National Aeronautics and Space Administration

Multi-Cycle Treasury Programs

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Hubble 2011: Science Year in Review

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The full contents of this book include *Hubble* science articles, an overview of the telescope, and more. The complete volume and its component sections are available for download online at:

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Hubble's Multi-Cycle Treasury Programs

During Servicing Mission 4 in May 2009, NASA's shuttle astronauts successfully installed two new instruments on *Hubble* and repaired two older ones. As a result, the space telescope now functions at its peak scientific potential, significantly better than ground-based telescopes operated in the near-ultraviolet and near-infrared portions of the spectrum. Since NASA plans no further servicing missions, astronomers now feel a sense of urgency to harness *Hubble*'s powerful capabilities fully by using it to deposit the largest possible volume of high-quality images into the mission's data archive. In this way, future generations of astronomers can "mine" this data treasury and continue to address the major questions in modern astronomy even after the telescope itself becomes inoperable.

Therefore, in August 2009, NASA and the Space Telescope Science Institute released a call to the astronomical community to submit bold proposals for a new class of *Hubble* observations called Multi-Cycle Treasury Programs (MCTPs). For the first time, observers were invited to submit programs that were unusually large and which spanned multiple years. It was recognized that in many cases such large programs would provide astronomers the opportunity to tackle key scientific questions that cannot be fully addressed through the smaller number of telescope orbits awarded in the standard time-allocation process. (See the "Operating *Hubble*" article in this book for a further definition of orbits and the allocation process.)

Approximately 750 *Hubble* orbits were allocated for use by these multi-cycle programs in each of three consecutive years. This total of 2,250 orbits equals 20 to 25 percent of the entire observing time available. Participation in the programs was open to all categories of observers, both domestic and foreign, including those at educational institutions, profit and nonprofit organizations, NASA centers, and other government agencies.

In response to the call, researchers submitted 39 proposals, and a specially convened peer-review panel selected four. Two of the proposals were very similar, so the panel suggested that these two submittals be merged into one program. Thus, three MCTPs were approved: the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), the

This Hubble *image of galaxy cluster MACS J1206.2-0847 was taken as part of the CLASH survey, one of three large Multi-Cycle Treasury Programs. Galaxy clusters act like giant cosmic lenses, magnifying, distorting, and bending any light that passes through them, an effect known as gravitational lensing. This effect can also produce multiple images of the same distant object. In this image, astronomers uncovered 47 multiple images of 12 newly identified, distant galaxies.*

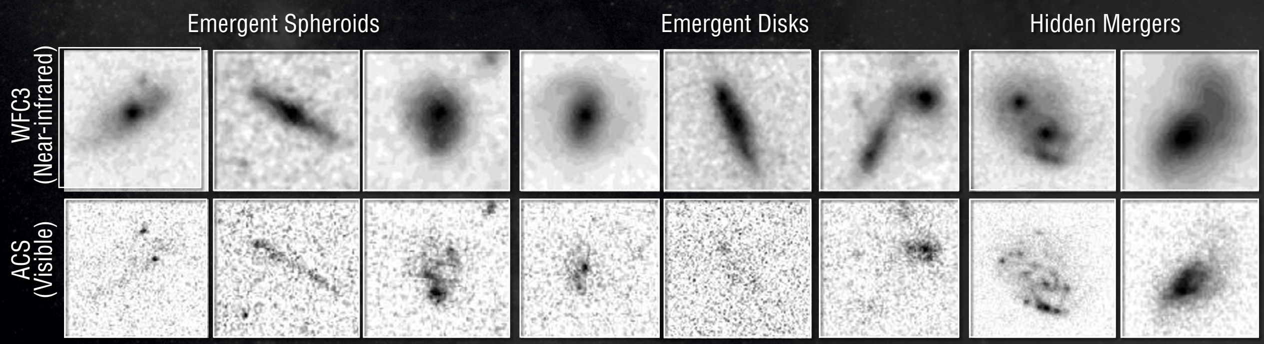
Cluster Lensing And Supernova Survey with *Hubble* (CLASH), and the Panchromatic *Hubble* Andromeda Treasury (PHAT). Unlike typical *Hubble* observations that give one-year proprietary data rights to the principal investigator who proposed the observation, the images and spectra from the MCTPs have no such period. Instead, they are immediately put into *Hubble*'s data archive where the observations are immediately accessible to all.

The following sections describe these three programs.

