CHAPTER – III

RADIO ASTRONOMY: AN OVERVIEW

3.1 Introduction

Astronomy is one of the oldest of all sciences. Prehistoric cultures left behind astronomical artifacts such as the Egyptian monuments and Stonehenge, and early civilizations such as the Babylonians, Greeks, Chinese, Indians, and Maya performed methodical observations of the night sky. However, the invention of the telescope was required before astronomy was able to develop into a modern science. Historically, astronomy has included disciplines as diverse as astrometry, celestial navigation, observational astronomy, the making of calendars, and even astrology, but professional astronomy is nowadays often considered to be synonymous with astrophysics (Astronomy, n.d.).

During the 20th century, the field of professional astronomy split into observational and theoretical branches. Observational astronomy is focused on acquiring data from observations of celestial objects, which is then analyzed using basic principles of physics. Theoretical astronomy is oriented towards the development of computer or analytical models to describe astronomical objects and phenomena. The two fields complement each other, with theoretical astronomy seeking to explain the observational results, and observations being used to confirm theoretical results (Unsöld and Baschek, 2001; Astronomy, n.d.).

From Vedic literature, it can be seen that the ancient Indians were primarily interested in astronomy for its predictive features, its ability to allow them to forecast, in particular, the rainy season, which was of prime importance to all agricultural communities. Astronomy is the study of celestial objects, phenomena, and origins. Astronomy is not only the oldest of all sciences, but it can also be called the mother of all sciences. Astrophysics, a related field, studies the behavior of astronomical phenomena and related physico-chemical interactions in outer space. It includes the study of cosmology, plasma, kinetics, stellar physics, convolution and non-equilibrium, radiation transfer theory, non-Euclidian geometry, mathematical modeling, galactic structure theory and relativistic astronomy. (Harris, n.d.)

Astronomy in India was well developed in ancient times culminating in the writing of Surya Siddhanta in the fifth century. Astronomy is one of the sciences which have had much stimulus to its advancement by virtue of the contributions made by early Indian thinking. The efforts of Arybhatta, Varahamihira, Brahmagupta and Bhaskara are monumental and have been. Keeping up to this tradition, India has presently quite a large number of active astronomers and astrophysicists whose interests put together cover the entire span of the electromagnetic spectrum. But the growth of astronomy and science in general was hindered by the political vicissitudes in the medieval period. The main occupation of Indian astronomers for the next thousand years was the precise calculation of the planetary orbits and developing algorithms for the solution of the mathematical equations that arose in the process (Harris, n.d.).

3.2 Definition

The word astronomy (from the Greek words astron (ἄστρον), "star" and -nomy from nomos (νόμος), "law" or "culture") literally means "law of the stars" (or "culture of the stars" depending on the translation).

Use of terms "Astronomy" and "Astrophysics"

Generally, either the term "astronomy" or "astrophysics" may be used to refer to this subject. (Scharringhausen) (Odenwald) Based on strict dictionary definitions, "astronomy" refers to "the study of objects and matter outside the Earth's atmosphere and of their physical and chemical properties" (Merriam-Webster) and "astrophysics" refers to the branch of astronomy dealing with "the behavior, physical properties, and dynamic processes of celestial objects and phenomena". (Merriam-Webster) In some cases, as in the introduction of the introductory textbook The Physical Universe by Frank Shu, "astronomy" may be used to describe the qualitative study of the subject, whereas "astrophysics" is used to describe the physics-oriented version of the subject. However, since most modern astronomical research deals with subjects related to physics, modern astronomy could actually be called astrophysics. Various departments that research this subject may use "astronomy" and "astrophysics", partly depending on whether the department is historically affiliated with a physics department, and many professional astronomers actually have physics degrees. (Odenwald) One of the leading scientific journals in the field is named Astronomy and Astrophysics.

Radio Astronomy is the branch of astronomy that utilizes extraterrestrial radiation in radio wavelengths rather than visible light for the study of the universe.

The study of celestial objects by measurement of the radio waves they emit. Radio astronomy has enabled the detection and study of objects such as pulsars, quasars, radio galaxies, and other objects, some of which emit considerably less radiation at other wavelengths. Radio astronomy has contributed to the discovery of cosmic background radiation and has enhanced the understanding of solar activity and the structure of galaxies (Radio astronomy, n.d.).

