ft. Sumner, New Mexico	Balloon successful, mission failed
Cheng/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 2, 1997	Palestine, Texas	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	June 11, 1997	Palestine, Texas	Successful
Orr, Simpson/National Scientific Balloon Facility, Wallops Flight Facility	Test Flight	June 23, 1997	Fairbanks, Alaska	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	June 30, 1997	Fairbanks, Alaska	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	July 8, 1997	Fairbanks, Alaska	Successful
Aprile/Columbia University	Gamma Ray/X-Ray Astrophysics	July 25, 1997	Palestine, Texas	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Ormes, Orito/Goddard Space Flight Center, High Energy Accelerator Research Organization (KEK-Japan)	Cosmic Ray Astrophysics	July 28, 1997	Lynn Lake, Canada	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 2, 1997	Palestine, Texas	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	August 13, 1997	Palestine, Texas	Balloon and mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 14, 1997	Palestine, Texas	Balloon succeeded, mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 24, 1997	Palestine, Texas	Successful
Aprile/Columbia University	Gamma Ray/X-Ray Astrophysics	August 25, 1997	Palestine, Texas	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	August 30, 1997	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	September 2, 1997	Lynn Lake, Canada	Successful
Binns/Washington University	Cosmic Ray Astrophysics	September 24, 1997	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	October 4, 1997	Ft. Sumner, New Mexico	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	October 15, 1997	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	November 11, 1997	Brazil	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	November 20, 1997	Brazil	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	January 7, 1998	Antarctica	Balloon and mission failed

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Candeleria/National Scientific Balloon Facility	Test Flight	February 11, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	February 18, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	February 20, 1998	Palestine, Texas	Successful
Farman/National Scientific Balloon Facility	Test Flight	March 20, 1998	Ft. Sumner, New Mexico	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	March 24, 1998	Palestine, Texas	Successful
Farman/National Scientific Balloon Facility	Test Flight	April 9, 1998	Ft. Sumner, New Mexico	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	April 10, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	April 19, 1998	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	April 22, 1998	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 16, 1998	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful
Brune/Pennsylvania State University	Upper Atmosphere Research	May 18, 1998	Ft. Sumner, New Mexico	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	May 21, 1998	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Pickett/Jet Propulsion Laboratory	Upper Atmosphere Research	May 24, 1998	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 28, 1998	Ft. Sumner, New Mexico	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	June 18, 1998	Fairbanks, Alaska	Balloon succeeded, mission unsuccessful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	June 29, 1998	Fairbanks, Alaska	Balloon succeeded, mission unsuccessful
Klein/National Scientific Balloon Facility	Test Flight	July 18, 1998	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 30, 1998	Lynn Lake, Canada	Successful
Richards/University of California, Berkeley	IR/Submillimeter Astrophysics	August 2, 1998	Palestine, Texas	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 4, 1998	Lynn Lake, Canada	Successful
Wilkins/Prairie View A&M University	Special Projects	August 18, 1998	Palestine, Texas	Successful
Bukiet/New Jersey Institute of Technology	Special Projects	August 21, 1998	Wallops Flight Facility	Successful
Pierce/Virginia Space Grant Consortium	Special Projects	August 22, 1998	Wallops Flight Facility	Successful
Tucker/Brown University	IR/Submillimeter Astrophysics	August 25, 1998	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 30, 1998	Lynn Lake, Canada	Successful
Klein, Silverberg/National Scientific Balloon Facility, NASA Goddard Space Flight Center	Test Flight	September 28, 1998	Fort Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Raque/Wallops Flight Facility	Test Flight	October 13, 1998	Fort Sumner, New Mexico	Successful
Raque/Wallops Flight Facility	Test Flight	October 15, 1998	Fort Sumner, New Mexico	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	December 29, 1998	Antarctica	Successful

[a] "NASA Research Carriers Program Sounding Rocket and Balloon Projects Schedule," Copy provided by Keith Koehler, NASA Wallops Flight Facility Public Affairs Office.

Table 4–64. Magellan Mission Events[a]

Date	Event
May 4, 1989	Launch.
August 10, 1990	Venus orbit insertion and spacecraft checkout.
September 15, 1990– May 14, 1991	First mapping cycle: Radar mapping; Mapped 84 percent of the surface of the planet, with resolution 10 times better than achieved by the earlier Soviet Venera 15 and 16 missions.
May 15, 1991	Extended mission begins.[b]
May 15, 1991– January 14, 1992	Cycle 2: Imaged the south pole region and gaps from Cycle 1.
January 15, 1992– September 13, 1992	Cycle 3: Filled remaining gaps and collected stereo imagery; brought mapping coverage to 98 percent of the planet, with a resolution of approximately 100 m.
September 14, 1992– May 23, 1993	Cycle 4: Obtained gravity data by pointing the Magellan antenna toward Earth and measuring the Doppler shift in radio transmissions. These measurements were used to estimate variations in the gravitational field of Venus.
May 24, 1993– August 2, 1993	Aerobraking to circularize orbit and global gravity measurements.
August 3, 1993– August 29, 1994	Cycle 5: Gravity data acquisition using circularized orbit.
September 1994	Cycle 6: Collected high-resolution gravity data and conducted radio science experiments. Windmill experiment: Observed behavior of molecules in upper atmosphere.
October 11, 1994	Descent into Venus atmosphere.
October 12, 1994	Radio signal lost.

[a] "Magellan Mission to Venus," *http://nssdc.gsfc.nasa.gov/planetary/magellan.html* (accessed September 16, 2005). Also "Magellan Mission at a Glance," *http://www2.jpl.nasa.gov/magellan/fact.html* (accessed August 16, 2005). "Magellan: Mission Plan," *http://nssdc.gsfc.nasa.gov/planetary/mgncycles.html* (accessed September 19, 2005).

[b] There is some inconsistency about when the extended mission began. Most often, it is considered to have begun after the first mapping cycle. However, according to the former project manager, Douglas Griffith, Cycles 1–4 were funded by prime mission funding while Cycles 5 and 6 were funded by additional funding. He considers the extended mission to begin with Cycle 5. (E-mails from Douglas Griffith and Ron Baalke, September 19, 2005).

Table 4–65. Magellan Mission Characteristics

Launch Date/Launch Site	May 4, 1989/Cape Canaveral
Date of Reentry	Burned up in Venus's atmosphere October 12, 1994.
Launch Vehicle	STS-30/*Atlantis*
NASA Role	Mission management, operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives[a]	Program objective: • To place a satellite carrying a radar sensor into orbit around Venus to obtain scientific data regarding the surface of Venus, to reduce and analyze these data, and to make the results available to the public and the scientific community. Mission objectives: • To obtain near global (greater than 70 percent coverage) radar images of the planet's surface, with resolution equivalent to optical imaging of 1 km (0.62 mi) per line pair. • To obtain a near global topographic map with 50-km (31-mi) spatial and 100-m (328-ft) vertical resolution. • To obtain near global (greater than 76 percent) gravity field data with 700-km (435-mi) or better resolution and 2 milligals to 3 milligals accuracy. • To develop an understanding of the geological evolution of the planet, principally its density distribution and dynamics.
Orbit Characteristics (around Venus):	
Apogee	8,029 km (4,990 mi)
Perigee	250 km (155 mi)
Inclination (deg)	86
Period (min)	195 (first cycle), 94 (fifth cycle)
Weight	Spacecraft: 3,449 kg (7,603 lb) at time of injection into Venus transfer orbit Radar sensor: 126 kg (278 lb)
Dimensions	Spacecraft: length: 6.4 m (21 ft), diameter: 4.6 m (15.1 ft); parabolic dish antenna: 3.6 m (11.8 ft); solar panels spanned 9.2 m (30.2 ft); total area of solar panels: 12.6 sq m (135.6 sq ft)
Shape	Bus: 10-sided
Power Source	Solar panels and nickel cadmium batteries
Prime Contractor	Spacecraft: Martin Marietta Astronautics Group; radar sensor: Hughes Aircraft Co.
PIs	Radar: Gordon Pettengill, Massachusetts Institute of Technology Gravity: William Sjogren, Jet Propulsion Laboratory; and Georges Balmino, France[b]

Table 4–65. Magellan Mission Characteristics (Continued)

Instruments and Experiments	The radar system consisted of the radar sensor, high-gain antenna, and altimeter antenna. The radar sensor operated as a SAR at 2,385-GHz frequency in the S-band. The high-gain antenna transmitted and received active radar pulses for the SAR mode and collected microwave energy passively emitted by Venus for the radiometer mode. In the SAR mode, the images had a radar resolution better than 270 m (886 ft) with a minimum of four incoherent looks (to reduce speckle) over an altitude range from 250 km to 2,100 km (155 mi to 1,305 mi). When the radar system operated as a passive radiometer, the temperature resolution was 2 K. As an altimeter, the radar used a separate fan beam antenna pointed vertically at the planet's surface to measure the heights of geologic features. Magellan altimetry had a vertical resolution of less than 30 m (98 ft) with a spot size of 20 km to 55 km (12 mi to 34 mi). In addition to the antennae, the radar system consisted of a single box of flight hardware containing a stable local oscillator; pulse repetition frequency/timing; range dispersion; transmitter; output network; receiver; baseband processor; data formatter; and telemetry and command. Each unit was duplicated to provide redundancy that could be switched by ground command.[c]
Results[d]	Magellan mapped 98 percent of the planet's surface with radar and compiled a high-resolution gravity map of 95 percent of the planet. Key scientific findings included the following: • Evidence relating to the role of impacts, volcanism, and tectonism in the formation of Venusian surface structures. • Discovery that the surface of Venus was covered largely by volcanic materials. Volcanic surface features, such as vast lava plains, fields of small lava domes, and large shield volcanoes were common. • There were few impact craters, suggesting that the surface was, in general, geologically young—less than 800 million years old. • The presence of lava channels more than 6,000 km (3,728 mi) long suggested river-like flows of extremely low-viscosity lava that probably erupted at a high rate. • Large pancake-shaped volcanic domes suggested the presence of a type of lava produced by extensive evolution of crustal rocks.

Table 4–65. Magellan Mission Characteristics (Continued)

Results	• The typical signs of terrestrial plate tectonics—continental drift and basin floor spreading—were not in evidence on Venus. The planet's tectonics were dominated by a system of global rift zones and numerous broad, low domical structures called coronae, which were produced by the upwelling and subsidence of magma from the mantle. • Although Venus had a dense atmosphere, the surface revealed no evidence of substantial wind erosion; it revealed evidence of limited wind transport of dust and sand only. This contrasted with Mars, where there was a thin atmosphere but substantial evidence of wind erosion and transport of dust and sand.

[a] "Magellan Mission Operations Report," Report no. E-844-89-30-01, NASA Office of Space Science and Applications, p. viii. (NASA History Office Electronic Document 30712).

[b] "Magellan Fact Sheet," *http://nssdc.gsfc.nasa.gov/planetary/factsheet.html* (accessed October 12, 2005).

[c] "Magellan Mission Operations Report," Report no. E-844-89-30-01, NASA Office of Space Science and Applications (NASA History Office Electronic Document 30712).

[d] "Magellan Fact Sheet," *http://nssdc.gsfc.nasa.gov/planetary/factsheet.html* (accessed October 12, 2005).

Table 4–66. Galileo Major Mission Events (1989–1999)

Date	Event
October 18, 1989	Launch from Kennedy Space Center on Space Shuttle *Atlantis*, STS-34
October 1989–December 1997	Primary mission
February 10, 1990	Venus flyby, at altitude of 16,000 km (10,000 mi)
December 8, 1990	First Earth flyby, at altitude of 960 km (597 mi)
April 11, 1991	Galileo unsuccessfully attempts to unfurl its high gain antenna
October 29, 1991	Asteroid Gaspra flyby, at 1,601 km (1,000 mi)
December 8, 1992	Second Earth flyby, at altitude of 303 km (188 mi), end of VEEGA phase
August 28, 1993	Asteroid Ida flyby, at 2,400 km (1,400 mi)
July 16–July 22, 1994	Comet Shoemaker-Levy 9, observed impacts of comet fragments into Jupiter
July 13, 1995	Atmospheric probe released
July 27, 1995	First sustained firing of Galileo main rocket engine
November 26, 1995	Orbiter enters Jupiter's environment, crossing from interplanetary space into its magnetosphere
December 7, 1995	Probe enters Jupiter's atmosphere; relays data for 58 minutes
December 7, 1995	Orbiter arrives at Jupiter, passes Europa and Io, fires main engine to brake into Jupiter's orbit
December 7, 1995–December 7, 1997	Prime mission orbital tour, 11 orbits
March 1996	Engineers radio new software to Galileo permitting data compression for low gain antenna transmission
September 6, 1996	Closest approach, 261 km (162 mi), to Ganymede
December 7, 1997	Completed primary mission
December 8, 1997–December 31, 1999	Galileo Europa Mission (GEM)
December 16, 1997–May 4, 1999	Europa campaign, eight orbits
December 16, 1997	Closest approach, 201 km (125 mi), to Europa
May 5, 1999–October 10, 1999	Jupiter water/Io torus study
October 11, 1999–December 31, 1999	Io campaign

Table 4–67. Galileo Encounters at Jupiter (1995–1999[a])

Orbit	Target	Date	Altitude
0	Io	December 7, 1995	897 km (558 mi)
G1	Ganymede	June 27, 1996	835 km (519 mi)
G2	Ganymede	September 6, 1996	261 km (162 mi)
C3	Callisto	November 4, 1996	1,136 km (706 mi)
E4	Europa	December 19, 1996	692 km (430 mi)
5	None		
E6	Europa	February 20, 1997	586 km (364 mi)
G7	Ganymede	April 5, 1997	3,102 km (1,928 mi)
G8	Ganymede	May 7, 1997	1,603 km (996 mi)
C9	Callisto	June 25, 1997	418 km (260 mi)
C10	Callisto	September 17, 1997	535 km (333 mi)
E11	Europa	November 6, 1997	2,043 km (1,270 mi)
E12[b]	Europa	December 16, 1997	201 km (125 mi)
13	None		
E14	Europa	March 29, 1998	1,644 km (1,022 mi)
E15	Europa	May 31, 1998	2,515 km (1,562 mi)
E16	Europa	July 21, 1998	1,834 km (1,140 mi)
E17	Europa	September 26, 1998	3,582 km (2,226 mi)
E18	Europa	November 22, 1998	2,271 km (1,411 mi)
E19	Europa	February 1, 1999	1,439 km (894 mi)
C20	Callisto	May 5, 1999	1,321 km (821 mi)
C21	Callisto	June 30, 1999	1,048 km (651 mi)
C22	Callisto	August 14, 1999	2,299 km (1,429 mi)
C23	Callisto	September 16, 1999	1,052 km (654 mi)
I24	Io	October 11, 1999	611 km (380 mi)
I25	Io	November 26, 1999	301 km (187 mi)

[a] "Galileo End of Mission Press Kit," p. 10.
[b] Beginning of Galileo Europa Mission (GEM).