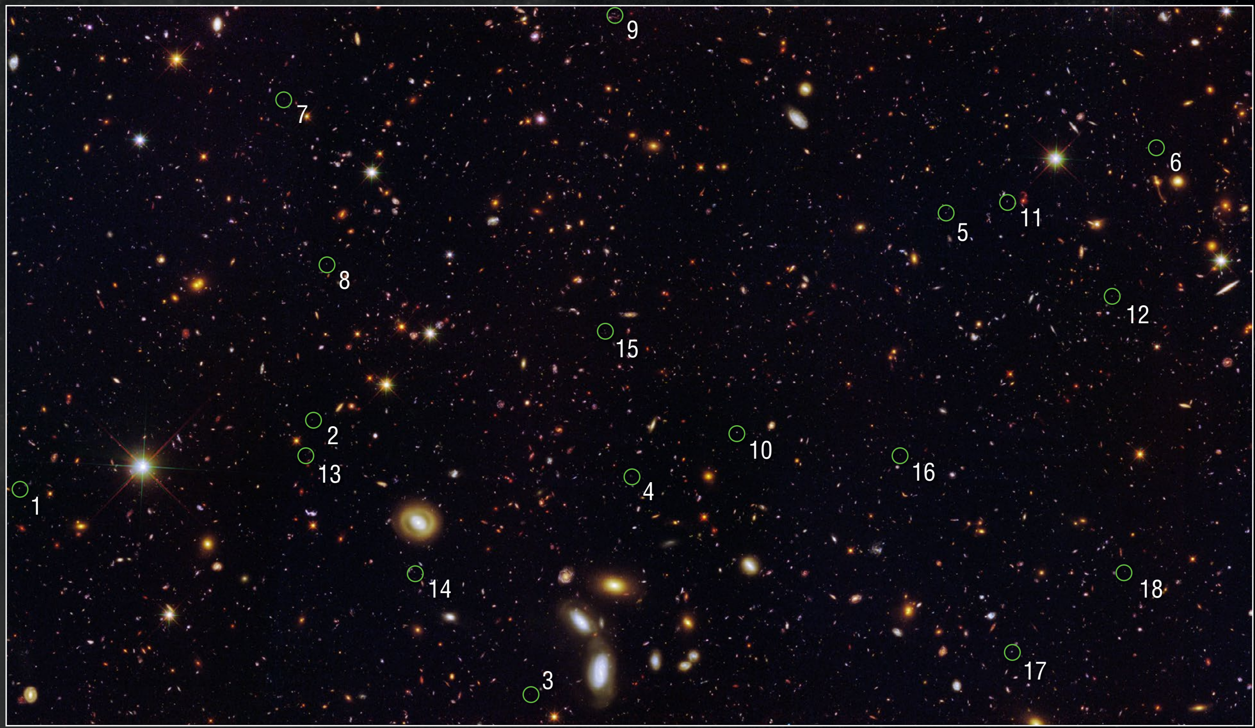
CANDELS

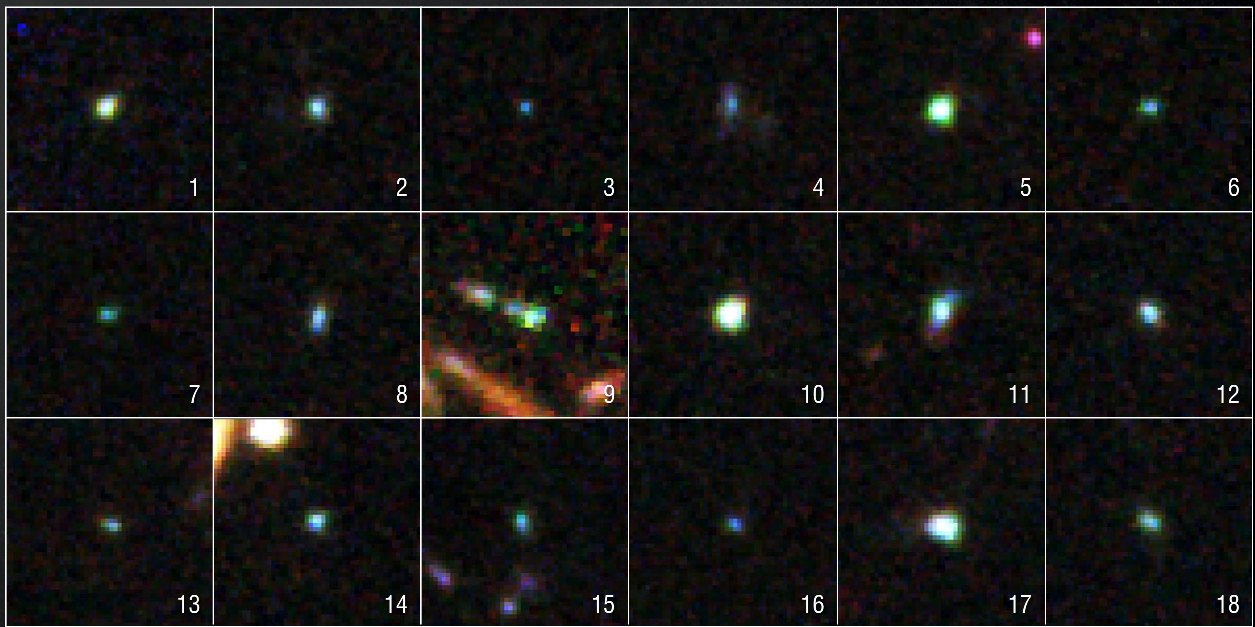
CANDELS is an in-depth imaging survey of the distant universe being carried out with *Hubble*'s Wide Field Camera 3 (WFC3) and Advanced Camera for Surveys (ACS) instruments. By looking deeper into space (and hence further back in time), the CANDELS program follows the evolution of galaxies from the time of their infancies into the present. The program also indirectly explores the nature of cosmic dark energy—the mysterious force believed to be accelerating the expansion of the universe. It does this by measuring the brightness of distant Type Ia supernovas and using this data to calculate how cosmic expansion rates vary with time. (See sidebar on page 134.)

CANDELS is the largest observing project in the history of the *Hubble* mission, with 902 orbits of observing time allocated. This is equivalent to nearly three months of time on the telescope if executed successively. Initiated in 2010, the CANDELS observations are scheduled episodically through 2013. The program is led by California astronomer Sandra Faber and Maryland astronomer Henry Ferguson with a team of more than 100 Co-investigators from 12 countries.



The CANDELS Multi-Cycle Treasury Program makes use of the near-infrared channel of the WFC3 camera (top row) and the visible-light capability of the ACS camera (bottom row). Using these two instruments, astronomers expect that the CANDELS observations will reveal new details about the distant universe and probe the nature of cosmic dark energy.





As part of the ongoing CANDELS survey, Hubble's *sensitive, near-infrared camera has uncovered an extraordinary population of tiny, young galaxies brimming with star formation. This image reveals 18 such galaxies (circled in green) that are typically a 100 times less massive than the Milky Way galaxy, yet they produce stars at such a rapid pace that their stellar content would double in just 10 million years. By comparison, the Milky Way galaxy at its current stage of development would take a 1,000 times longer to double its population of stars.*

Because the WFC3 and ACS instruments are so sensitive, the CANDELS observations allow researchers to view distant galactic objects at a time when they are only a few hundred million years old. (For comparison, the Milky Way is at least 12 billion years old.) Compared with the previous *Hubble* Deep Field observations, which targeted very small areas of the sky, CANDELS is a wide-field program that captures many more objects across a larger field of view. Scientists need this larger sample to get a good statistical picture of how galaxies like the Milky Way grew from smaller "seeds" in the early universe. The CANDELS observations are to provide this sample and paint a unique statistical picture of how galaxies built up over time.