3.3 Historical Developments of Radio Astronomy

Before Jansky observed the Milky Way in the 1930s, physicists speculated that radio waves could be observed from astronomical sources. In the 1860s, James Clerk Maxwell's equations had shown that electromagnetic radiation is associated with electricity and magnetism, and could exist at any wavelength. Several attempts were made to detect radio emission from the Sun by experimenters such as Nikola Teslaand Oliver Lodge, but those attempts were unable to detect any emission due to technical limitations of their instruments. The early history of radio astronomy begins in 1894, with Sir Oliver Lodge. Lodge attempted detection of radiation from the sun at centimeter wavelengths. Unfortunately over the next forty years, further attempts also failed due to inadequate detection techniques (Ghigo, 2003; Gale, 2005).

The initial detection of radio waves from an astronomical object was made in the 1930s, when Karl Jansky observed radiation coming from the Milky Way. Subsequent observations have identified a number of different sources of radio emission. These include stars and galaxies, as well as entirely new classes of objects, such as radio galaxies, quasars, pulsars, andmasers. The discovery of the cosmic microwave background radiation, regarded as evidence for the Big Bang theory, was made through radio astronomy (Gale, 2005).

Radio astronomy is conducted using large radio antennas referred to as radio telescopes, that are either used singularly, or with multiple linked telescopes utilizing the techniques of radio interferometry and aperture synthesis. The use of interferometry allows radio astronomy to achieve high angular resolution, as the resolving power of an interferometer is set by the distance between its components, rather than the size of its components.

Karl Jansky made the discovery of the first astronomical radio source serendipitously in the early 1930s. As an engineer with Bell Telephone Laboratories, he was investigating static that interfered with short wave transatlantic voice transmissions. Jansky detected three separate groups of static; local thunderstorms, distant thunderstorms and a steady hiss-type static of unknown origin. The unknown source that Jansky found is the center of the Milky Way as he was able to show by determining its position on the sky (Gale, 2005)..

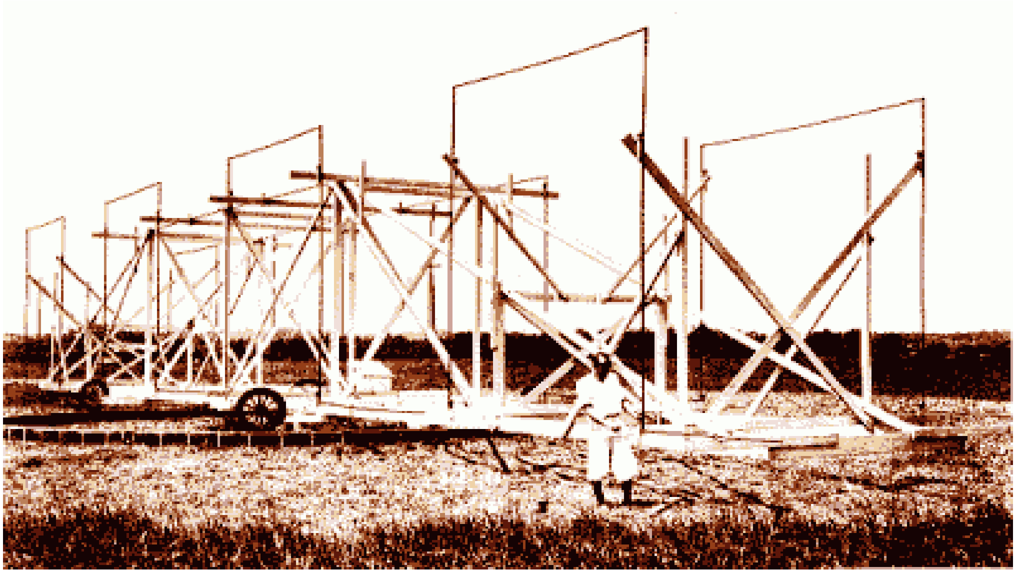

Image 1: Jansky standing with his antenna

Using a largedirectional antenna, Jansky noticed that his analog pen-and-paper recording system kept recording a repeating signal of unknown origin. Since the signal peaked about every 24 hours, Jansky originally suspected the source of the interference was the Sun crossing the view of his directional antenna. Continued analysis showed that the source was not following the 24-hour daily cycle of the Sun exactly, but instead repeating on a cycle of 23 hours and 56 minutes. Jansky discussed the puzzling phenomena with his friend, astrophysicist and teacher Albert Melvin Skellett, who pointed out that the time between the signal peaks was the exact length of a sidereal day, the timing found if the source was astronomical, "fixed" in relationship to the stars and passing in front of the antenna once every Earth rotation. (Gale, 2005). By comparing his observations with optical astronomical maps, Jansky eventually concluded that the radiation source peaked when his antenna was aimed at the densest part of the Milky Way in the constellation of Sagittarius. (Jansky, 1933) He concluded that since the Sun and other stars were not large emitters of radio noise, the strange radio interference may be generated by interstellar gas and dust in the galaxy. (Jansky's peak radio source, one of the brightest in the sky, was designated Sagittarius A in the 1950s and, instead of being galactic "gas and dust", has since been found to be emitted by electrons in a strong magnetic field from the complex of objects found in that area) (Gale, 2005; Kambič, 2010).