Table 4–68. Galileo Mission Characteristics

Launch Date/Launch Site	October 18, 1989/Kennedy Space Center
Date of Reentry	No reentry. Mission ended on September 21, 2003, when the spacecraft passed into Jupiter's shadow and disintegrated.
Launch Vehicle	STS-34/*Atlantis*
NASA Role	Project management; designing, building, testing, operating, and tracking the spacecraft and probe
Responsible (Lead) Center	Jet Propulsion Laboratory: Mission operations, design and development of orbiter; Ames Research Center: Developed probe
Mission Objectives	Primary objectives: • Deliver an entry probe to make *in situ* measurements of the atmosphere of Jupiter and to place an orbiter around Jupiter with the ability to provide imaging, remote sensing, and magnetospheric investigation of Jupiter and its satellites during nearly two years of orbital operations. Secondary goals: • Collect Venus science and Earth-Moon imaging data, available during the VEEGA portion of the trajectory. • Obtain asteroid images during passages through the asteroid belt. • During the planetary cruise phase, obtain gravity wave detection and measurements of the interplanetary medium, solar magnetic field, and solar wind structure. Science objectives: • Investigate the chemical composition and physical state of Jupiter's atmosphere. • Characterize the morphology, physical state, and dynamic properties of the Jovian satellites. • Analyze the structure and physical dynamics of the Jovian magnetosphere.
Orbit/Trajectory Characteristics	VEEGA trajectory using gravity assist maneuvers with Venus and Earth; varying orbits around Jupiter and Jupiter's moons.
Weight[a]	Orbiter: 2,223 kg (4,902 lbs), at launch; included a 118-kg (260-lb) science payload and 925 kg (2,040 lb) of propellant Probe: 339 kg (750 lb) total
Dimensions[b]	Orbiter: 5.3 m (17 ft) high; magnetometer boom extended 11 m (36 ft) to one side Probe: 127 cm (50 in) diameter, 91 cm (36 in) high
Power Source	Radioisotope thermoelectric generators
Prime Contractor	Jet Propulsion Laboratory (orbiter), Hughes Aircraft Company (probe)

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	Probe: • ASI PI: Alvin Seiff, Ames Research Center The ASI provided information about temperature, density, pressure, and molecular weight of atmospheric gases. These quantities were determined from the measured deceleration of the Probe during the atmospheric entry phase. During the parachute-descent phase, temperature and pressure were measured directly by sensors extending from the body of the spacecraft. • NMS PI: Hasso Niemann, Goddard Space Flight Center The NMS analyzed the chemical composition of gases by measuring their molecular weights. • HAD PI: Ulf von Zahn, Bonn University, Germany The HAD determined the ratio of hydrogen to helium in Jupiter's atmosphere. This instrument accurately measured the refractive index of Jovian air to precisely determine the helium abundance. • NEP PI: Boris Ragent, Ames Research Center The NEP located and measured cloud particles in the immediate vicinity of the Galileo Probe. This instrument used measurements of scattered light from a laser beam directed at an arm extending from the Probe to detect and study cloud particles. • NFR PI: Larry Sromovsky, University of Wisconsin The NFR sensed the differences between the flux of light and heat radiated downward and upward at various levels in Jupiter's atmosphere. Such measurements could provide information on the location of cloud layers and power sources for atmospheric winds. This instrument used an array of rotating detectors capable of sensing small variations in visible and infrared radiation fluxes. • LRD PI: Louis Lanzerotti, Bell Laboratories The LRD was used together with the scaling, data processing, and data formatting of the EPI. The LRD and EPI shared the electrical system collecting the LRD data. The LRD searched and recorded radio bursts and optical flashes generated by lightning in Jupiter's atmosphere. These measurements were made using an optical sensor and radio receiver on the Probe.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	• EPI PI: Louis Lanzerotti, Bell Laboratories The EPI was used before entry to measure fluxes of electrons, protons, alpha particles, and heavy ions as the Probe passes through the innermost regions of Jupiter's magnetosphere and ionosphere. • Doppler Wind Experiment This experiment used variations in the frequency of the radio signal from the Probe to derive variation of wind speed with altitude in Jupiter's atmosphere. Orbiter (Despun Platform): • Solid-State Imaging (SSI) Camera Team Leader: Michael J. S. Belton, National Optical Astronomy Observatories The 1,500-mm (59-in)-focal length telescopic camera system obtained images of Jupiter's satellites in visible light at resolutions 20 to 1,000 times better than Voyager's best, largely because it flew closer to the satellites. The CCD sensor of 800 pixels by 800 pixels was more sensitive and had a broader color detection band than the vidicons of Voyager. • Near-Infrared Mapping Spectrometer (NIMS) PI: Robert Carlson, Jet Propulsion Laboratory The NIMS measured the surface and atmospheric thermal, compositional, and structural nature of the Galilean satellites. • UVS PI: Charles Hord, University of Colorado The investigation included the UVS on the despun platform and the Extreme Ultraviolet Spectrometer (EUVS) on the spun section. The investigation determined the loss rates of volatile gases from the Galilean satellites and studied the composition and structure of the upper Jovian atmosphere, including atmospheric gases, aerosols, etc. The investigation also examined the physical processes occurring in the Io plasma torus. The EUVS was a modified flight spare of the Voyager UVS. • Photopolarimeter Radiometer (PPR) PI: James E. Hansen, Goddard Institute for Space Studies The PPR observed light in the visible and infrared wavelengths and provided data on atmospheric composition and thermal/reflected energy distribution and radiation.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	Orbiter (Spinning Spacecraft Section) • MAG PI: Margaret G. Kivelson, University of California, Los Angeles The MAG sensed strength and fluctuations of magnetic fields in the spacecraft's immediate environment. The magnetometer sensors were mounted on an 11-meter (36-foot) boom to minimize interference from the spacecraft. • EUVS PI: Charles Hord, University of Colorado The EUVS determined loss rates of volatile gases from the Galilean satellites and studied the composition and structure of the upper Jovian atmosphere. As Galileo spun, the EUVS observed a narrow ribbon of space perpendicular to the spin axis. • Energetic Particles Detector (EPD) PI: D. J. Williams, The Johns Hopkins University, Applied Physics Laboratory The EPD measured the energy, composition, intensity, and angular distribution of electrons, protons, and heavy ions in the spacecraft's immediate environment. • Plasma Investigation Subsystem (PLS) PI: Lou Frank, University of Iowa In the spacecraft's immediate environment, the PLS detected and measured low-energy charged particles (ions), as well as their composition; energy; temperature density; and three-dimensional distribution and bulk motions. • Plasma Wave Subsystem (PWS) PI: Donald A. Gurnett, University of Iowa This instrument studied waves generated by charged particles. The instrument measured the electrostatic and electromagnetic components of waves and wave-particle interactions in three dimensions. • Dust Detector Subsystem (DDS) PI: Eberhard Grun, Max-Planck-Institute für Kernphysik, Germany This instrument determined the mass, velocity, charge, and flight direction of submicron particles in interplanetary space and the Jovian system. • Heavy Ion Counter (HIC) (engineering experiment) PI: Edward Stone, Jet Propulsion Laboratory, California Institute of Technology This experiment assessed the potentially hazardous charged-particle environments that the spacecraft flew through. The experiment provided data on collisions with ionized sulfur and oxygen atoms trapped in the Jovian magnetic field.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments[c]	• Radio Science: Celestial Mechanics Team Leader: John Anderson, Celestial Mechanics Jet Propulsion Laboratory This instrument determined masses and internal structures and motions of bodies from spacecraft tracking. • Radio Science: Propagation Team Leader: H. Taylor Howard, Stanford University This instrument determined satellite radii and atmospheric structure from radio propagation. Interdisciplinary Investigators • Frances Bagenal, University of Colorado • Andrew F. Cheng, The Johns Hopkins University • Fraser P. Fanale, University of Hawaii • Peter Gierasch, Cornell University • Donald M. Hunten, University of Arizona • Andrew P. Ingersoll, California Institute of Technology • Wing-Huen Ip, NSPO/RDD, Taipei • Michael McElroy, Harvard University • David Morrison, Ames Research Center • Glenn S. Orton, Jet Propulsion Laboratory • Tobias Owen, State University of New York • Alain Roux, Centre de Recherches en Physique de l'Environment • Christopher T. Russell, University of California at Los Angeles • Carl Sagan, Cornell University • Gerald Schubert, University of California at Los Angeles • William H. Smyth, Atmospheric & Environmental Research, Inc. • James Van Allen, University of Iowa
Results	The Galileo mission accomplished more than 70 percent of its science mission objectives. A significant finding, the discovery of a frozen ocean of water covering Europa, led to speculation about the possibility of life on the moon. The discovery of "warm ice" or possibly liquid water, and later cracks where warm water "environmental niches" might exist as well as icebergs, raised questions prompting scientists to call for another mission to Europa.[d] See additional results in the mission narrative above.

Table 4–68. Galileo Mission Characteristics (Continued)

Remarks	Galileo accomplished the following "firsts":[e] • First mission to make a close flyby of an asteroid (Gaspra) • First mission to discover a satellite of an asteroid (Ida's satellite Dactyl) • First multispectral study of the moon • First atmospheric probe to enter Jupiter's atmosphere • First spacecraft to go into orbit around Jupiter • First direct observations of a comet impacting a planet (Shoemaker-Levy 9)

[a] "Galileo End of Mission Press Kit." Galileo press contact representative cited end-of-mission press kit as most reliable. "Galileo Mission Operation Report," "Galileo Jupiter Arrival Press Kit," and JPL Galileo Web site all have different figures for size and weight.

[b] "Galileo End of Mission Press Kit."

[c] "Galileo's Science Instruments," *http://www2.jpl.nasa.gov/galileo/instruments/* (accessed August 18, 2005). Also "The Galileo Probe Spacecraft," *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/probe_spacecraft.html* (accessed May 4, 2006). "Galileo Jupiter Arrival Press Kit," December 1995, pp. 38–40, *http://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf* (accessed September 12, 2005).

[d] Roger D. Launius in Siddiqi, p. 8.

[e] "Galileo Project Information," *http://nssdc.gsfc.nasa.gov/planetary/galileo.html* (accessed September 17, 2005).

Table 4–69. Discovery Missions Approved by NASA, 1993–1998[a]

Mission	Selection Year	Launch Date	Mission Description
NEAR	1993	February 1996	The first spacecraft to orbit and study an asteroid
Mars Pathfinder	1993	December 1996	Demonstrated a less costly method of landing a spacecraft and science instruments on Mars using a small rover to explore Martian terrain
Lunar Prospector	1994	January 1998	Offered insight on the Moon's origin and evolution; also sought to determine whether water ice existed at the Moon's poles
Stardust	1995	February 1999	The first spacecraft to collect comet and interstellar dust particles and return them to Earth
CONTOUR	1997	July 2002	To encounter and study at least three comets
Genesis	1997	August 2001	Collected wind particles to improve understanding of the evolution of the solar system

[a] Snyder, "NASA and Planetary Exploration," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* p. 296.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics

Launch Date/Launch Site	February 17, 1996/Cape Canaveral
Date of Reentry	Communication with spacecraft ended February 28, 2001.
Launch Vehicle	Delta II 7925
NASA Role	Instrument team leaders; provided magnetometer
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Mission objectives:[a] • Place a satellite carrying multiple scientific instruments into orbit around the near-Earth asteroid 433 Eros. • Carry out quantitative and comprehensive measurements for one year of the asteroid's composition and structure. • Reduce and analyze these data. • Make the results available to the scientific community and the public. Science objectives:[b] • Characterize the physical and geological properties of a near-Earth asteroid and infer its elemental and mineralogical composition. • Clarify relationships between asteroids, comets, and meteorites. • Further understand the processes and conditions during the formation and early evolution of the planets.
Orbit Characteristics	Interplanetary trajectory
Weight	805 kg (1,775 lb)
Dimensions	Eight 18 sq ft (1.75 sq m) panels; height: 9.2 ft (2.8 m) from bottom of spacecraft to top of its main antenna; solar panels: 6 ft by 4 ft (1.8 m by 1.2 m); main dish antenna: 5 ft (1.5 m) diameter
Shape	Octagonal
Power Source	Solar cells
Prime Contractor	The Johns Hopkins University Applied Physics Laboratory
Instruments and Experiments	• Multispectral Imager (MSI) Team Leader: Joseph Veverka, Cornell University The MSI imaged Eros in multiple spectral bands to determine its size, shape, and spin characteristics to map mineral distributions and provide data for optical navigation. The MSI was equipped with a 537-pixel by 224-pixel CCD imaging detector with five-element, radiation-hard refractive optics capable of photographing details on Eros' surface as small as 10 ft (3 m) in diameter.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments	Adapted by the APL from a military remote sensing system, the instrument covered the spectral range from 0.4 microns to 1.1 microns. The instrument had an eight-position filter wheel with filters chosen to optimize sensitivity to minerals expected to occur on Eros. The MSI had a FOV of 2.26 degrees by 2.95 degrees and a pixel resolution corresponding to 31 ft by 53 ft (9.6 m by 16.2 m) from 62 mi (100 km). • MAG Team Leader: Mario H. Acuña, Goddard Space Flight Center The three-axis fluxgate magnetometer could measure the asteroid's magnetic field from dc to 10 Hz. The sensor head was mounted on the HGA feed, while the electronics were mounted on the spacecraft top deck. The sensor, supplied by NASA and the Goddard Space Flight Center, had eight selectable sensitivity levels. The MAG was used to search for and map any intrinsic magnetic field around Eros. • Near Infrared Spectrometer (NIS) Team Leader: Joseph Veverka, Cornell University The NIS mapped the distribution and abundance of surface minerals like olivine and pyroxene by measuring reflected sunlight in the near-infrared range from 0.8 micrometer to 2.7 micrometers in 64 channels. With the measurements of elemental composition from the X-Ray/Gamma-Ray Spectrometer (XGRS) and color imagery from the MSI, the NIS provided a link between asteroids and meteorites and clarified the processes by which asteroids formed and evolved. The NIS, adapted from a military remote sensing instrument, was a grating spectrometer dispersing light from the slit FOV across a pair of passively cooled, one-dimensional array detectors. One detector was a germanium array covering the lower wavelengths from 0.8 micron to 1.5 microns; the other was an indium-gallium-arsenide array covering 1.3 microns to 2.7 microns. Mirror scanning combined with spacecraft motion was used to build up hyperspectral images. The NIS also carried a diffuse gold calibration target that reflected sunlight into the spectrometer and provided in-flight spectral calibration.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments	• XGRS Team Leader: Jacob I. Trombka, Goddard Space Flight Center The XGRS consisted of two state-of-the-art sensors: an x-ray spectrometer and a gamma-ray spectrometer. It measured and mapped abundances of several dozen key elements at and near the surface of Eros. The x-ray spectrometer (XRS) detected the characteristic x-ray line emissions excited by solar x-rays from major elements in the asteroid surface. The XRS covered the energy range from 1 keV to 10 keV using three gas-proportional counters. The balanced, differential filter technique was used to separate the closely spaced magnesium, aluminum, and silicon lines below 2 keV. The gas-proportional counters directly resolved higher energy line emissions from calcium and iron. A mechanical collimator gave the XRS a 5-degree FOV to map the chemical composition at spatial resolutions as low as 1.2 mi (2 km). The XRS included a separate solar monitor system to continuously measure the incident spectrum of solar x-rays. In-flight calibration capability also was provided. The gamma-ray spectrometer (GRS) detected characteristic gamma rays in the range from 0.3-MeV to 10-MeV; the gamma rays emitted from specific elements in the surface such as potassium, silicon, and iron. The GRS used a body-mounted, passively cooled sodium iodide detector enveloped by an active bismuth germanate anti-coincidence shield to provide a 45-degree FOV.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments[c]	• NEAR Laser Rangefinder (NLR) Team Leader: Maria T. Zuber, Massachusetts Institute of Technology/Goddard Space Flight Center The NLR was a laser altimeter measuring the distance from the spacecraft to the asteroid surface to build up high-resolution topographic profiles. The NLR sent short bursts of laser light to the surface and then recorded the time required for the signal to return from the asteroid. It sent a small portion of each emitted laser pulse through an optical fiber of known length and a small portion of each pulse into the receiver, providing continuous in-flight calibration of the timing circuit. The ranging data was used to construct a global shape model and a global topographic map of Eros with horizontal resolution of about 1,000 ft (300 m). The NLR also measured detailed topographic profiles of surface features on Eros with a best spatial resolution of about 12 ft (4 m). The profiles were used as constraints on models of the origin and evolution of surface features. • Radio Science Experiment Team Leader: Donald K. Yeomans, Jet Propulsion Laboratory The radio science experiment consisted of a coherent X-band transponder measuring the radial velocities of the spacecraft relative to Earth, thus allowing the asteroid's gravity field to be mapped. It used the NEAR radio tracking system to determine the mass and mass distribution of the asteroid. Measurements were made of the two-way Doppler shift in radio frequency between the spacecraft and Earth to an accuracy of better than 0.025 in/sec (0.1 mm/sec). These measurements were used to determine line-of-sight velocity variations induced in the spacecraft's motion by the changing gravitational effects produced by the neighboring asteroid. Combined with data from other NEAR instruments, this information allowed accurate modeling of Eros' density and mass distribution.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Results	The NEAR mission science instruments observed about two-thirds of Eros on December 23, 1998, during a flyby past the asteroid. The NEAR mission discovered that Eros was smaller than expected and that the asteroid had two medium-sized craters, a long surface ridge, and a density similar to the density of Earth's crust. The NEAR mission also discovered that Eros had two medium-sized craters, a long surface ridge, and a density similar to that of Earth's crust.[d]

[a] "Near Earth Asteroid Rendezvous Pre-Launch Mission Operation Report," February 2, 1996, p. 4 (NASA History Office Folder 31049).

[b] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," p. 7, *http://near.jhuapl.edu/media/99-1030B_NEARMarch.pdf* (accessed May 4, 2006).

[c] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," pp. 15–17.

[d] Most NEAR discoveries were made after 1998, after the period covered in this volume.

Table 4–71. Lunar Prospector Mission Characteristics

Launch Date/Launch Site	January 6, 1998/Kennedy Space Center
Date of Reentry	Impacted on Moon July 31, 1999.
Launch Vehicle	Athena II
NASA Role	Mission management
Responsible (Lead) Center	Ames Research Center
Mission/Science Objectives	Science objectives: • "Prospect" the lunar crust and atmosphere for potential resources, including minerals, water ice, and certain gases. • Map the Moon's gravitational and magnetic fields. • Learn more about the size and content of the Moon's core.
Orbit Characteristics:	
Apogee	Initial orbit: 63 mi (100 km) around Moon; lowered after one year to obtain detailed measurements Final orbit: ~18 mi (30 km)
Perigee	Initial orbit: 63 mi (100 km) around Moon Final orbit: ~18 mi (30 km)
Inclination (deg)	89.2 (polar)
Period (min)	118 min (100-km orbit), 112 min (40 km-orbit), 111 min (30-km orbit)
Weight	295 kg (650 lb) (fueled)
Dimensions	1.4 m by 1.2 m (4.6 ft by 4 ft)
Shape	Cylindrical drum
Power Source	Solar cells and nickel cadmium battery
Prime Contractor	Lockheed Martin
Instruments and Experiments	• Neutron Spectrometer (NS): PI: William Feldman, Los Alamos National Laboratory The NS searched for water by indirectly detecting hydrogen on the Moon's surface. Located 63 mi (100 km) above the Moon's surface, the NS did not detect hydrogen directly. Instead, it looked for "cool" neutrons—neutrons that have bounced off a hydrogen atom somewhere on the lunar surface. The NS weighed 8.5 lb (3.9 kg), consumed 2.5 W of power, and produced 49 bps. It was deployed together with the APS. This was the first use of neutron spectroscopy for planetary science.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Instruments and Experiments	• GRS PI: G. Scott Hubbard, Ames Research Center The GRS mapped abundances of 10 elements on the Moon's surface: thorium, potassium, uranium, iron, oxygen, silicon, aluminum, calcium, magnesium, and titanium. The GRS was especially sensitive to the heavy, radioactive element thorium and the light element potassium. These were particularly plentiful in the Moon's youngest rocks, the last part of the crust to solidify. This mapping provided information on the composition of the surface layer and the Moon's origin and evolution. The GRS weighed 19 lb (8.6 kg), used 3 W of power, and produced data at a rate of 688 bps. It was deployed on one of the Lunar Prospector's three booms. • Alpha Particle Spectrometer (APS) PI: Alan Binder, Lockheed Martin The APS detected alpha particles emitted by radioactive gases, such as radon and polonium, leaking out of the lunar interior. The APS detected outgassing events to determine their frequency and location. Outgassing suggested volcanic and tectonic events indicating the activity level of the Moon. The APS weighed 9 lb (4 kg), consumed 7 W of power and produced data at a rate of 181 bps. • MAG and Electron Reflectometer (ER) PI (MAG): Mario Acuña, Goddard Space Flight Center; Lon Hood, University of Arizona PI (ER): Robert Lin, University of California Berkeley The MAG and ER mapped lunar magnetic fields and provided information on the size and characteristics of the Moon's inner core. The instruments were copies of detectors on board the Mars Global Surveyor spacecraft, launched in December 1996, with some modifications to adapt them for a spinning spacecraft. The magnetic fields measured by the MAG were a combination of Earth's magnetic field, the field carried from the Sun by the solar wind, and the Moon's field, which is extremely weak compared to that of Earth. The MAG was mounted on a boom 8.5 ft (2.6 m) from the spacecraft to isolate it from the magnetic fields generated by the spacecraft's own electronics.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Instruments and Experiments[a]	The ER, a remote instrument, measured the magnetic field at the surface of the Moon. Together with the MAG, the two instruments detected local variations in the Moon's magnetic field arising from selenological features on the lunar surface. The ER was linked to the MAG by a smaller 2.5-ft (0.8-m) boom. The combined weight of the MAG and ER was approximately 11 lb (5 kg). Together, the two instruments used 4.5 w of power, and produced 670 bps of data. • Doppler Gravity Experiment (DGE) PI: Alex Konopliv, NASA Jet Propulsion Laboratory The DGE mapped the global lunar gravity field and provided an enhanced model of the Moon's gravity known to be non-uniform as a result of mass concentrations (mascons) distributed below the Moon's surface. The newly derived operational lunar gravity map was used to perform monthly orbit adjustments needed to counteract the uneven gravity field of the Moon that degraded the orbit over time.
Results	NS data allowed mission scientists to establish the existence of significant concentrations of hydrogen at the lunar poles based on telltale dips in the epithermal neutron energy spectra sent back to Earth by the NS. If, as some scientists suspected, this excess hydrogen existed as part of frozen water molecules buried in permanently shadowed craters at the lunar poles, there could be as much as 260 million metric tons of water ice (75 billion gallons of water) on the Moon. The GRS acquired the first global measurements of gamma-ray spectra from the lunar surface. Since gamma rays coming from the lunar surface carry information about lunar elemental composition, this data set comprised the first direct elemental composition measurements made for the entire lunar surface.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Results	By mission's end, the MAG and ER experiment obtained more than 700,000 electron reflection measurements distributed over the entire Moon. This was sufficient to map most of the lunar surface at 3-degree resolution and some regions at 0.5-degree (15-km) (9.3-mi) resolution. Measurements also showed systematic variations in magnetic field strength over the different mare units. The primary mission yielded 100-km (62-mi) altitude measurements of crustal magnetic fields over the entire surface. The MAG and ER measurements established that miniature magnetospheres were forming around concentrations of strong crustal magnetic fields occurring diametrically opposite specific impact basins. A remarkable property of these miniature magnetospheres was that they sometimes disappeared. Initial measurements of the lunar-induced magnetic dipole moment were obtained using magnetometer data when the Moon was in a lobe of the geomagnetic tail. These measurements were consistent with the presence of a metallic core with a radius between 250 km and 430 km (155 mi and 267 mi). This was compatible with independent evidence from gravity and laser ranging data, which suggested a ~300-km (186-mi)-radius core. The extended mission, with its lower altitude, provided the DGE with the means to generate an improved lunar gravity model, uncover additional mascons (mass concentrations), and further refine our understanding of the Moon's interior. The APS collected voluminous high-quality data throughout the primary mission and experienced more solar activity than predicted.[b]

[a] "Introduction to Instruments," *http://lunar.arc.nasa.gov/results/instruments.htm* (accessed May 18, 2006).

[b] "Lunar Prospector, End of Mission & Overview," Press Kit, July 1999.

Table 4–72. Clementine Mission Characteristics

Launch Date/Launch Site	January 25, 1994/Vandenberg Air Force Base
Date of Reentry	No reentry. Mission ended June 1994.
Launch Vehicle	Titan IIG
NASA Role	Science team, use of DSN, lunar and asteroid navigation
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To demonstrate advanced lightweight components and technologies under extended exposure to the space environment. • To collect data of interest to the international civilian scientific sector and to stimulate public interest in space exploration. Scientific goals: • To image the entire lunar surface and the asteroid 1620 Geographos during a close flyby,
Orbit Characteristics:	Lunar orbit
Apogee	4,594 km (2,855 mi)
Perigee	2,162 km (1,343 mi)
Inclination (deg)	90
Period (min)	300
Weight	424 kg (935 lb) (with propellant)
Dimensions	1.14 m (3.7 ft) diameter by 1.88 m (6.2 ft) length
Shape	Octagonal
Power Source	Solar panels and battery
Prime Contractor	National Research Laboratory, Lawrence Livermore
Principal Investigator	Eugene M. Shoemaker
Instruments and Experiments	• Charged Particle Telescope (CPT): Designed to measure the flux and spectra of energetic protons (3 MeV–80 MeV) and electrons (25 KeV–500 KeV). The primary goals of the investigation were the following: — Study the interaction of Earth's magnetotail and interplanetary shocks with the Moon. — Monitor the solar wind in regions far removed from other spacecraft as part of a multimission coordinated study. — Measure the effects of incident particles on the operating ability of the spacecraft solar cells and other sensors.