Investigators have designed CANDELS to focus on two critical epochs in cosmic history: "Cosmic Dawn" (less than one billion years after the Big Bang when the first seeds of cosmic structure began to take shape) and "Cosmic High Noon," (two billion to four billion years after the Big Bang). During the latter epoch, galaxies appear to have experienced a surge of growth caused by huge, gravity-driven streams of gas flowing into them along an invisible web of dark matter.

Looking at "Cosmic Dawn," the team's scientists plan to compile the first definitive census of infant galaxies. During this epoch, galaxies such as the Milky Way were growing from the influx of intergalactic gas, but had formed less than 1 percent of their total complement of stars. Astronomers expect that CANDELS will reveal hundreds—perhaps thousands—of similar systems and enable measurements of their key properties: size, star formation rate, and stellar mass. The survey is also designed to map the positions of these infant galaxies in space to assess their clustering. The amount of clustering is one of the best ways to measure the gravitational effect and mass of these galaxies' dark-matter content, which is invisible to telescopes.

Studying "Cosmic High Noon," astronomers expect to see the blueprints of future galactic structures. Galaxies viewed from this ancient epoch look profoundly different from those seen today. Unlike the stately pinwheels of today's mature spirals, these early galaxies are patchy, chaotic, and filled with newly formed stars. Astronomers believe that within this apparent disarray there may exist a "scaffolding" or early framework of older, redder stars. If true, these stars would be especially apparent in the near-infrared images taken by the WFC3.

Observations from CANDELS are also expected to provide a snapshot of the birth of cosmic black holes at this "High Noon" epoch. *Hubble* has already shown that every nearby large galaxy harbors a massive black hole at its center, each weighing up to a billion solar masses. It is believed these galaxy cores shone brightly as quasars during this "High Noon" period as

In data taken to date by the CANDELS Multi-Cycle Treasury Program, astronomers have found supermassive black holes growing in surprisingly small galaxies. The finding suggests that central black holes formed at an earlier stage in galaxy evolution. This montage of four small, young galaxies comes from a Hubble *sample of 28 low-mass galaxies located 10 billion light-years away.*

the result of an associated peak in the amount of available free gas to fall into these swelling black holes—the process that feeds the quasar-jet phenomenon. A current cosmological theory suggests that supermassive black holes primarily result from galaxy mergers, which force vast quantities of gas into galaxy centers, triggering star formation and black-hole growth. By combining WFC3 images with X-ray and far-infrared data from other observatories, the team's astronomers hope to test the validity of this theory and identify the timescale for the formation of galactic cores.

In a portion of the project led by Maryland astronomer Adam Riess, the survey also seeks to characterize the nature of cosmic dark energy by measuring the brightness of Type Ia supernovas to within 2.5 billion years of the Big Bang. By leaping over intervening epochs to a time when the effect of dark energy on cosmic acceleration was negligible and ordinary matter dominated the universe, the program permits the first clean test of the constancy of Type Ia standard candles independent of the influence of dark energy. (See page 134 for an explanation of "standard candles.")

The *Hubble* observatory is uniquely suited to conduct CANDELS. In the near-infrared part of the spectrum, the sky background seen from the ground is very bright, so *Hubble*'s position above the glowing atmosphere affords the telescope much better views than those from the ground. Also, *Hubble*'s superb resolution enables scientists to measure galaxy sizes, study their morphologies, and readily compare them with other *Hubble* images to identify changes like supernovas.

CLASH

While the CANDELS program focuses on distant galaxies and what they can tell us about the nature of dark energy, the Cluster Lensing And Supernova Survey with *Hubble* (CLASH) program is designed to probe the distribution of dark matter with unequalled precision in 25 massive galaxy clusters. Such clusters are the largest gravitationally bound structures yet to form in the universe. Reflecting conditions in the cosmos at large, these clusters are evidently dominated by an enigmatic material called dark matter—some 85 percent or more by mass. Visible galaxies comprise only about 5 percent of the universe's mass; the remaining 10 percent consists of hot gas between the galaxies that can be detected by X-ray telescopes.

Although dark matter makes up the bulk of the universe's mass, it behaves neither like the "normal" atomic members of the periodic table of elements nor the subatomic particles that comprise them. In fact, it can only be detected by measuring how its gravity tugs on normal matter and warps the fabric of space-time. Such distortions are visible in and around massive galaxy clusters, because the combined mass of their visible galactic material and their invisible dark matter is sufficient to bend the path of light coming from behind the clusters. Like passing through an optical lens, the light from these remote galaxies is bent and amplified in mathematically predictable ways by the amount and placement of the intervening mass. This phenomenon is called *strong* gravitational lensing. The distribution of matter in the cluster (including its dark matter) can be inferred from the distorted shapes and uneven brightness of any background objects.

In a similar but not as evident process known as *weak* gravitational lensing, a small but systematic alignment of background sources around an intervening mass can be detected. This effect is identified by measuring small variations between the orientations and shapes of galaxies seen in and around a galaxy cluster as compared with carefully calculated statistical averages of these features. Careful analysis can distinguish the presence of a small shearing or converging effect in the shapes of these galaxies, the magnitude of which can then be used to derive the distribution of dark matter within the cluster.

This detail of the CLASH galaxy cluster MACS J1206.2-0847 shows the phenomenon called strong gravitational lensing. Newly revealed, very distant galaxies that reside behind the foreground cluster of galaxies appear as multiple, distorted arcs and smears (see examples marked by arrows).