Jansky announced his discovery in 1933. He wanted to investigate the radio waves from the Milky Way in further detail, but Bell Labs reassigned him to another project, so he did no further work in the field of astronomy. His pioneering efforts in the field of radio astronomy have been recognized by the naming of the fundamental unit of flux density, thejansky (Jy), after him. The Jansky is equivalent to 10^(-26) watts per m^2 per Hz.

Jansky was the first to detect radio emission from the Galaxy. The image 1 shows Jansky standing with his antenna (Photo courtesy of Bell Laboratories). This rotatable antenna looks similar to a merry-go-round; the rotation allowed it to move along with the static. The work done by Jansky included receiving frequencies in the range of 15 to 30 MHz (approximately 15-m wavelengths). Jansky published three reports on his findings, which were largely ignored for many years to come.

Image 2: Grote Reber with his telescope, the prototype for modern radio telescopes

In 1937 Grote Reber, also a radio engineer, read about Jansky's work. Reber built a parabolic, 9.5-m diameter, reflector dish in his backyard. This was the first radio telescope used for astronomical research. Reber spent years studying cosmic radio waves at various wavelengths, while other astronomers still didn't get involved. He finally detected celestial radio emission at approximately 2-m. The image below shows Reber with his telescope, the prototype for modern radio telescopes (courtesy of NRAO). Reber continued his investigations of radio sources and confirmed that radio emission arose from the Galactic plane. Reber, in 1944, published the first radio frequency sky maps. Reber's telescope is displayed at the National Radio Astronomy Observatory (NRAO) in Green Bank West Virginia (Ghigo, 2004).

The first observation of radio emission from the sun was made in 1942, by J.S. Hey. Hey was working with the British Army Operational Research Group analyzing all occurrences of jamming of Army radar sets. A system for observing and recording jamming was organized. This eventually led Hey to conclude that the sun was radiating intense radio emission. Later that same year, G.C. Southworth made the first successful observations of thermal radio emission from the sun; he did this at centimeter wavelengths. The next important discovery regarding radio waves from beyond the solar system were discrete sources of emission. In 1946, J.S. Hey, S.J. Parsons, and J.W. Phillips observed fluctuations in the intensity of cosmic radio waves from the constellation Cygnus. In the next ten years thousands of discrete sources were identified, including galaxies and supernovae (Hey, 1973).

Most gases in galaxies are invisible to optical telescopes but can be seen by radio telescopes. Fast moving electrons, neutral atoms and molecules generously emit at radio wavelengths. In 1951, H. I. Ewen and E. M. Purcell, detected the spectral line emission from neutral Hydrogen that fell into the radio spectrum. For the first time, astronomers could determine the shape of our own home galaxy.

In 1963 Bell Laboratories assigned Arno Penzias and Robert Wilson the task of tracing the radio noise that was interfering with the development of communication satellites. Penzias and Wilson discovered that no matter where the antenna was pointed there was always non-zero noise strength, even where the sky was visibly empty. A simple solution would have been to reset their receivers to zero, but they persisted in tracing the source. This major discovery made by Penzias and Wilson was the cosmic background radiation and the strongest evidence for the big bang. Penzias and Wilson won the Nobel Prize in physics for their discovery in 1978. The image shows Penzias and Wilson with their 6m horn antenna (Photo courtesy of Lucent Technologies, Bell Labs Innovation). The horn shape was used because the field of view remains unobstructed allowing for a precise measurement of the effective collecting area of the antenna (Smith, 2013).