Table 4–72. Clementine Mission Characteristics (Continued)

Instruments and Experiments	• The single-element telescope had a 10-degree, half-angle FOV. The detector, a silicon surface-barrier type with an area of 100 sq mm (0.16 sq in) and a thickness of 3 mm (0.1 in), was shielded so as to prevent protons below 30 MeV from reaching it from directions other than via the aperture. The signal from the detector was broken up into nine channels, the lowest six dedicated to electron detection and the highest three to protons and heavier ions. • Ultraviolet/Visible CCD Camera (UV/Vis): The UV/Vis were designed to study the surfaces of the Moon and the asteroid Geographos at five different wavelengths in the UV and visible spectrum. This experiment yielded information on the petrologic properties of the surface material on the Moon, as well as giving images useful for morphologic studies and cratering statistics. The Geographos rendezvous was cancelled due to equipment malfunction. • Near-Infrared (NIR) CCD Camera: This experiment was designed to study the surfaces of the Moon and the near-Earth asteroid 1620 Geographos at six different wavelengths in the near-infrared spectrum. This experiment yielded information on the petrology of the surface material on the Moon. The rendezvous with Geographos was cancelled due to equipment malfunction. • Long-Wavelength Infrared (LWIR) Camera: This camera was designed to image darkside features on both the Moon and the near-Earth asteroid 1620 Geographos in the thermal infrared spectrum and to allow measurement of thermal properties of material on both bodies, from which an assessment of regolith characteristics could be made. The Geographos phase of the mission was cancelled due to equipment malfunction. • Laser Image Detection and Ranging (LIDAR) System: This system was designed to measure the distance from the spacecraft to a point on the surface of the Moon, allowing an altimetric map to be made. The experiment also was designed to measure distances to the surface of Geographos, but this mission phase was cancelled.

Table 4–72. Clementine Mission Characteristics (Continued)

Instruments and Experiments	• High-Resolution Camera: This camera consisted of a telescope with an image intensifier and a frame-transfer CCD imager. The imaging system was designed to study selected portions of the surfaces of the Moon and the near-Earth asteroid 1620 Geographos, although the asteroid rendezvous was cancelled. This experiment allowed detailed study of surface processes on the Moon and, combined with spectral data, allowed high-resolution compositional and geologic studies. • Star Tracker Cameras (2): Each camera consisted of a knife-edge baffle vane and a lens mounted to the CCD camera housing. Both cameras were located at one end of the spacecraft near the main thruster. The main purpose of the star tracker cameras was to image the background stars to provide attitude determination for the spacecraft. This was done by comparing stellar images to an on–board star catalog to establish absolute angular references for navigation. Images of Earth and the Moon for scientific purposes could also be obtained. • S-Band Transponder Doppler Gravity Experiment: This experiment used measurements of perturbations in the motion of the spacecraft to infer the lunar gravity field. Clementine was equipped with an S-band microwave transponder and two S-band omnidirectional high-rate antennae used for tracking by the Naval Research Laboratory tracking station in Pomonkey, Maryland and the NASA DSN. The calculated lunar gravity field could be used to model subsurface lunar structure. The Pomonkey station measured velocity to an accuracy of 3 mm/s (0.1 in/s), while the DSN stations achieved about 0.3 mm/s (0.01 in s). More than 361,000 observations were made, approximately 57,000 at less than 1,000-km (621-mi) altitude. • Bistatic Radar Experiment: This experiment used the radio transmitting equipment aboard Clementine to search the Moon's polar regions for evidence of ice in permanently shadowed craters. The basic method of bistatic radar involved a spacecraft transmitting a radio signal at a point on the target body. Reflections of these signals from the target were received on Earth. Properties of the received reflections could be interpreted to give information on the target surface.

Table 4–72. Clementine Mission Characteristics (Continued)

Results	• Produced first global digital map of the Moon. • Found water ice at lunar pole (later disproved). • After leaving lunar orbit, a malfunction in one of the on-board computers on May 7, 1994, caused a thruster to fire until it had used up all its fuel, leaving the spacecraft spinning at about 80 revolutions per minute with no spin control. This made the remainder of the mission, a flyby of the near-Earth asteroid Geographos, impossible. The spacecraft remained in geocentric orbit and continued testing the spacecraft components until the end of the mission.

[a] Regeon et al, "The Clementine Lunar Orbiter."

Table 4–73. Mars Observer Mission Characteristics

Launch Date/Launch Site	September 25, 1992/Cape Canaveral Air Force Station
Date of Reentry	Lost contact with spacecraft on August 22, 1993.
Launch Vehicle	Titan III with Transfer Orbit Stage
NASA Role	Project management, Mars Observer Laser Altimeter, Magnetometer/Electron Reflectometer, Pressure Modulator Infrared Radiometer
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	• Determine the global elemental and mineralogical character of Mars' surface material. • Define the planet's global topography and gravitational field. • Establish the nature of the Martian magnetic field. • Determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle. • Explore the structure and aspects of the circulation of the Martian atmosphere.
Orbit Characteristics	Did not go into orbit around Mars
Weight	Total weight: 2,573 kg (5,672 lb) Payload weight: 156 kg (344 lb)
Dimensions	Launch configuration: 1.6 m by 2.2 m by 1.1 m (5.2 ft by 7.2 ft by 3.6 ft)[a] Spacecraft bus: 2.9 m by 2.9 m by 3.2 m (9.5 ft by 9.5 ft by 10.5 ft)[b] Solar panels (6): each 183 cm by 219 cm[c] (72 in by 86 in) Solar array area: 24.5 sq m[d] (263.7 sq ft)
Power Source	Solar arrays (six panels), two nickel cadmium batteries
Prime Contractor	Astro-Space Division of General Electric
Instruments and Experiments	• Mars Observer Camera (MOC) PI: Michael C. Malin, Malin Space Science Systems, Inc. The MOC was a line-scan camera designed to take low-resolution images of Mars on a daily basis for studies of the climate. The MOC also took medium-resolution and high-resolution images of selected areas to study surface geology and interactions between the surface and the atmosphere. • Thermal Emission Spectrometer (TES) PI: Philip R. Christensen, Arizona State University The TES was designed to map the mineral content of surface rocks, frosts, and the composition of clouds. • Mars Observer Laser Altimeter (MOLA) PI: David E. Smith, NASA Goddard Space Flight Center The MOLA was designed to measure the topographic relief of the Martian surface.

Table 4–73. Mars Observer Mission Characteristics (Continued)

Instruments and Experiments[e]	• Magnetometer/Electron Reflectometer (MAG/ER) PI: Mario H. Acuña, Goddard Space Flight Center The MAG/ER was designed to determine the nature of the magnetic field of Mars and its interactions with the solar wind. • Pressure Modulator Infrared Radiometer (PMIRR) PI: Daniel J. McCleese, Jet Propulsion Laboratory The PMIRR was designed to measure dust and condensates in the atmosphere, as well as profiles of temperature, water vapor, and dust opacity as they change with latitude, longitude, and season. • GRS Team Leader: William V. Boynton, University of Arizona The GRS was designed to measure the abundance of elements (uranium, thorium, potassium, iron, and silicon, for example) on the surface of Mars. • Radio Science Experiment: Team Leader: G. Leonard Tyler, Stanford University This experiment was designed to use the spacecraft radio with an ultrastable oscillator to measure atmospheric refractivity as it varied with altitude to determine the temperature profile of the atmosphere. The experiment also was designed to use tracking data to measure the gravity field of Mars.
Results	Unsuccessful. Contact was lost on August 22, 1993, while the spacecraft was preparing for its August 24 orbit insertion around Mars.
Remarks	It was believed that the spacecraft developed a critical leak in its propulsion system, sending it out of control. The spacecraft most likely flew past Mars and went into orbit around the Sun with an orbital period of approximately 500 days.[f]

[a] "Mars Observer Press Kit," September 1992, p. 19 (NASA History Office Folder 16615).
[b] "Mars Observer," QuickLook, *http://msl.jpl.nasa.gov/QuickLooks/marsobsQL.html* (accessed August 11, 2005).
[c] "Mars Observer Press Kit."
[d] "Mars Observer," QuickLook.
[e] "Mars Observer," QuickLook. Also "Mars Observer Press Kit," pp. 34–35.
[f] "General Questions," Mars Global Surveyor, *http://mars.jpl.nasa.gov/mgs/faqs/faq_general.html* (accessed August 11, 2005).

Table 4–74. Mars Global Survey Mission Characteristics

Launch Date/Launch Site	November 7, 1996/Kennedy Space Center
Date of Reentry	No reentry. Completed primary mission on January 31, 2001. Still orbiting Mars as of mid-2005.
Launch Vehicle	Delta 7925
NASA Role	Project management, mission operations, science operations, PIs for the Mars Orbiter Laser Altimeter and Magnetometer/Electron Reflectometer investigations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	• To enhance the understanding of the geosciences and climatology of Mars. This will be accomplished by characterizing surface morphology at high spatial resolution to quantify surface characteristics and geologic processes; determining the composition and mapping the distribution of surface minerals, rocks, and ices; measuring the thermophysical properties of the surface; determining globally the topography, geodetic figure, and gravitational field; establishing the nature of the magnetic field and mapping the crustal remnant field; monitoring global weather and the thermal structure of the atmosphere; and studying surface-atmosphere interaction by monitoring surface features, polar caps, polar thermal balance, atmospheric dust, and condensate clouds over a seasonal cycle. • To provide multiple years of in-orbit relay communications capability for Mars landers and atmospheric probes for any nation interested in participating in international Mars exploration. • To support planning for future Mars missions through data acquisition, with special emphasis on those measurements that could impact landing site selection.[a] Program objectives: • Launch a spacecraft to Mars during the 1996 opportunity. • Insert the spacecraft into a near Sun synchronous polar orbit at Mars. • Carry out a global survey of Mars during one Martian year to collect at least 70 percent of the science data available for acquisition from the scientific instruments.
Orbit Characteristics Around Mars[b]	
Apogee	378 km (235 mi) average
Perigee	378 km (235 mi) average
Period (min)	120
Weight	2,337 lb (1,060 kg) fueled

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Dimensions	Bus: 5 ft by 5 ft by 10 ft (1.5 m by 1.5 m by 3 m); 40 ft (12 m) across with fully deployed solar panels; high gain antenna: 10 ft (3 m) deployed on a 6.5-ft (2-m) boom
Shape	Rectangular
Power Source	Solar arrays and batteries
Prime Contractor	Lockheed Martin
Instruments and Experiments	• TES: PI: Philip Christensen, Arizona State University The TES analyzed infrared radiation from the surface. From these measurements, scientists determined several important properties of the rocks and soils comprising the Martian surface, including the following: — The thermophysical properties of Martian surface materials. — The composition and surface distribution of Martian rock and soil and the past presence of water on Mars. — The growth and contraction of the polar ice caps, as well as the amount of radiation absorbed, reflected, and emitted by the caps and the composition of the ice. — The circulation and dynamics of the atmosphere during a Martian year, the atmospheric pressure and temperature distribution, and the long-term climate. — The composition and distribution of atmospheric dust and clouds. This information will extend and improve measurements of thermal infrared emission instruments carried by earlier missions (Mariners 6, 7, and 9 and Vikings 1 and 2).[c] • MOLA PI: David Smith, Goddard Space Flight Center The MOLA measured the height of Martian surface features. A laser fired pulses of infrared light 10 times each second, striking a 160-m (525-ft) area on the surface. By measuring the length of time it took for the light to return to the spacecraft, scientists determined the distance to the planet's surface. Data from this instrument gave scientists elevation maps precise to within about 30 m (100 ft). Scientists used these maps to construct a detailed topographic map of the Martian landscape.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• MAG/ER PI: Mario Acuña, Goddard Space Flight Center The MAG/ER was used to search for evidence of a planetary magnetic field and measure its strength (if it existed). These measurements provided critical tests for current speculations about the early history and evolution of the planet. The instrument also scanned the surface to detect remnants of an ancient magnetic field, providing clues to the Martian past when the magnetic field may have been stronger due to the planet's higher internal temperature. Unlike the other instruments, the magnetometer sensors were not attached to the main body of the spacecraft. Instead, each one of the two sensors sat at opposite ends of the spacecraft at the tips of the spacecraft's two solar panels. This placement ensured that the data generated from the magnetometer sensors was not "polluted" by magnetic signals from the spacecraft system. The electron reflectometer sensor was mounted on the instrument platform because it was not sensitive to weak magnetic fields. The MAG and ER operated during the cruise phase of the mission. During the aerobraking phase, the spacecraft crossed the Martian bow shock formed by the supersonic interaction of the planet with the solar wind at least twice per orbit. The MAG/ER detected these crossings and generated valuable data for determining the global extent of the Martian magnetic field. During the mapping orbit, the MAG/ER operated continuously.[d] • Radio Science Team Leader: G. Leonard Tyler, Stanford University This instrument used data provided by the spacecraft's telecommunications system, high-gain antenna, and onboard ultra-stable oscillator to map variations in the gravity field by noting where the spacecraft speeded up and slowed down during its passage around Mars. From these observations, a precise map of the gravity field could be constructed and related to the structure of the planet. In addition, scientists studied how radio waves were distorted as they passed through the atmosphere of Mars to measure the atmosphere's temperature and pressure.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• MOC PI: Michael Malin, Malin Space Science Systems Inc. The MOC was designed to obtain images of the surface and atmosphere of Mars to study the meteorology/climatology and geology of Mars. The camera's primary objectives were the following: — Obtain global, synoptic views of the Martian surface and atmosphere on a daily basis to understand the meteorological and climatological changes during the mission. — Monitor surface and atmospheric features for changes on temporal scales from hours to years and on a spatial scale necessary for resolving the details of their morphology. — Systematically examine local areas at high spatial resolution to quantify surface/atmosphere interactions and geologic processes operating on short timescales. • The MOC was the flight spare of the camera used on the Mars Observer mission and was essentially identical.[e] The MOC used a "push-broom" technique that built a long, ribbon-like image while the spacecraft passed over the planet. The camera provided low-resolution global coverage of the planet everyday, collecting images through red and blue filters. It also obtained medium-resolution and high-resolution images of selected areas. To acquire images to satisfy its objectives, the Mars Global Surveyor MOC consisted of a narrow-angle assembly and a wide-angle assembly. The wide-angle lens was used to accumulate a weather map of Mars each day showing surface features and clouds at a resolution of about 7.5 km (4.6 mi). These global views were similar to the types of views obtained by weather satellites orbiting Earth. The narrow-angle lens imaged small areas of the surface at a resolution of 2 m to 3 m (6.5 ft to 9.5 ft). These pictures were sharp enough to show small geologic features such as boulders and sand dunes; they may also be used to select landing sites for future missions.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• Mars Relay Radio System (Relay Communications Experiment) PI: Jacques E. Blamont, CNES The Mars Global Surveyor carried a radio receiver/ transmitter supplied by the French space agency CNES, which was originally designed to support the Russian Mars '94 mission (renamed Mars '96) but lost during launch. At the time of this mission, the system was planned to relay data from the microprobes carried on the upcoming 1998 Mars Global Surveyor Lander mission as well as serve as a backup for data relay from the lander itself. Data relayed from the surface to the Mars Global Surveyor was to be stored in the large solid-state memory of the orbiter's camera, where it would be processed for return to Earth. This collaborative effort would maximize data collection. Following support of the Mars '98 mission, the Mars relay system was expected to provide multiple years of in-orbit communications relay capability for future international Mars missions. The Mars Relay consisted of an 86-cm (33.8-in) high, 2.5-kg (5.5-lb) quadrifilar helix fiberglass antenna mast mounted on the spacecraft and an electronics box and coaxial cable. The system received data from the surface missions and routed them for storage to the large on-board storage memory buffer of the MOC. The stored transmissions were then routed to Earth via the MOC. The transmission frequency to the Mars ground stations was 437.1 MHz at 1.3 W. The receive frequencies (from the stations) were 401.5 MHz and 405.6 MHz. The antenna FOV ranged from limb to limb.[f]