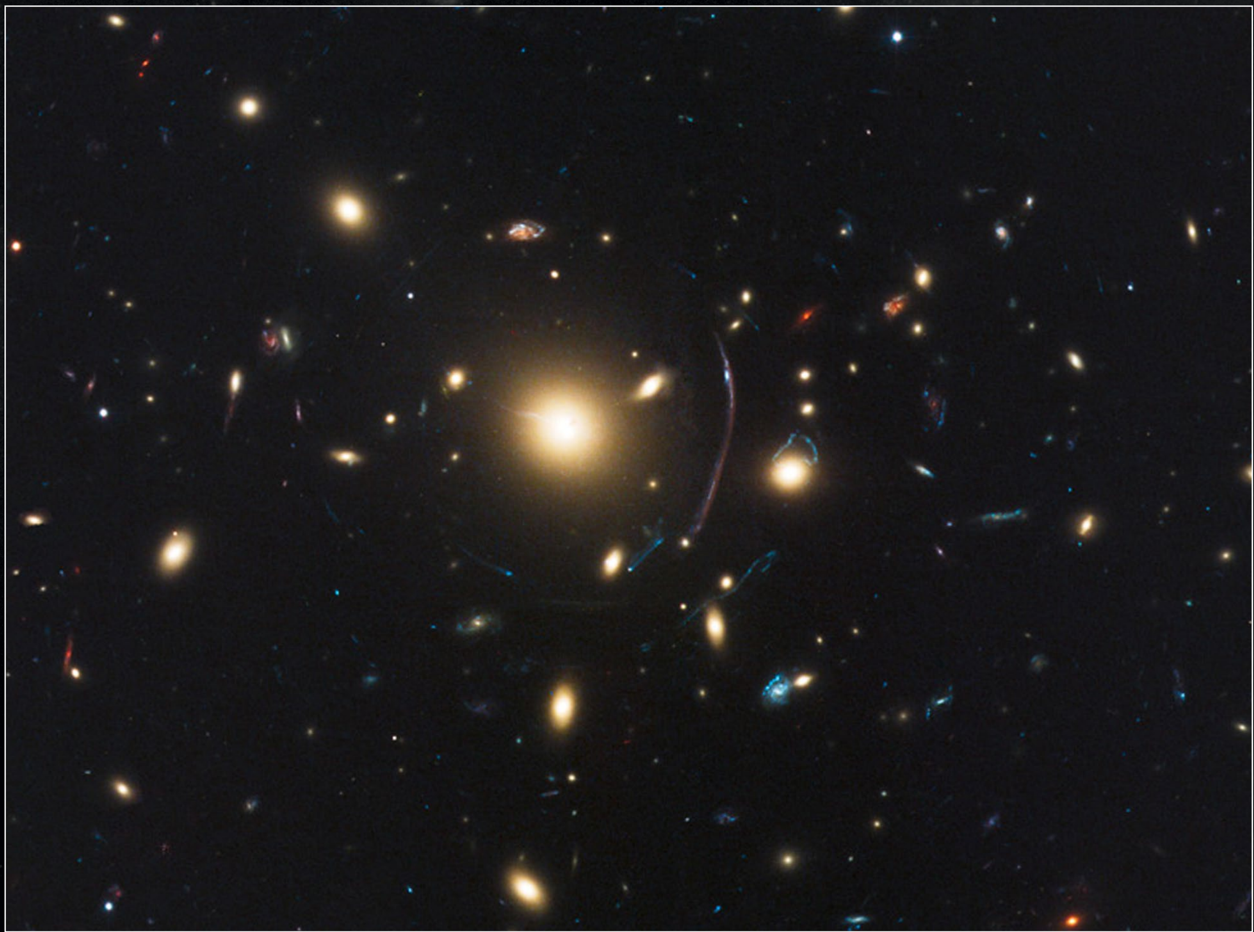
Maryland-based astronomer Marc Postman leads the CLASH team. The program was awarded 524 orbits of *Hubble* observing time (more than one-and-a-half months) for use during the three consecutive annual observing cycles beginning in October 2010. In observing and analyzing the data from their targeted 25 galaxy clusters, the CLASH team hopes to accomplish four main science goals:

- To map the distribution of dark matter in galaxy clusters with unprecedented accuracy using strong and weak gravitational lensing. Such dark-matter maps may reveal new clues about the formation of large structures in the universe.
- To detect Type Ia supernovas out to a distance of approximately 10.3 billion light years, allowing researchers to test the constancy of dark energy's repulsive force over history and look for any evolutionary effects in the supernovas themselves. (See sidebar on Type Ia supernovas on page 134.)

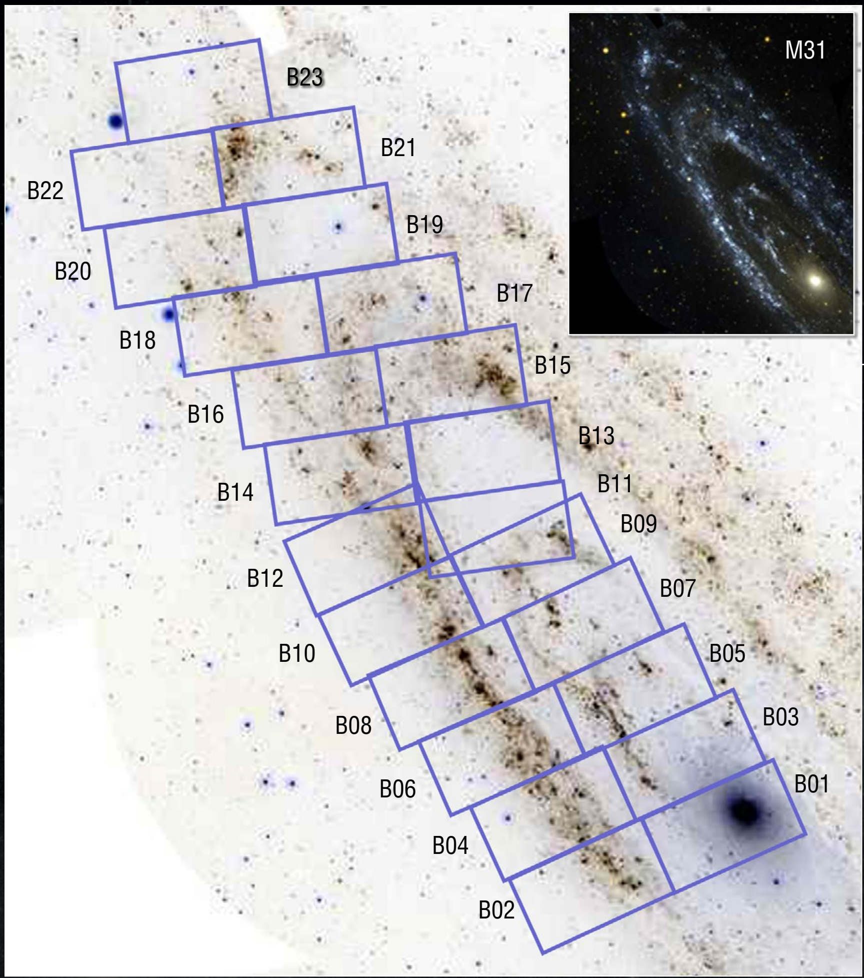
- To detect and characterize some of the most distant galaxies yet discovered using the magnifying power of gravitational lenses. This should reveal details about the universe from a time when it was less than 800 million years old.
- To study the internal structure and development of the galaxies in and behind these clusters.