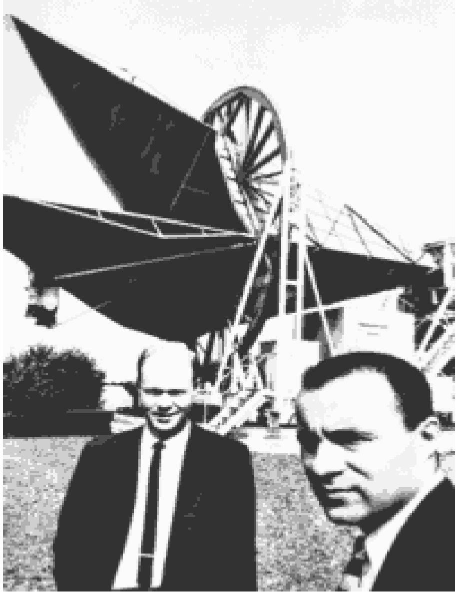

Image 3: Penzias and Wilson with their 6m horn antenna

In the late 1960's, radio pulsars, predicted only by theories of stellar evolution, were discovered by Jocelyn Bell-Burnell and Anthony Hewish. Bell-Burnell and Hewish were working at what is now called the Nuffield Radio Astronomy Observatory at Cambridge, England. Pulsars are very strongly magnetized, spinning neutron stars. Neutron stars are so dense that one teaspoon of this star would weigh as much as all the cars and trucks in the U.S. put together. Anthony Hewish and Martin Ryle won the Nobel Prize for this discovery in 1974 (Smith, 2013).

At Cambridge University, where ionospheric research had taken place during World War II, J.A. Ratcliffe along with other members of the Telecommunications Research Establishment that had carried out wartime research into radar, created a radiophysics group at the university where radio wave emissions from the Sun were observed and studied. This early research soon branched out into the observation of other celestial radio sources and interferometry techniques were pioneered to isolate the angular source of the detected emissions. Martin Ryle and Antony Hewish at the Cavendish Astrophysics Group developed the technique of Earth-rotation aperture synthesis. The radio astronomy group in Cambridge went on to found the Mullard Radio Astronomy Observatory near Cambridge in the 1950s. During the late 1960s and early 1970s, as computers (such as theTitan) became capable of handling the computationally intensive Fourier transform inversions required, they used aperture synthesis to create a 'One-Mile' and later a '5 km' effective aperture using the One-Mile and Ryle telescopes, respectively. They used the Cambridge Interferometer to map the radio sky, producing the famous 2C and 3C surveys of radio sources (Smith, 2013).

3.4 Radio Astronomy Research in India

Ancient Indian astrology is based upon sidereal calculation. The sidereal astronomy is based upon the stars and the sidereal period is the time that it takes the object to make one full orbit around the Sun, relative to the stars. It can be traced to the final centuries BC with the Vedanga Jyotisha attributed to Lagadha, one of the circum-Vedic texts, which describes rules for tracking the motions of the Sun and the Moon for the purposes of ritual. After formation of Indo-Greek kingdoms, Indian astronomy was influenced by Hellenistic astronomy (adopting the zodiacal signs or *rāśis*). Identical numerical computations for lunar cycles have been found to be used in India and in early Babylonian texts. (Neugebauer, 1952).

Aryabhata (476–550), in his magnum opus *Aryabhatiya* (499), propounded a computational system based on a planetary model in which the Earth was taken to be spinning on its axis and the periods of the planets were given with respect to the Sun. He accurately calculated many astronomical constants, such as the periods of the planets, times of the solar and lunar eclipses, and the instantaneous motion of the Moon. Early followers of Aryabhata's model included Varahamihira, Brahmagupta, and Bhaskara II. Astronomy was advanced during the Sunga Empire and many star catalogues were produced during this time. The Sunga period is known as the "Golden age of astronomy in India". Brahmagupta (598-668) was the head of the astronomical observatory at Ujjain and during his tenure there wrote a text on astronomy, the *Brahmasphutasiddhanta* in 628. He was the earliest to use algebra to solve astronomical problems. He also developed methods for calculations of the motions and places of various planets, their rising and setting, conjunctions, and the calculation of eclipses (Thurston, 1996; Joseph, 2000).

Bhāskara II (1114–1185) was the head of the astronomical observatory at Ujjain, continuing the mathematical tradition of Brahmagupta. He wrote the *Siddhantasiromani* which consists of two parts: *Goladhyaya* (sphere) and *Grahaganita* (mathematics of the planets). He also calculated the time taken for the Earth to orbit the sun to 9 decimal places. The Buddhist University of Nalanda at the time offered formal courses in astronomical studies.

Other important astronomers from India include Madhava of Sangamagrama, Nilakantha Somayaji and Jyeshtadeva, who were members of the Kerala school of astronomy and mathematics from the 14th century to the 16th century. Nilakantha Somayaji, in his *Aryabhatiyabhasya*, a commentary on Aryabhata's *Aryabhatiya*, developed his own computational system for a partially heliocentric planetary model, in which Mercury, Venus, Mars, Jupiter and Saturn orbit the Sun, which in turn orbits the Earth, similar to the Tychonic system later proposed by Tycho Brahe in the late 16th century. Nilakantha's system, however, was mathematically more efficient than the Tychonic system, due to correctly taking into account the equation of the centre and latitudinal motion of Mercury and Venus. Most astronomers of the Kerala school of astronomy and mathematics who followed him accepted his planetary model (Ramasubramanian et al., 1994; Joseph, 2000).