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments[g]	• Accelerometer PI: Dr. Gerald M. Keating, Langley Research Center The accelerometer instrument measured changes in velocity as the spacecraft performed aerobraking maneuvers in the Martian thermosphere. The accelerometer data could be used to deduce atmospheric drag on the spacecraft so atmospheric densities could be estimated. The z-axis accelerometer was aligned closely to the spacecraft velocity vector. It had a sensitivity of 0.332 mm/sec per count, allowing measurements up to at least 170 km (106 mi) altitude. A typical set of accelerometer measurements during aerobraking spanned from about 200 seconds before periapsis to 200 seconds after periapsis, about 30 degrees of latitude. Additional measurements obtained before and after this period were used to determine accelerometer bias for each pass. Measurements were obtained every 0.1 second. Accelerations of 1 micro-g were detected.[h]
Results	At the end of 1998, the Mars Global Surveyor continued with excellent aerobraking performance. The orbital period was less than 3 hours. The spacecraft was very healthy. See the narrative above for science results.

[a] "Mars Global Surveyor," Fact Sheet, Jet Propulsion Laboratory, *http://www.jpl.nasa.gov/news/fact_sheets/mgs.pdf* (accessed August 10, 2005).

[b] "Mars Global Surveyor," *http://nssdc.nasa.gov/planetary/marsurv.html* (accessed August 11, 2005).

[c] "Thermal Emission Spectrometer (TES)," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=2* (accessed May 22, 2006).

[d] "The MGS Magnetometer and Electron Reflectometer," *http://mgs-mager.gsfc.nasa.gov/instrument.html* (accessed May 22, 2006).

[e] "Mars Orbiter Camera," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=1* (accessed May 22, 2006).

[f] "Mars Relay Communications Experiment," NSSDC Master Catalog, Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=6* (accessed May 22, 2006).

[g] "Mars Global Surveyor Arrival Press Kit," September 1997, pp. 32–33, *http://www.jpl.nasa.gov/news/press_kits/mgsarriv.pdf* (accessed August 11, 2005).

[h] "Accelerometer," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=7* (accessed May 22, 2006).

Table 4–75. Mars Pathfinder Mission Characteristics

Launch Date/Launch Site	December 4, 1996/Cape Canaveral Air Station
Date of Reentry	No reentry. Final data transmission: September 27, 1997.
Launch Vehicle	Delta II 7925/PAM-D
NASA Role	Project management; design, build, and operate Pathfinder
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives[a]	• Demonstrate a simple, less costly system at fixed price for placing a science payload on the surface of Mars at one-fifteenth the Viking price tag. • Demonstrate NASA's commitment to low-cost planetary exploration by completing the mission for a total cost of $280 million including the launch vehicle and mission operations. • Demonstrate the mobility and usefulness of a microrover on the surface of Mars. Rover mission objectives: Conduct technology experiments, science experiments, and mission experiments, specifically:[b] Technology Experiments — Mars Terrain Geometry Reconstruction from Imagery — Mars Basic Soil Mechanics — Mars Dead Reckoning Sensor Performance and Path Reconstruction/Recovery — Sinkage in Each Martian Soil Type — Logging/Trending of Vehicle Performance Data — Rover Thermal Characterization — Rover Imaging Sensor Performance — UHF Link Effectiveness — Material Abrasion — Material Adherence Rover Science Experiments — Alpha Proton X-Ray Spectrometer — APXS Deployment Mechanism — Imaging Mission Experiments — Lander Imaging — Damage Assessment
Weight	Lander: 1,1,973 lb (895 kg) fueled; 1,766 lb (801 kg) dry Rover: 23 lb (10.6 kg)
Dimensions	Lander: 3 ft (0.9 m) tall Rover: 2 ft (65 cm) long, 1.5 ft (48 cm) wide, 1 ft (30 cm) tall
Shape	Lander: tetrahedron, three sides, and base
Power Source	Solar panels, batteries
Prime Contractor	Jet Propulsion Laboratory

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Instruments and Experiments	Lander: • Imager for Mars Pathfinder PI: Peter Smith, University of Arizona The Imager for Mars Pathfinder was a stereo imaging system with color capability provided by 11 individual geologic filters, four pairs of atmospheric filters, and two pairs of stereo filters. It had three physical subassemblies: 1) a camera head with the stereo imaging system; filter wheel; CCD; pre-amp; and mechanisms and stepper motors; 2) an extendable mast with electronic cabling; and 3) two plug-in electronics cards (CCD data card and power supply/motor drive card) that plugged into slots in the Warm Electronics Box within the lander. With its mast fully extended, the Imager for Mars Pathfinder stood 5 ft (1.5 m) above the ground. The close-up lens enabled the Pathfinder to take high-resolution shots of magnetic windblown dust that adhered to a special dust collector mounted on the Imager for Mars Pathfinder. Atmospheric investigations were carried out using Imager for Mars Pathfinder images including measuring aerosol opacity periodically by imaging the Sun through two narrowband filters; investigating magnetic properties; and observing wind direction using a small wind sock mounted above a reference grid and a calibration and reference target mounted to the lander. • ASI/MET package Instrument Definition Team Leader: Alvin Seiff, San Jose State University Science Team Leader: John T. “Tim” Schofield, NASA Jet Propulsion Laboratory The ASI/MET was an engineering subsystem that acquired atmospheric information during lander descent through the atmosphere and during the entire landed mission. The ASI/MET measured accelerations over a wide variety of ranges from the micro-g accelerations experienced upon entering the atmosphere to the peak deceleration and landing events in the range of 30g’s to 50g’s. Data acquired during the lander’s entry and descent permitted reconstruction of profiles of atmospheric density, temperature, and pressure from altitudes above 100 km (60 mi) from the surface. It took advantage of the heritage provided by the Viking mission experiments.

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Instruments and Experiments[c]	The ASI/MET depended on the attitude and information management subsystem of the lander. It consisted of sensors at three different heights and used windsocks to detect wind direction and speed. A wind sensor on top of the mast sensed temperature differences among six temperature sensors that measured wind speed and direction. A sensor on the base of the lander measured atmospheric pressure. • Magnets for measuring magnetic properties of soil. • Wind socks: Three wind socks were located at various heights on the meteorology mast to determine the speed and direction of winds at the Pathfinder landing site. The wind socks were imaged repeatedly by the Imager for Mars Pathfinder. The orientations of the wind socks were measured in the images to determine the wind velocity at three heights above the surface. This information was used to estimate the aerodynamic roughness of the surface in the vicinity of the lander and to determine the variation in wind speed with height. Because the earlier Viking landers had wind sensors at only one height, such a vertical wind profile was never measured on Mars. This new knowledge helped develop and modify theories of how dust and sand particles were lifted into the Martian atmosphere by winds, for example. Because erosion and deposition of wind-blown materials were such an important geologic process on the surface of Mars, the results of the wind sock experiment were of interest to geologists and atmospheric scientists. Rover: • Alpha Proton X-ray Spectrometer (APXS) PI: Rudolph Rieder, Max Planck Institute for Chemistry, Germany Co-investigators: Thanasis Economou, University of Chicago and Henry Wanke, Max Planck Institute for Chemistry, Germany This instrument determined the elements making up the rocks and soil on Mars. The APXS was derived from instruments flown on the Russian Vega and Phobos missions, and it was identical to the unit to fly on the Russian Mars '96 landers. The Mars Pathfinder rover mobility allowed the APXS to take spectral measurements of the Martian dust and move to distinct rock outcroppings, permitting analysis of native rock composition for the first time. • Three cameras. • Technology experiments.

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Results	Extremely successful. The primary mission concluded on August 4, 1997. The final transmission was on September 25, 1997. The mission returned 2.3 billion bits of information, including more than 16,500 images from the lander, 550 images from the rover, and more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors.

[a] "Mars Pathfinder Mission Objectives," *http://mpfwww.jpl.nasa.gov/MPF/mpf/mission_obj.html* (accessed August 23, 2005).

[b] "Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/mission.html* (accessed August 23, 2005).

[c] "Mars Pathfinder Instrument Descriptions," *http://mpfwww.jpl.nasa.gov/MPF/mpf/sci_desc.html#IMP* (accessed August 23, 2005). Also "Mars Pathfinder Landing," Press Kit, July 1997, pp. 36–38, *http://www2.jpl.nasa.gov/files/misc/mpflanhq.pdf* (accessed May 2, 2006).

Table 4–76. Mars '96 Instruments

Instruments	Description
Orbiter instruments:	
Surface and Atmosphere Studies:	
Stereo-Spectral Imaging System	This system was designed to study the Martian surface and atmosphere and provide cartographic support for other experiments and future missions. It consisted of a Multifunctional High Resolution Stereoscopic TV Camera, a WAOSS Wide-Angle Stereoscopic TV Camera, and an OMEGA Visible and Infrared Mapping Spectrometer.
Planetary Fourier Spectrometer	This spectrometer would monitor three-dimensional temperature and pressure fields; perform global mapping of winds; study variations of water and carbon monoxide in space and time; and investigate the optical depth, phase function, size distribution, and chemical composition of aerosols.
Mapping Radiometer	This radiometer was designed to investigate the thermal inertia of the Martian soil and the diurnal and seasonal dynamics of the temperature regime. It also was designed to search for anomalous heat sources and conduct thermal studies of the atmosphere.
High Resolution Mapping Spectrophotometer	This spectrophotometer would perform spectrophotometry of the planet in absorption bands of some rocks that may exist on the Martian surface to determine the surface composition. It also would study the nature of aerosols by measuring spectral and angular distributions of brightness both above the planetary limb and of certain cloud-covered areas.
Multichannel Optical Spectrometer	This spectrometer was designed to observe vertical concentration profiles of ozone, water vapor, carbon monoxide, oxygen, dust, and temperature in the middle and lower atmosphere. It also was designed to measure the global distribution of water vapor.
Ultraviolet Spectrophotometer	This spectrophotometer would measure hydrogen, helium, and oxygen distributions in the upper atmosphere of Mars; determine deuterium abundance in the Martian atmosphere; observe high-altitude temperature profiles of the atmosphere; and observe the neutral component of the interstellar-interplanetary medium.
Long-Wave Radar	This radar would study the underlying surface structure of the Martian cryolithospheres, determine the depth of occurrence of ice-bearing rocks and their geographic distribution, and estimate the dielectric parameters of soil. The radar would measure the global distribution of height profiles of electron number-density in the Martian upper ionosphere to study the dynamics of the solar wind interaction with the Martian upper atmosphere.