The CLASH team would also like to refine the predictions of recently developed computer models that attempt to simulate the development of these large-scale structures. There is some evidence that these clusters may have more highly concentrated central cores than simulations have suggested. Using the CLASH observations, team members hope they can conclusively determine whether this is the case. If it is, this finding might suggest new constraints on the influence of dark energy during the early universe.

Galaxy cluster Abell 383, located in the constellation Eridanus (the River), is another target of the CLASH program. Scientists recently identified 27 lensed images in this Hubble *image, produced from nine different background sources.*



Two large elliptical galaxies dominate the center of galaxy cluster RX 31347-1145, but contribute only a relatively small amount of the cluster's mass. The bright blue, edge-on galaxy in the lower right portion of the image is not a member of the cluster, but a foreground galaxy.



The PHAT observations are grouped into 23 "bricks." Each brick consists of a mosaic of 18 Hubble *pointings in a six-by-three array. Odd-numbered bricks extend from the bulge (B01) area of the galaxy and out along its major axis. The even-numbered bricks form an adjacent strip that covers the blue star-forming ring of one of the galaxy's spiral arms. (Photo credit: NASA/JPL/California Institute of Technology)*

PHAT

Focusing on the nearby universe, the Panchromatic *Hubble* Andromeda Treasury (PHAT) program is an extensive, multi-wavelength study of the Andromeda galaxy (M31), which is the nearest large spiral galaxy to the Milky Way. Astronomers expect to map approximately one-third of M31's star-forming disk across a wide range of ultraviolet, optical, and near-infrared wavelengths. Such observations are sensitive to stars of many types and evolutionary phases: from hot, hydrogen-burning dwarfs; through luminous red giants; to extremely hot, helium-burning objects nearing the end of their lives.

The team expects to image more than 100 million stars and then catalog them by their identifiable characteristics such as luminosity and temperature. Using this data, the scientists plan to calibrate and refine existing computer models of stellar evolution and thereby improve their general understanding of stellar ages and aging processes.

M31 is the only other large spiral galaxy besides the Milky Way within the cluster of approximately 55 galaxies known as the *Local Group*. The galaxy's well-determined, relatively close distance of 2.5 million light-years not only permits *Hubble* to distinguish its individual stars, but also provides astronomers the advantage of knowing that all these stars are essentially at the same distance. Thus, stars in M31 that appear brighter are not brighter because they are closer; rather, they are intrinsically more luminous. Moreover, M31 offers a superb view of a star's galactic environment, making it easier to characterize groups of stars by age, composition, and kinematics within the broader context of star-forming gas clouds.

The PHAT program targets M31's northeast quadrant. This is the area of the galaxy that is least obscured by gas and dust, as well as the least "contaminated" by stars from M32, a dwarf elliptical galaxy that is a satellite of M31. During the course of the program, *Hubble* is to look at parts of M31's central region, galactic bulge, and outer disk.

To streamline data collection, the PHAT team groups the observations into *bricks*, each of which is itself a mosaic of 18 WFC3 fields-of-view: six long by three wide. At each of the 18 telescope pointings within a brick, WFC3 records the scene using its infrared (IR) and ultraviolet-visible (UVIS) channels, along with the visible-light detector of the Advanced Camera for Surveys (ACS). The total program comprises 23 bricks.

Interestingly, WFC3 and ACS do not share identical fields of view. (See page 26 for more information on how *Hubble*'s cameras share the telescope's focal plane.) To solve this problem, the team's scientists devised a clever mapping solution to improve the telescope's observational efficiency. Since the two instruments can operate simultaneously, they divided the bricks into two seasons. Each season is separated by approximately six months. The first season completes a half-brick with ACS in visible light and covers the adjacent half-brick with WFC3's IR plus UVIS channels. In the second season, the telescope rotates 180 degrees, such that the primary WFC3 observations cover the first season's ACS observations and vice versa.

The PHAT program was awarded 834 orbits to use over three years—about two-and-a-half months of observing time. The team, led by Dr. Julianne Dalcanton of Washington State, enumerated the following ten primary science goals for their study:

To determine star formation histories on relatively small scales. The star formation history is a measurement of when groups of stars formed and with what particular chemical compositions. Scientists derive this history by analyzing the distribution of stellar colors and luminosities, which vary with the age and composition of a stellar population. With millions of stars available, one can subdivide M31 into very small regions and then measure the star formation histories within each of them. These measurements allow researchers to track how star formation spreads through spiral arms, how it changes with distance from the galaxy's center, and how the star formation process interacts with the interstellar environment.

To improve stellar evolution models, calibrated at ultraviolet through near-infrared wavelengths. Models of stellar evolution allow astronomers to predict a star's color and luminosity throughout its lifetime. These models are essential for interpreting observations of all distant galaxies. Using the PHAT data, astronomers hope to improve these models for stars rich in "heavy" elements (heavier than hydrogen and helium), and for observations at ultraviolet and near-infrared wavelengths.

To characterize variations in the stellar mass function from approximately 3 to 30 solar masses. Stars formed together within a large cloud of interstellar gas do not possess the same mass, but their masses range according to a distribution known as the *initial mass function*. While it is widely assumed that this distribution is the same for stars formed everywhere, there is both observational evidence and theoretical analysis suggesting that the initial mass function may vary depending on the chemical composition of the star-forming cloud and the rate at which stars condense. A goal of the PHAT program is to detect young stars with masses comparable to or larger than the Sun's, while also revealing thousands of young star clusters across the regions of M31's bulge and disk. Stellar mass estimates derived from the program's multi-color imaging should therefore better define the initial mass function for stars over a wide range of galactic environments.