Table 4–76. Mars '96 Instruments (Continued)

Instruments	Description
Gamma-ray Spectrometer	This spectrometer was designed to perform geochemical mapping of the elemental composition of Martian surface rocks; the spectrometer used high spatial resolution and accuracy to determine the abundance of natural radioactive elements, basic rock-forming elements, and minor elements.
Neutron Spectrometer	This spectrometer was designed to determine the water content in the surface layer of Martian soils.
Quadrupole Mass Spectrometer	This spectrometer would determine the composition of the Martian upper atmosphere and ionosphere; measure height profiles of the atmospheric ion and neutral composition; and measure seasonal and diurnal variations of the Martian upper atmosphere and ionosphere.
Plasma Physics:	
Energy-Mass Ion Spectrograph and Neutral-Particle Imager	This instrument was designed to study the interaction between the plasma and neutrals near Mars and investigate plasma ion composition. The instrument consisted of an ion-mass imaging spectrometer, two neutral particle imagers, and a scanner platform.
Fast Omnidirectional Non-Scanning Energy-Mass Analyzer	This analyzer would investigate the structure, dynamics, and origin of plasma formations in the near-Mars space. The analyzer used measurements of three-dimensional distribution of hot ions and flux parameters with high time resolution.
Omnidirectional Ionospheric Energy-Mass-Spectrometer	This spectrometer was designed to study the dynamics of the Martian ionosphere and the ion composition of the thermal plasma of ionospheric origin in the magnetosphere of Mars.
Ionospheric Plasma Spectrometers	These two spectrometers would measure the Martian ionosphere and the cold plasma convection in the Martian magnetosphere. The instrument consisted of two identical ion energy spectrometers; a set of 28 retarding potential analyzers, a spherical ion probe; and a spherical retarding potential analyzer operating in a floating mode with periodic measurements of integral cold ion energy spectra.
Electron Analyzer and Magnetometer	This instrument would measure, with high accuracy and high time resolution, the three-dimensional distribution of electron velocity and magnetic field vector in the plasma environment of Mars and the solar wind.
Wave Complex	This instrument was designed to study the Martian magnetosphere oblateness by the solar wind and of the energy transfer through the shock and planetopause; identify instabilities in the ionosphere and magnetosphere; and study waves of atmospheric origin generated by sand storms and lightning.
Low-Energy Charged Particle Spectrometer	This spectrometer would carry out detailed studies of energetic particle radiation in the Martian environment and monitor low-energy cosmic rays along the Earth-to-Mars trajectory.

Table 4–76. Mars '96 Instruments (Continued)

Instruments	Description
Astrophysics and Cruise:	
Precision Gamma Spectrometer	This spectrometer was designed to measure gamma radiation from the Martian surface, powerful solar flares, and gamma-ray bursts. The spectrometer would operate continuously along the Earth-to-Mars trajectory while recording cosmic gamma rays. In orbit around Mars, the instrument would measure gamma spectra of the surface.
Cosmic and Solar Gamma-Burst Spectrometer	This spectrometer would carry out high-precision localization of gamma-ray burst sources using data from Ulysses and near-Earth satellites.
Stellar Oscillation Photometer	This photometer would study pulsations, rotations, and the internal structure of stars through long-term, continuous, and high-accuracy photometry of stars along the Earth-to-Mars trajectory.
Solar Oscillation Photometer	This photometer would study the Sun's internal structure from measurements of solar brightness oscillations through long-term, continuous, and high-accuracy photometry of the Sun along the Earth-to-Mars trajectory.
Radiation/Dosimetry Control Complex	This instrument was intended to study radiation conditions along flight trajectories to Mars and near the planet and determine the energy spectra; measure the Sun's x-ray flux; identify the mass composition of charged particle fluxes; and determine the spatial distribution of charged particle fluxes within a wide energy range.
Small Station scientific payload:	
Meteorology Instrument System	This system consisted of temperature sensors; an absolute pressure sensor; a relative humidity sensor; an optical depth sensor; and an ion anemometer.
Descent Phase Instrument System	This system included an accelerometer, as well as pressure and temperature sensors.
Alpha-particle, Proton and X-ray Spectrometer	This spectrometer performed measurements of the elemental composition of Martian soils beginning with carbon.
Seismometer, Magnetometer, and Inclinometer	This instrument consisted of a three-component magnetometer with an inclinometer on the boom, a vertical-component seismometer, and an electronics unit.
Panoramic Camera	This camera took a TV panorama of the Martian landscape around the small station.
Descent Camera	This camera performed imaging with a resolution of 20 m (65.6 ft) to 1 cm (0.4 in) during parachute descent.
Mars Oxidant Experiment	This experiment studied the presence of an oxidizing agent in the Martian soil and atmosphere inferred from the results of biology experiments on board the Viking landers in the mid-1970s.

Table 4–77. Mars Climate Orbiter Mission Characteristics

Launch Date/Launch Site	December 11, 1998/Cape Canaveral Air Force Station
Date of Reentry	None; lost contact
Launch Vehicle	Delta II 7425
NASA Role	Mission design; spacecraft and payload development, integration, testing, and launch; mission operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	(Same mission objectives for Climate Orbiter and Polar Lander missions)[a] • Develop and launch two spacecraft to Mars during the 1998 Mars transfer opportunity. • One orbiter and one lander spacecraft. • Separate Med-Lite launch vehicles. • Development cost capped at $183.9 million (real-year dollars). • Collect and return to Earth science data resulting from the in situ and remote investigations of the Martian environment by the Lander and Orbiter spacecraft. • Landing site targeted near south pole (~80°S). • 90-day primary lander mission. • 400-km (249-mi) near-circular, near-polar mapping orbit. • Two-year science mapping, five-year data relay mission. Climate Orbiter science objectives: • Analyze the composition of surface materials, characterize daily and seasonal weather patterns and frost deposits, and monitor surface and atmospheric interactions to better understand the planet as a global system. • Study variations in atmospheric dust and volatile materials, such as carbon dioxide and water, in both their vapor and frozen forms; track these variations during a full Martian year (687 Earth days). • Identify surface reservoirs of volatile material and dust and observe their seasonal variations. Use the orbiter's imager and sounder to characterize surface compositional boundaries and changes that might occur with time or seasons.

Table 4–77. Mars Climate Orbiter Mission Characteristics (Continued)

Mission Objectives	• Explore climate processes that stir up or quell regional and global dust storms, as well as atmospheric processes transporting volatiles such as water ice clouds and dust around the planet. • Search for evidence of Mars' ancient climate, which some scientists believe was temperate and more Earth-like with a thicker atmosphere and abundant flowing water. Layered terrain in the polar regions suggests more recent, possibly cyclic, climate change. Studies of Mars' early climate compared with Earth's may explain whether internal or external factors (such as changes in Mars' orbit) are primary drivers of climate change.
Orbit Characteristics	Did not enter orbit
Weight	629 kg (1,387 lb) total, consisting of 338 kg (745 lb) spacecraft and 291 kg (642 lb) fuel
Dimensions	Main bus: 2.1 m (6.9 ft) tall, 1.6 m (5.4 ft) wide, 2 m (6.4 ft) deep; solar array wingspan: 5.5 m (18 ft) tip to tip
Power Source	Solar array
Prime Contractor	Lockheed Martin
Instruments and Experiments	• Mars Color Imager (MARCI) PI: Michael Malin, Malin Space Science Systems Inc. The MARCI combined nadir-pointed pushframe wide-angle and medium-angle cameras. Near the end of the Orbiter's cruise phase, the MARCI acquired approach images of Mars. • Pressure Modulator Infrared Radiometer (PMIRR) PIs: Daniel McCleese, Jet Propulsion Laboratory and Vassili Moroz, Space Research Institute, Moscow The PMIRR was a nine-channel limb and nadir-scanning atmospheric sounder designed to vertically profile atmospheric temperature, dust, water vapor, and condensate clouds. The PMIRR also was designed to quantify surface radiative balance.
Results	Unsuccessful; was lost on arrival at Mars on September 23, 1999.

[a] "Mars Climate Orbiter/Mars Polar Lander Mission Overview," *http://mars.jpl.nasa.gov/msp98/mission_overview.html* (accessed August 24, 2005).

Table 4–78. Mars Polar Lander Mission Characteristics

Launch Date/Launch Site	January 3, 1999/Cape Canaveral Air Station
Date of Reentry	None; lost at arrival at Mars
Launch Vehicle	Delta II 7425
NASA Role	Program management
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	(Same mission objectives for Climate Orbiter and Polar Lander missions)[a] Science objectives: • Land on the layered terrain in Mars' south polar region. • Search for evidence relating to ancient climates and more recent periodic climate change. • Present a picture of the current climate and seasonal change at high latitudes; in particular, present a picture of the exchange of water vapor between the atmosphere and ground. • Search for near-surface ground ice in the polar regions and analyze the soil for physically and chemically bound carbon dioxide and water. • Study surface morphology (forms and structures), geology, topography, and weather of the landing site.
Orbit Characteristics	None; did not enter orbit
Weight	Lander: 1,270 lb (576 kg) total, consisting of 639-lb (290-kg) lander and 141 lb (64 kg) of propellant, 181-lb (82-kg) cruise stage, 309-lb (140-kg) aeroshell and heat shield Deep Space 2: 7.9 lb (3.9 kg) total
Dimensions	Lander: 3.5 ft (1.06 m) tall, 12 ft (3.6 m) wide Deep Space 2: aeroshell 11 in (275 mm) high, 14 in (350 mm) diameter; enclosing a forebody (penetrator) 4.2 in (105.6 mm) long, 1.5 in (39 mm) diameter; and an aftbody (ground station) 4.1 in (105.3 mm) high (plus 5-in (127-mm) antenna), 5.3 in (136 mm) diameter
Power Source	Solar panels (lander), batteries (Deep Space 2)
Prime Contractor	Lockheed Martin
Instruments and Experiments	Lander: • Mars Volatiles and Climate Surveyor instrument suite: This instrument suite was designed to perform *in situ* investigations to address the science theme "Volatiles and Climate History" on Mars and to conduct meteorology, imaging, and soil composition experiments. This integrated package included a surface stereo imager; robotic arm with camera; meteorology package; and thermal and evolved gas analyzer. — Surface stereo imager PIs: Peter Smith, University of Arizona and H. Uwe Keller, Max Planck Institut für Aeronomie, Germany

Table 4–78. Mars Polar Lander Mission Characteristics (Continued)

Instruments and Experiments	— Meteorology package Co-investigators: David Crisp and Randy May, NASA Jet Propulsion Laboratory and Ari-Matti Harri, Finnish Meteorological Institute — Thermal and evolved gas analyzer PI: William Boynton, University of Arizona • Mars Descent Imager: PI: Michael Malin, Malin Space Science Systems Inc. The imager was to take approximately 30 pictures as the lander descended toward the surface of Mars, beginning just before heat-shield ejection at an altitude of about 5 mi (8 km) and continuing until landing. • LIDAR instrument: PI: V.S. Linkin, IKI, Russia The LIDAR instrument was supplied by the Russian Space Agency. This instrument emitted pulses of energy and then detected their echo while they bounced off material in the atmosphere. The instrument carried a microphone in its electronics box. Deep Space 2: • Sample collection/water detection experiment • Soil thermal experiment • Atmospheric descent accelerometer • Impact accelerometer
Results	Lost on arrival at Mars on December 3, 1999.

[a] "Mars Climate Orbiter/Mars Polar Lander Mission Overview," *http://mars.jpl.nasa.gov/msp98/mission_overview.html* (accessed August 24, 2005).

Table 4–79. Cassini-Huygens Mission Characteristics

Launch Date/Launch Site	October 15, 1997/Cape Canaveral Air Force Station
Date of Reentry	Operating as of mid-2005.
Launch Vehicle	Titan IVB/Centaur
NASA Role	Project management, spacecraft operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Science objectives:[a] Saturn • Determine the temperature field, cloud properties, and composition of Saturn's atmosphere. • Measure the planet's global wind field, including waves and eddies; make long-term observations of cloud features to see how they grow, evolve, and dissipate. • Determine the internal structure and rotation of the deep atmosphere. • Study daily variations and relationships between the ionosphere and the planet's magnetic field. • Determine the composition, heat flux, and radiation environment present during Saturn's formation and evolution. • Investigate sources and nature of Saturn's lightning. Titan • Determine the relative amounts of different components of the atmosphere; determine the mostly likely scenarios for the formation and evolution of Titan and its atmosphere. • Observe vertical and horizontal distributions of trace gases; search for complex organic molecules; investigate energy sources for atmospheric chemistry; determine the effects of sunlight on chemicals in the stratosphere; study formation and composition of aerosols (particles suspended in the atmosphere). • Measure winds and global temperatures; investigate cloud physics, general circulation, and seasonal effects in Titan's atmosphere; search for lightning. • Determine the physical state, topography, and composition of Titan's surface; characterize its internal structure. • Investigate Titan's upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Mission Objectives	Magnetosphere • Determine the configuration of Saturn's magnetic field, which is nearly symmetrical with Saturn's rotational axis. Also, study the field's relation to the modulation of Saturn kilometric radiation—a radio emission from Saturn believed to be linked to the way electrons in the solar wind interact with the magnetic field at Saturn's poles. • Determine the current systems, composition, sources, and concentrations of electrons and protons in the magnetosphere. • Characterize the structure of the magnetosphere and its interactions with the solar wind and with Saturn's moons and rings. • Study how Titan interacts with the solar wind the ionized gases within Saturn's magnetosphere. The Rings • Study the configuration of the rings and dynamic processes responsible for ring structure. • Map the composition and size distribution of ring material. • Investigate the interrelation of Saturn's rings and moons, including imbedded moons. • Determine the distribution of dust and meteoroid distribution in the vicinity of the rings. • Study the interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere. Icy Moons • Determine the general characteristics and geological histories of Saturn's moons. • Define the different physical processes that have created the surfaces, crusts, and subsurfaces of the moons. • Investigate compositions and distributions of surface materials, particularly dark, organic-rich materials and condensed ices with low melting points. • Determine the bulk compositions and internal structures of the moons. • Investigate interactions of the moons with Saturn's magnetosphere and ring system; investigate possible gas injections into the magnetosphere.
Weight	Cassini: 5,712 kg (12,593 lb) with fuel and Huygens probe; Cassini orbiter alone (unfueled): 2,125 kg (4,685 lb) Huygens: 320 kg (705 lb)
Dimensions	Cassini: 6.8 m (22.3 ft) high, 4 m (13.1 ft) wide Boom: 11 m (36 ft) Huygens: 2.7 m (8.9 ft) diameter
Shape	Main body: cylindrical

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Power Source	Radioisotope thermoelectric generators
Prime Contractor	Lockheed Martin
Instruments and Experiments	Orbiter Instruments: • Cassini Plasma Spectrometer (CAPS) PI: David T. Young, Southwest Research Institute The CAPS is a direct sensing instrument measuring the energy and electrical charge of particles, such as electrons and protons, that the instrument encounters. The CAPS measures the molecules originating from Saturn's ionosphere and determines the configuration of Saturn's magnetic field. The CAPS also investigates plasma in these areas as well as the solar wind within Saturn's magnetosphere. • Cosmic Dust Analyzer (CDA) PI: Eberhard Grün, Max Planck Institute für Kernphysik, Germany The CDA is a direct sensing instrument measuring the size, speed, and direction of tiny dust grains near Saturn. Some of these particles orbit Saturn while others may come from different solar systems. Cassini's CDA is more advanced than corresponding instruments on the Galileo and Ulysses spacecraft. Cassini's CDA also can determine trajectories (orbits), speeds, and chemical compositions of the dust particles impacting the Saturn system, allowing scientists to determine where the dust originated. • Composite Infrared Spectrometer (CIRS) PI: Virgil G. Kunde, Goddard Space Flight Center The CIRS is a remote sensing instrument measuring the infrared light coming from an object (such as an atmosphere or moon surface) to learn about its temperature and composition. The CIRS measures infrared emissions from atmospheres, rings, and surfaces in the Saturn system to determine their composition, temperatures, and thermal properties. The spectrometer maps in three dimensions to determine temperature and pressure profiles with altitude, gas composition, and the distribution of aerosols and clouds.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	The CIRS evolved from the Voyager Infrared Interferometer Spectrometer (IRIS) and is a significant improvement, with a spectral resolution 10 times greater than IRIS. A larger wavelength range is covered, with more closely spaced data points, greatly increasing the details able to be seen in the spectrum. A narrow angle camera is also built into a reflecting telescope with a 2,000-mm (79-inch) focal length and 0.35-degree FOV. The CIRS consists of two combined interferometers, operating in the far-infrared (10 cm^{-1} –600 cm^{-1}) and mid-infrared (600 cm^{-1} –1,400 cm^{-1}). The two interferometers share a common telescope and scanner. The instrument also can observe the dark side of Saturn, view lightning, and make other readings normally obscured by the Sun. It can also look at Saturn's aurora for changes in temperature. • Ion and Neutral Mass Spectrometer (INMS) Team Leader: J. Hunter Waite, Southwest Research Institute The INMS is a direct sensing instrument analyzing charged particles (such as protons and heavier ions) and neutral particles (such as atoms) near Titan and Saturn to learn more about their atmospheres. It also measures the positive ion and neutral environments of Saturn's icy satellites and rings. • Imaging Science Subsystem (ISS) Team Leader: Carolyn C. Porco, University of Arizona The ISS is a remote sensing instrument that captures images in visible, infrared, and UV light. The ISS includes two cameras: a Wide Angle Camera (WAC) and a Narrow Angle Camera (NAC). The WAC takes a broad, wide-angle picture. The NAC has higher resolution and can record small areas in fine detail. The NAC can see a penny 1.5 cm (0.5 in) across from a distance of nearly 4 km (2.5 mi). The ISS returns thousands of images of Saturn and its rings and moons. Each camera uses a sensitive CCD as its detector. Each CCD consists of a 1,024 square array of pixels, 12 microns on a side. The camera's system allows for many data collection modes, including on-chip data compression. Both cameras are fitted with spectral filters that rotate on a wheel to view different bands within the electromagnetic spectrum ranging from 0.2 micron to 1.1 microns. At Saturn, the cameras observe the planet's atmosphere and cloud turbulence in different spectral wavelengths. In this way, the instrument can see both horizontal and vertical layers. They also study Saturn's rings and the surfaces of Saturn's moons.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Dual Technique MAG PI: David J. Southwood, Imperial College of Science & Technology, U.K. The MAG is a direct sensing instrument measuring the strength and direction of the magnetic field around Saturn. The magnetic fields are generated partly by the intensely hot molten core at Saturn's center. Measuring the magnetic field is one way to probe Saturn's extremely hot core. The MAG consists of a vector/scalar helium magnetometer sensor; a fluxgate magnetometer sensor; a data processing unit; three power supplies; and operating software and electronics associated with the sensors. • Magnetospheric Imaging (MIMI) Mass Spectrometer PI: Stamatios Krimigis, The Johns Hopkins University The MIMI Mass Spectrometer is a direct and remote sensing instrument that produces images and other data about particles trapped in Saturn's huge magnetosphere. This information is used to study the overall configuration and dynamics of the magnetosphere and its interactions with the solar wind, Saturn's atmosphere, Titan, rings, and icy satellites. The MIMI Mass Spectrometer studies all possible sources of energy in and around Saturn, the hot plasma in Saturn's magnetosphere, as well as storms and Saturn kilometric radiation. • Radio Detection and Ranging (RADAR) Instrument Team Leader: Charles Elachi, Jet Propulsion Laboratory The RADAR instrument is a remote active and remote passive sensing instrument producing maps of Titan's surface and measuring the height of surface objects by bouncing radio signals off the surface and timing their return. Radio waves can penetrate the thick veil of haze surrounding Titan. The RADAR instrument also listens for radio waves that Saturn or its moons may produce. The RADAR instrument operates in three ways: imaging, altimetry, and radiometry. Each mode allows the collection of different types of data, from straightforward imaging to three-dimensional modeling to passive collection of information, such as recording the energy emanating from a planet's surface. The RADAR instrument offers the opportunity to observe and map the synchrotron emissions at a new frequency (13.8 GHz) that is not possible from Earth-based telescopes. This opportunity comes from the Cassini radiometer's capability to separate the atmospheric thermal emission from synchrotron emission.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Radio and Plasma Wave Science (RPWS) Instrument PI: Donald A. Gurnett, University of Iowa The RPWS instrument is a direct and remote sensing instrument that receives and measures radio signals coming from Saturn, including radio waves given off by the interaction of the solar wind with Saturn and Titan. The RPWS instrument measures the electric and magnetic wave fields in the interplanetary medium and planetary magnetospheres. The instrument also determines the electron density and temperature near Titan and in some regions of Saturn's magnetosphere. The RPWS instrument studies the configuration of Saturn's magnetic field and its relationship to Saturn kilometric radiation, as well as monitoring and mapping Saturn's ionosphere, plasma, and lightning from Saturn's atmosphere. The RPWS instrument also determines dust and meteoroid distributions throughout the Saturn system and between the icy satellites, the rings, and Titan. • Radio Science Subsystem (RSS) Team Leader: Arvydas Kliore, Jet Propulsion Laboratory The RSS detects small changes in the phase and/or amplitude of a radio signal starting at the spacecraft and traveling to antennae on Earth. These small changes provide detailed information on several subjects including planetary gravitational fields, the mass of a moon, the structure of planetary rings, and the atmospheric and ionospheric structure of planets and moons. The RSS is unique in that only half of the instruments are carried aboard Cassini. The other half of instruments stays on Earth in the DSN complexes. While touring Saturn, the RSS instrument performs a series of radio occultations of Saturn's rings and atmosphere. An occultation is performed when Cassini sends a radio signal from the spacecraft through the rings to Earth. The information received on Earth gives scientists clues into the structure of the ring system. Similar occultations are performed on Saturn's atmosphere, allowing scientists to gather information on the global temperature, pressure, and zonal winds in Saturn's upper atmosphere. The RSS uses the spacecraft X-band communication link, S-band downlink, and Ka-band uplink and downlink for data acquisition.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Ultraviolet Imaging Spectrograph (UVIS) PI: Larry L. Esposito, University of Colorado, Boulder The UVIS is a remote sensing instrument that captures images of UV light reflected off objects, such as the clouds of Saturn and its rings, to learn more about their structure and composition. Designed to measure UV light over wavelengths from 55.8 nm to 190 nm, this instrument also helps determine the composition, distribution, aerosol particle content, and temperatures of their atmospheres. This instrument differs from other types of spectrometers in that it can take both spectral and spatial readings. It is particularly adept at determining the composition of gases. Spatial observations take a wide-by-narrow view, only one pixel tall and 60 pixels across. The spectral dimension is 1,024 pixels per spatial pixel. Additionally, it can take so many images that it can create movies to show how material is moved by other forces. • Visual and Infrared Mapping Spectrometer (VIMS) PI: Robert H. Brown, University of Arizona The VIMS is a remote sensing instrument consisting of two cameras in one: the first measures visible wavelengths, and the second detects infrared to learn more about the composition of moon surfaces, the rings, and the atmospheres of Saturn and Titan. The VIMS also observes the sunlight and starlight passing through the rings to learn more about ring structure. The VIMS measures reflected and emitted radiation from atmospheres, rings, and surfaces over wavelengths from 0.35 micrometer to 5.1 micrometers. It also helps determine the compositions, temperatures, and structures of these objects. Scientists use the VIMS to perform long-term studies of cloud movement and morphology in the Saturn system to determine the planet's weather patterns. The VIMS measures the locations where, and under what conditions, "pre-biotic" materials (the minor building blocks of life) are found to possibly provide clues about the origins of life. The VIMS also studies lightning and the planet's moons.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	Probe Instruments: • Huygens Atmospheric Structure Instrument: PI: Marcello Fulchignoni, Paris Observatory, France This instrument contains a suite of sensors measuring the physical and electrical properties of Titan's atmosphere. Accelerometers measure forces in all three axes as the probe descends through the atmosphere. Since the aerodynamic properties of the probe are already known, it is possible to determine the density of Titan's atmosphere and detect wind gusts. If the probe lands on a liquid surface, this instrument would be able to measure the probe motion due to waves. • Temperature and pressure sensors also measure the thermal properties of the atmosphere. The Permittivity and Electromagnetic Wave Analyzer component measures the electron and ion conductivities of the atmosphere and searches for electromagnetic wave activity. On the surface of Titan, the analyzer measures the conductivity and permittivity (i.e., the ratio of electric flux density produced to the strength of the electric field producing the flux) of the surface material. • Doppler Wind Experiment (DWE) PI: Michael K. Bird, University of Bonn, Germany The DWE measures the wind speed during Huygens's descent through Titan's atmosphere by observing changes in the carrier frequency of the probe due to the Doppler effect. • Descent Imager/Spectral Radiometer (DISR) PI: Martin G. Tomasko, University of Arizona The DISR makes a range of imaging and spectral observations using several sensors and fields of view. By measuring the upward and downward flow of radiation, the radiation balance or imbalance of the thick Titan atmosphere is measured. Solar sensors measure the light intensity around the Sun due to scattering by aerosols in the atmosphere. This permits calculation of the size and number density of the suspended particles. Two imagers (one visible, one infrared) observe the surface during the latter stages of the descent and, as the probe slowly rotates, build a mosaic of pictures around the landing site. A side-view visible imager also obtains a horizontal view of the horizon and the underside of the cloud deck. For spectral measurements of the surface, a lamp switches on shortly before landing, augmenting the weak sunlight.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments[b]	• Gas Chromatograph Mass Spectrometer (GCMS) PI: Hasso B. Neimann, Goddard Space Flight Center A versatile gas chemical analyzer identifying and measuring chemicals in Titan's atmosphere, the GCMS is equipped with samplers filled at high altitude for analysis. The spectrometer builds a model of the molecular masses of each gas, and the gas chromatograph accomplishes a more powerful separation of molecular and isotopic species. During descent, the GCMS analyzes pyrolysis products (samples altered by heating) passed to it from the Aerosol Collector Pyrolyser. Finally, the GCMS measures the composition of Titan's surface after a safe landing. This investigation is made possible by heating the GCMS instrument just before impact to vaporize the surface material on contact. • Aerosol Collector and Pyrolyser (ACP) PI: Guy M. Israel, Service d'Aeronomie du Centre National de la Recherche Scientifique, France The ACP draws in aerosol particles from the atmosphere through filters, then heats the trapped samples in ovens to vaporize volatiles and decompose the complex organic materials. The products are then flushed along a pipe to the GCMS instrument for analysis. Two filters are provided to collect samples at different altitudes. • The Surface-Science Package (SSP) PI: John C. Zarnecki, University of Kent, UK The SSP contains sensors to determine the physical properties of Titan's surface at the point of impact. These sensors also determine whether the surface is solid or liquid. An acoustic sounder, activated during the last 100 meters (328 feet) of the descent, continuously determines the distance to the surface, measuring the rate of descent and the surface roughness (due to waves, for example). During descent, measurements of the speed of sound provide information on atmospheric composition and temperature, and an accelerometer accurately records the deceleration profile at impact, providing information on the hardness and structure of the surface. A tilt sensor measures any pendulum motion during the descent and indicates the probe attitude after landing.
Results	Successfully traveled to Saturn and inserted probe into Titan.

[a] "Cassini Launch Press Kit," *http://www.jpl.nasa.gov/news/press_kits/cassini.pdf* (accessed August 16, 2005).

[b] "Spacecraft–Cassini Orbiter Instruments," *http://saturn.jpl.nasa.gov/spacecraft/instruments-cassini-intro.cfm* (accessed August 16, 2005). Also "Spacecraft–Huygens Probe Instruments," *http://saturn.jpl.nasa.gov/spacecraft/instruments-huygens.cfm* (accessed August 16, 2005).