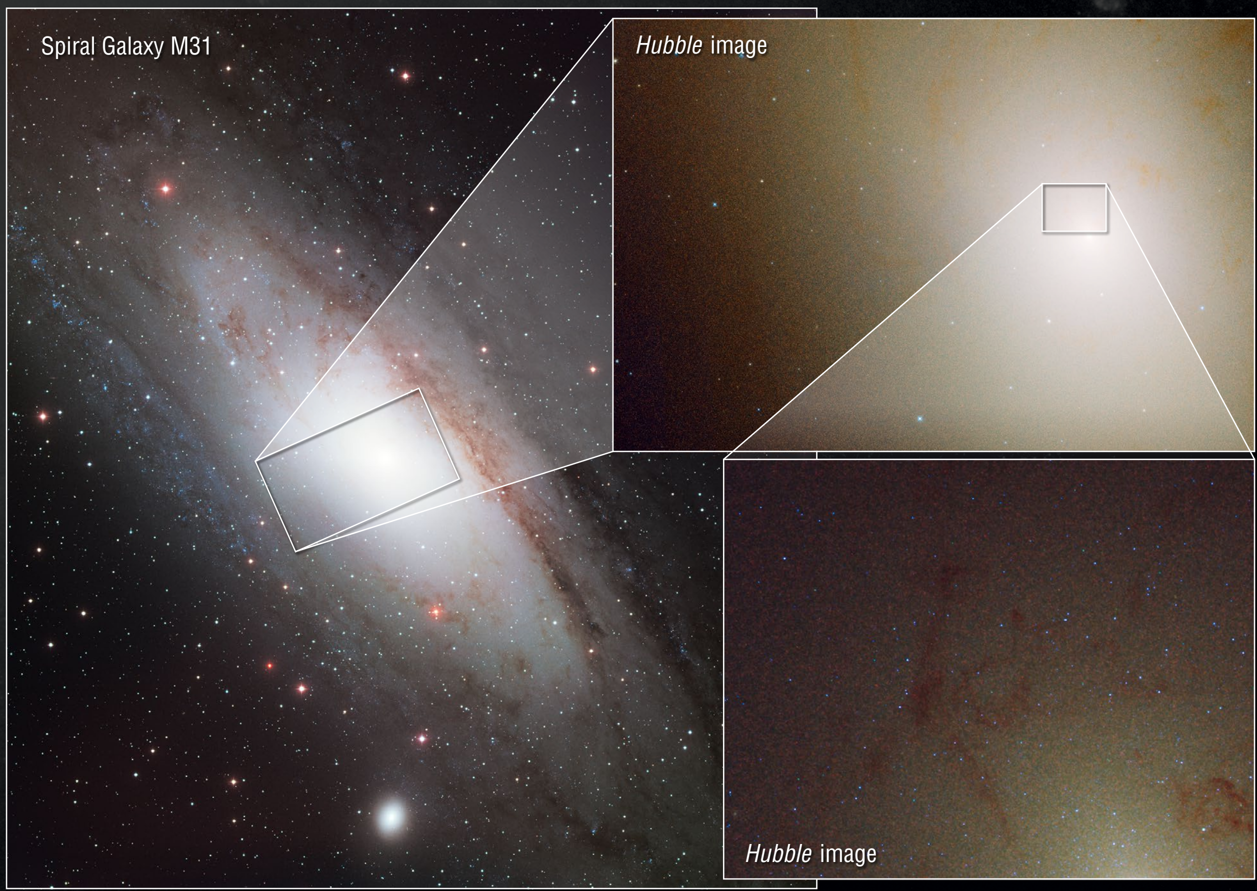
To develop and study well-defined catalogs of stellar clusters at all ages. Star clusters contain many stars that were born under the same conditions, have approximately the same ages, have similar chemical compositions, and lie at the same distance. In the PHAT program, astronomers hope to uncover many more star clusters than are known to exist in M31 and plan to study these clusters over a wide range of wavelengths. Clusters are excellent tracers for determining the age distribution of stars within the disk and halo of M31, and thus, help to reveal how the galaxy was shaped over time.

To create maps of interstellar dust, and characterize the effect of this dust on the light from stars. Interstellar dust exists everywhere in galaxies and can block the light from stars, making them appear redder and dimmer. Astronomers seek to understand how the dust forms, how much dust resides in different environments, and how the dust impacts the measurements made along different lines of sight. By using data from NASA's *Spitzer Space Telescope* and other facilities that have previously provided infrared imaging of the Andromeda galaxy, researchers hope to determine where the large dust features lie and study them in detail with *Hubble*.

To calibrate star formation indicators. Many different methods exist for measuring star formation in distant galaxies. However, all rely on correctly interpreting the integrated light from billions of stars to infer the rate of star formation. In M31, astronomers can actually separate out tens of millions of individual stars, and determine a detailed history of star formation for many smaller regions within the galaxy. By comparing these rates with those that would be inferred from the integrated light of those same regions, astronomers can produce far more accurate calibrations for converting integrated light into star-formation rates in distant galaxies.

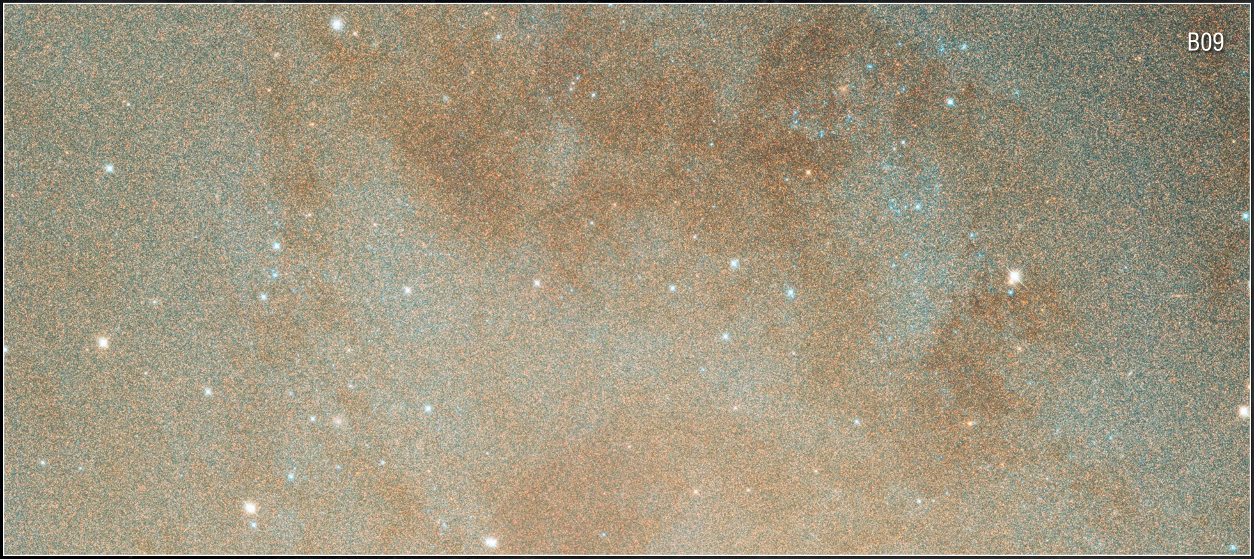
To place quantitative constraints on the coupling between star formation and the interstellar medium. The PHAT program is a wide-field survey that enables researchers to look for correlations and trends between how star formation has shaped and impacted the interstellar medium, that is, the material between stars. Instead of just studying a specific line

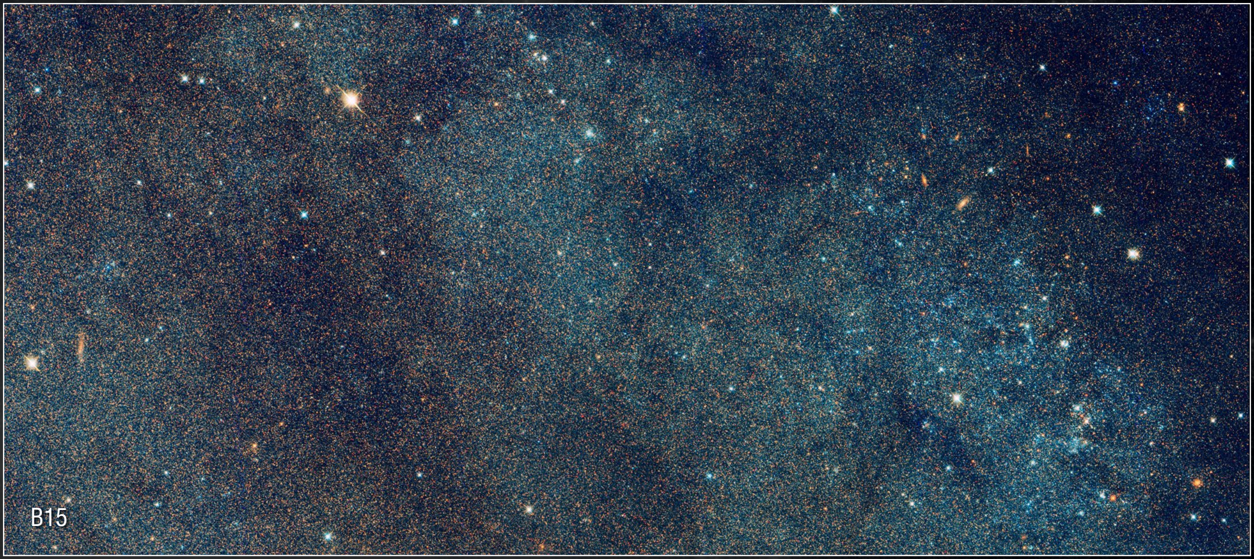
As part of the ongoing PHAT Multi-Cycle Treasury Program, Hubble *has recently examined the hub region of galaxy M31 to uncover a large, rare population of roughly 8,000 hot, bright stars. The image at left shows a ground-based view. The rectangular box marks the region studied by* Hubble. *At the top right is a view that is 7,900 light-years across and reveals the galaxy's crowded central region. The bright area near the center of this image is a grouping of stars nestled around the galaxy's black hole. The blue dots sprinkled throughout the image are ultra-blue stars whose population increases around the crowded hub. The blue stars are old Sun-like stars that have prematurely cast off their outer layers of material, exposing their extremely blue-hot cores. In the most detailed image, shown at bottom right, the blue stars are seen to reside in and around dark dust clouds. This image is 740 light-years wide. (Photo credit: [lower left] Wisconsin-Indiana Yale NOAO/Kitt Peak National Observatory mosaic)*



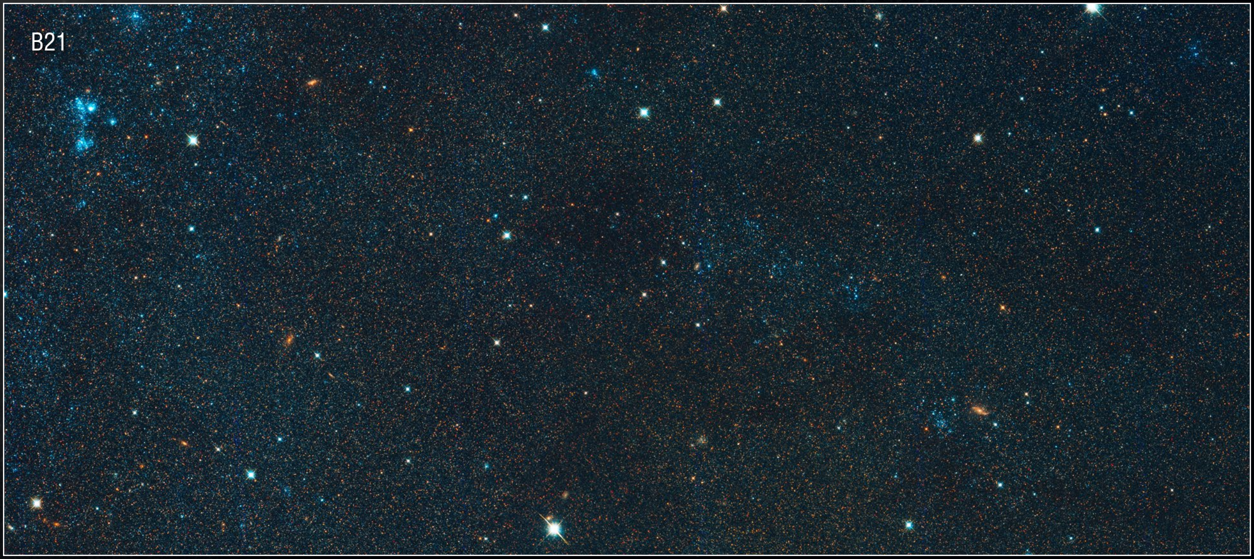
Detailed views of four image "bricks" from the PHAT program are shown on this and the next page. Their relative positions within the Andromeda galaxy can be found on the observational image map on page 94.