Table 4–80. Voyager Events

Date	Event
1977	Mariner Jupiter/Saturn 1977 is renamed Voyager.
August 20, 1977	Voyager 2 launched from Kennedy Space Flight Center.
September 5, 1977	Voyager 1 launched from Kennedy Space Flight Center. Voyager 1 returns first spacecraft photo of Earth and Moon.
March 5, 1979	Voyager 1 makes its closest approach to Jupiter.
July 9, 1979	Voyager 2 makes its closest visit of Jupiter.
November 12, 1980	Voyager 1 flies by Saturn. Voyager 1 begins its trip out of the solar system .
August 25, 1981	Voyager 2 flies by Saturn.
1982	The DSN upgrades two 26-m antennae to 34-m.
January 24, 1986	Voyager 2 has the first-ever encounter with Uranus. NASA's DSN begins upgrades including expansion of 64-m antennae to 70-m.
1987	Voyager 2 "observes" Supernova 1987A.
1988	Voyager 2 returns first color images of Neptune.
August 25, 1989	Voyager 2 is the first spacecraft to observe Neptune. Voyager 2 begins its trip out of the solar system, below the ecliptic plane.
January 1, 1990	Begins Voyager Interstellar Mission.
February 14, 1990	Last Voyager Images–Portrait of the solar system.
February 17, 1998	Voyager 1 passes Pioneer 10 to become the most distant human-made object in space.

Table 4–81. Astro Mission Characteristics

Launch Date	Astro-1: December 2, 1990 Astro-2: March 2, 1995
Platform	Astro-1: STS-35 Astro-2: STS-67
Lead NASA Center	Marshall Space Flight Center
Instruments/Experiments	• HUT PI: Arthur F. Davidsen, The Johns Hopkins University The HUT recorded spectra in the 425-angstrom to 1,850-angstrom wavelength range, with emphasis on the largely unexplored region between 900 angstroms and 1,200 angstroms. It weighed 1,700 lb (771 kg); was 12 ft (3.7 m) long and 4 ft (1.2 m) wide; had a 0.9 meter (36-in) f/2.0 primary mirror and prime focus; and had a Rowland-circle design spectrograph. The primary mirror was coated with iridium for high reflectivity in the UV bandwidth. It had a collecting area of 5,300 sq cm (822 sq in), and at the focal plane the scale was 115 arc seconds per mm. The spectrograph separated UV light from an astronomical object into its component wavelengths for detailed analysis. The spectrograph consisted of an aperture wheel assembly, a 200-mm (7.9-in) osmium-coated concave grating, and a photon-counting detector. The detector included a microchannel plate intensifier with a cesium iodide photocathode array (pulse counting) with 1,024 channels. The spectrograph resolution was 75 microns. Using the first order of the grating permitted observations in the 850-angstrom to 1850-angstrom region, with a resolution of about 3 angstroms. In addition, the second order of the grating could also provide access to the 425-angstrom to 925-angstrom region with 1.5-angstrom resolution. The spectrograph recorded the UV spectrum electronically and transmitted the information to Earth for study. The spectrograph operated in four distinct modes: histogram mode, high-time resolution mode, cumulative unprocessed mode, and single scan mode. The first two modes were used in flight for observations of astrophysical objects. The last two modes were unprocessed modes used only for diagnostic purposes.

Table 4–81. Astro Mission Characteristics (Continued)

Instruments/Experiments	• UIT PI: Theodore P. Stecher, Goddard Space Flight Center The UIT obtained deep, wide-field UV images of the sky in the 1,200-angstrom to 3,200-angstrom range. It had the largest FOV of any sensitive UV imaging system planned for flight in the 1990s and was sensitive enough to record a blue star of 25th magnitude during a 30-minute exposure. The UIT was a 38-cm (15-in) f/9 Ritchey Chretien telescope with two selectable cameras mounted behind the primary mirror. The focal length of the primary mirror was 352.9 cm (139 in), and the nominal pixel size after digitization was 20 microns. Each camera had a six-position filter wheel to accommodate metal-dielectric interference filters, crystalline plates, or fused quartz. The first camera had a CsTe photocathode and was designed to operate in the 1,250-angstrom to 3,000-angstrom range. The second camera had a CsI photocathode and was designed to operate in the 1,200-angstrom to 1,700-angstrom range. The cameras were magnetically focused two-stage image intensifiers, which produced images recorded on 70-mm film. The resulting images covered a 40-arc-minute FOV, with a resolution of 3 arc seconds. Each unit contained 1,000 frames of astronomical film. Developed after the mission, each frame of film was digitized to form a 2,048 pixel by 2,048 pixel array for computer analysis.[a] • Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE) PI: Arthur D. Code, University of Wisconsin, Madison The WUPPE made the first high-quality, high signal-to-noise-ratio polarization measurements of faint UV sources in the 1,400-angstrom to 3,200-angstrom range with a FOV of 3.3 arc minutes by 4.4 arc minutes and a resolution of 6 angstroms. This was the first and most comprehensive effort to exploit the unique powers of polarimetry at wavelengths not visible on Earth. Before the development and flight of this experiment on this mission, virtually no such data existed because of the difficulty in obtaining these measurements with the degree of accuracy required for astronomical observations.[b] The Cassegrain-type telescope used its 50-cm (20-in) diameter f/10 mirror with an area of 1,800 cm^2 (279 sq in) to reflect UV light to a spectropolarimeter, where two rotating wheels were used to select the focal plane aperture and the polarimetry analyzer. The spectropolarimeter measured the degree and direction of polarization at many different wavelengths.

Table 4–81. Astro Mission Characteristics (Continued)

Instruments/Experiments[c]	• Broad Band X-ray Telescope (Astro-1 only) PI: Dr. Peter J. Serlemitsos, Goddard Space Flight Center The BBXRT obtained x-ray spectra covering the 0.3-keV to 10.0-keV band. It viewed high-energy objects such as active galaxies, quasars, and supernovas. It was mounted on a separate pointing system secured by a support structure in the cargo bay. For joint observations, the BBXRT was aligned with the UV telescopes to see the same objects, but it also could be pointed independently to view other x-ray sources. Ground controllers operated the BBXRT remotely. The BBXRT consisted of two coaligned telescopes with focal lengths of 3.8 m (12.5 ft) and diameters of 40 cm (15.7 in). Each telescope contained a thin-foil conical mirror assembly made of 118 curved, gold-plated aluminum reflectors and a segmented, cryogenically cooled lithium-drifted silicon spectrometer at the focal plane. The whole optical system provided a total collecting area of 765 cm^2 (118.6 sq in) at 1.5 keV, and 300 cm^2 (46.5 sq in) at 7 keV.[d]
Remarks[e]	These missions demonstrated the benefits of human interaction in on-orbit astronomy. Besides being able to position the orbiter most advantageously for observations, crew members also could manually acquire observation targets.

a “UIT Technical Summary,” *http://praxis.pha.jhu.edu/instruments/uit_info.html* (accessed August 25, 2005).

b “WUPPE Technical Summary,” *http://praxis.pha.jhu.edu/instruments/wuppe_info.html* (accessed August 25, 2005). Also “The Wisconsin Ultraviolet Photo-Polarimeter Experiment,” *http://praxis.pha.jhu.edu/instruments/wuppe.html* (accessed August 25, 2005).

c “The Astro-1 Mission,” *http://praxis.pha.jhu.edu/astro1/astro1_mission.html* (accessed August 23, 2005).

d “BBXRT,” NASA’s HEASARC: Observatories, *http://heasarc.gsfc.nasa.gov/docs/bbxrt/bbxrt_about.html* (accessed August 25, 2005).

e “STS-67 Mission Archives,” *http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-67.html* (accessed May 9, 2006).

Table 4–82. Astro-2 HUT Scientific Achievements

Category	Description
Intergalactic Medium	The HUT science team's highest priority science goal was to detect and measure the characteristics of the primordial intergalactic medium (IGM), a hypothesized gas thought to be spread throughout the universe between the galaxies. The science team succeeded in performing multiple observations of a faint, high redshift quasar, using it as a "background" source to shine through the IGM; absorption of the quasars light at the "right" UV "colors" would indicate the presence of this elusive component of the universe.
Active Galaxy Nuclei	The HUT was used to observe the active galaxy NGC 4151, which may harbor an obscured black hole in its nucleus. The object was known to be variable on week-to-month timescales, and it had also been observed during Astro-1, providing an important comparison. NGC 4151 was observed to be about five times brighter during Astro-2 than it was during Astro-1. A detailed comparison of the differences allowed an unprecedented view of the structure of the region close to the black hole. Time variability during periods as small as two days may also be present in the Astro-2 data.
Elliptical Galaxies	During Astro-1, although only one elliptical galaxy and one "galactic bulge" region of a spiral galaxy (thought similar to an elliptical galaxy in many regards) were observed sufficiently to constrain models of the stars producing the faint UV light in these galaxies, these observations provided breakthroughs in understanding. The first results for six elliptical galaxies from Astro-2 were used to confirm and extend the preliminary Astro-1 results.

Table 4–82. Astro-2 HUT Scientific Achievements (Continued)

Supernova Remnants	These were the expanding gaseous nebulae created by supernova explosions, which often remain visible for thousands of years. As these nebulae expanded, they heated normally invisible regions of interstellar gas and caused them to glow. They provided new information not only about the stars that exploded but also the interstellar medium. Very few of these objects, however, were observable in UV light because of intervening absorption by dust and gas in the plane of our galaxy. Early Astro-2 results reported new detections for two galactic supernova remnants. The remnant called "Puppis A" was detected throughout the HUT wavelength range, producing insight into a cosmic collision between the supernova blast wave and an interstellar cloud. Also, the HUT was used to detect emission from a young remnant called SN 1006, so called because Chinese astronomers observed the supernova in 1006 A.D. This was a "young" supernova remnant, and the HUT detection was the first UV observation of such a fast interstellar shock wave, estimated to be traveling at 3,000 km/s (close to 1,900 mi/s).
Hottest Stars	Several of the hottest young stars in the nearby galaxies, called the Magellanic Clouds, were observed to determine their temperatures, masses, and radii. In addition, the HUT provided unique information on the stellar winds from these most massive of stars. Included in these observations was the current candidate for the most massive single star, a star nearly 200 times the mass of our Sun.
Cataclysmic Variable Stars	Certain cataclysmic variables undergo occasional outbursts in which their brightness increases by factors of 100 or more. The time between outbursts was not regular but varied from two weeks to months. The cause of these outbursts and their effects on the stars was poorly understood. On Astro-2, HUT scientists observed the dwarf nova U Geminorum 185 days after an outburst, which was the farthest away from an outburst that the system had ever been observed. During Astro-1, the HUT had observed this binary star just 10 days after an outburst. The comparison showed the clearest evidence yet that the white dwarf star not only got heated during an outburst, but that this heating primarily affected only a portion of the white dwarf's surface. Three bright novae were also available for observation in the month or so before the Astro-2 launch. These objects were still in their decline phase during the mission, and HUT observations of two objects had been reported, including a time sequence on one object. The HUT observations were used to determine the abundances of carbon, nitrogen, and oxygen in the expanding gaseous shells as well as the time variability of the emissions.

Table 4–82. Astro-2 HUT Scientific Achievements (Continued)

Symbiotic Stars	These objects were composed of two stars in the late stages of evolution orbiting each other at a distance similar to that of Earth from the Sun. One star was a hot white dwarf which irradiated its cooler red giant companion. Astronomers made far-UV observations of several symbiotic stars with both the HUT and WUPPE. They studied the effect of the hot star's intense UV radiation on the outer layers and stellar wind of the red giant star. This provided a unique perspective on the structure and evolution of red giant star atmospheres.
Solar System	HUT scientists observed the Jovian system for comparison with Astro-1 observations. This comparison permitted a better understanding of the importance of the changing solar input. (Astro-2 was near solar minimum, while Astro-1 was near solar maximum.) A coordinated observation of Jupiter's northern polar aurora between the HUT and the Hubble Space Telescope would provide unique information on the physical processes and excitation mechanisms in Jupiter's atmosphere and magnetosphere. The HUT also observed Venus and Mars. The atmospheres of these planets, although very different from each other in terms of density, were both dominated by carbon monoxide emissions. Comparison of the HUT observations would provide new insights into the atmospheres of Earth's nearest planetary neighbors.

Table 4–83. Spartan 201 Mission Characteristics

Mission/Date	SPARTAN 201-01: April 8, 1993 SPARTAN 201-02: September 13, 1994 SPARTAN 201-03: September 7, 1995 SPARTAN 201-04: November 19, 1997 SPARTAN 201-05: October 29, 1998
Description	Each mission released a free-flying, autonomous spacecraft from the Shuttle bay for up to approximately 45 hours to observe and investigate the heating of the solar corona and acceleration of the solar wind that originates in the corona.
Instruments/Experiments	• The Ultraviolet Coronal Spectrometer used UV emissions from neutral hydrogen and ions in the corona to determine the velocities of the coronal plasma within the solar wind source region, as well as the temperature and density distributions of protons. • The White Light Coronograph measured visible light to determine the density distribution of coronal electrons within the same regions. Because Earth's atmosphere interferes with emissions at these wavelengths, the measurements had to be made from space rather than from the ground.

Table 4–84. ORFEUS-SPAS Science Payload[a]

Instrument	Features
FUV	Coverage of the 90 nm–125 nm wavelength range; spectral resolution of 10,000; Microchannel Plate Detector with optimized spatial resolution
EUV	Coverage of the 40 nm–115 nm wavelength range; spectral resolution of 5,000; detection of individual photons
IMAPS	Coverage of 95 nm–115 nm wavelength range; spectroscopy of interstellar gas lines spectral resolution of about 240,000; sub-Doppler
SESAM	Carrier for optical samples to investigate degradation of surfaces and materials in space environment; 40 places for user-provided samples

[a] "Space Shuttle Mission STS-51 Press Kit," July 1993, p. 46, *http://www.jsc.nasa.gov/history/shuttle/shuttle_pk/pk/Flight_057_sts-051_press_kit.pdf* (accessed August 26, 2005).