of sight and measuring some star formation, the program's astronomers are planning to study a large percentage of the disk of M31. This allows them to quantify the process of star formation and stellar evolution through different lines of sight, mapping how certain environments share similar characteristics because of the types and epochs of star formation that have occurred in those environments.





To identify and characterize M31's variable stars. Variable stars are very interesting objects in astronomy because their variability is often linked with some other fundamental property, such as their intrinsic luminosity or their composition. While the PHAT survey does not look at a given part of M31 many times, researchers employ existing catalogs of known variable stars in the galaxy and then use the PHAT data to refine the properties of those stars. The PHAT survey is likely to discover variable stars that change on short time scales and, more importantly, it should provide much more context on the properties of the variable stars previously detected by other projects.



To measure the velocities of stars in different structural components of M31. The Andromeda galaxy features different structural components, each with associated stars: a bulge, many diverse clusters, spiral arms in a disk, and a halo. The stars of these components are intertwined with one another along a give line of sight. Currently, researchers can only differentiate them to a limited degree. However, using spectra gathered by *Hubble*, astronomers can measure the velocities of the stars that are moving in each of these various components. Stars in different regions should have varying velocity signatures, and these can be used to discern which stars belong in each component's population.

To cross-identify multi-wavelength sources and emission line objects. Hot gases in a galaxy emit light at certain specific wavelengths. These appear as bright *emission lines* when viewed with a spectroscope. The PHAT program's multi-wavelength observations should record a number of these emission lines and permit correlation of the emitting sources with objects cataloged in previous studies of M31.

Summary

The *Hubble* project is committing a significant percentage of the telescope's observing time over three annual observing cycles to collect extensive new datasets. Three unusually large and complex multi-cycle programs—CANDELS, CLASH, and PHAT—have begun to populate *Hubble*'s data archive with a treasure trove of excellent-quality observations that can serve the astronomical community for many years to come.

In the nearer term, however, researchers on these programs may be able to confirm or refute any number of currently held astronomical theories in areas ranging from star formation to cosmic structures and cosmology.

Dr. Sandra Moore Faber is a university professor of astronomy and astrophysics at the University of California, Santa Cruz, and works at the Lick Observatory. Born in Boston, Massachusetts, she obtained a bachelor's degree with high honors in physics from Swarthmore College and received her doctorate in astronomy from Harvard. Dr. Faber currently serves as co-principal investigator for the CANDELS program on *Hubble*. Her research focuses on the evolution of structure in the universe and the evolution and formation of galaxies. She is one of the authors of the cold dark matter theory for galaxy formation and led the team that found ubiquitous black holes at the centers of galaxies with *Hubble*. Dr. Faber is the recipient of many honors, including election to the National Academy of Sciences and the 2009 Bower Award and Prize for Achievement in Science from the Franklin Institute.

Dr. Henry C. Ferguson is an astronomer at the Space Telescope Science in Baltimore, Maryland. His research interests center on galaxy evolution and cosmology. He is co-principal investigator of *Hubble*'s CANDELS survey; leads the Institute team preparing to support instrument operations on the *James Webb Space Telescope*; and is also the head of the Galaxies Collaboration for the Large Synoptic Survey Telescope, a wide-field optical survey telescope to be built in Chile. Born in Schenectady, New York, Dr. Ferguson obtained his undergraduate degree from Harvard University in 1981 and his doctorate from the Johns Hopkins University in 1990. After a postdoctoral fellowship at the University of Cambridge in the United Kingdom, he was awarded a Hubble Fellowship at the Institute and joined the scientific staff in 1995. Dr. Ferguson is a fellow of the American Association for the Advancement of Science.

Dr. Marc Postman is an astronomer at the Space Telescope Science Institute. His primary research interests include making observational constraints on and discoveries about the formation and evolution of clusters of galaxies, large-scale structures in the cosmos, dark matter, and cosmology. He also works on the design and implementation of wide-field sky surveys and future mission concepts for large space telescopes. Dr. Postman is the principal investigator on CLASH. Born in New York City, he received his undergraduate degree in physics from the Massachusetts Institute of Technology and a doctorate in astronomy from Harvard University. After graduating, he spent three years as a postdoctoral fellow at Princeton University. He joined the Institute in 1989 where he presently serves as head of the Community Missions Office.

Dr. Julianne Dalcanton is a professor of astronomy at the University of Washington. The primary focus of her work is the origin and evolution of galaxies, their stellar content, and their use as probes of fundamental physics. Born in Pittsburgh, Pennsylvania, Dr. Dalcanton received her bachelor's degree in physics at the Massachusetts Institute of Technology and her doctorate in astrophysical sciences at Princeton University. A researcher for the Sloan Digital Sky Survey, in 1999 she found the survey's first new comet, which was officially named Comet Dalcanton in her honor. She currently leads two large observing programs on *Hubble*: the ACS Nearby Galaxy Survey Treasury (ANGST) and the PHAT program. She is actively engaged in science outreach through writing, teaching, and public speaking and is a contributor to the physics blog Cosmic Variance for *Discover Magazine*. (Photo credit: Kathy Sauber, University of Washington)