The IIA, which currently functions under India's Department of Science and Technology (DST), was founded in 1786 when William Petrie, an enlightened official of the East India Company, set up a small private observatory in his garden house in Madras (now Chennai). Significantly, this observatory provided a reference meridian for the survey of the treacherous Coromandal coast (Rao and Trotta, 2002).

In 1790, it was taken over by the East India Company and improved upon and augmented. Two years later, it was shifted to a newly built observatory building at Nugambakkam, a suburb of Madras, where it became the first modern public observatory outside Europe.

3.4.1 Radio Astronomy before Twentieth Century

In 1830 the observatory managed to acquire a 5-foot focus transit instrument and a 4-foot diameter mural circle. Using these instruments, Thomas Glanville Taylor prepared his celebrated Madras Catalogue, which listed the positions of 11,015 stars.

The year 1850 was a major watershed in the history of observatory, as it obtained its first fixed telescope, a 6-inch aperture equatorial telescope supplied by Lerebours and Secretan of Paris. Fourteen years later, the observatory acquired an 8-inch aperture equatorial telescope from London.

Both these telescopes helped Norman Robert Pogson discover five minor planets and six variable stars. Pogson's assistant Chintamani Ragoonathachary discovered a variable star R.Reticuli in 1867, the first recorded astronomical discovery by an Indian in modern times.

Significantly, the Madras Observatory monitored and studied the 1868 and 1871 total solar eclipses, as well as annular eclipse of June 6, 1872. In 1899, a solar physics observatory was set up at Kodaikanal with the view to study the sun and predict the behavior of the monsoons (Rao and Trotta, 2002).

3.4.2 Radio Astronomy in Twentieth Century

Solar photography and spectroscopy continued to be the mainstay of Kodiakanal Observatory with an occasional comet or nova breaking the monotony. In 1958, as part of the International Geophysical Year celebrations, the observatory acquired a 15-inch aperture solar tunnel telescope for the fine spectroscopic work.

In 1960, the renowned Indian astrophysicist Dr. Vainu Bappu took over as the Director of Kodaikanal Observatory. Incidentally, Bappu was instrumental in developing Kavalur as a major astrophysical research facility in India. The Kavalaur observatory (now known as Vainu Bappu Observatory) boasts a 1-meter Zeiss telescope as well as fully Indian-made 38-inch and 2.3-meter aperture telescopes.

The 2.3-meter telescope (also named for Bappu) has made significant contributions to the study of galactic dynamics and stellar physics.

In 1971, the Kodaikanal Observatory was renamed the Indian Institute of Astrophysics (IIA) and 1976 was shifted to Bangalore. Today its astronomical and astrophysical research is focused on studies of the sun and solar system objects as well as distant galaxies and quasars.

While studies of solar activities include sunspots, plages, prominences and solar chromosphere, solar system object study focuses on comets, planetary atmospheres and asteroid orbits.

In the area of stellar physics, IIA's research has made a significant contribution to the study of birth sites of stars, their early, late and post-AGB phases and stellar atmospheres.

IIA also has a long tradition of research in star clusters in out galaxy as well as nova and supernova explosions. Research in the extra-galactic astronomy covers nearby galaxies to the distant quasars. Similarly, IIA has been active in pursuing research into the phenomenon of gamma-ray bursts in collaboration with several national and international observatories.

Magneto hydrodynamic studies of the sun, radioactive process in the astrophysical objects, structure of the neutron stars, black hole physics, the structure and dynamics of galaxies and star clusters, origin of ultra high energy cosmic rays and dark matter physics form a part of the theoretical astrophysics research at IIA.

In addition to research facilities at its Bangalore headquarters, IIA derives support from its units at Kodaikanal, Kavalur, Gauribidanur, Hoskote and Hanle. A decameter radio telescope located at Gauribidanur built by IIA in association with the Raman Research Institute and commissioned in 1976 is used extensively for solar studies, including the detection of radio emissions from objects ranging from hot solar coronas to tiny pulsars. A laboratory for experiments in gravitational physics is also situated at Gauribidanur.

Incidentally, the IIA and Raman Research Institute have helped the University of Mauritius to build a T-shaped meter wave radio telescope at Bras D'eau in northeast Mauritius. It is being used extensively to map radio emissions from regions around the center and southern parts of our galaxy. (Rao and Trotta, 2002)

At Hoskote, near Bangalore, one finds the facility for the remote operations of 2-meter optical infrared telescope at Hanle in the high altitude Himalayan region. This remote control facility works through India's INSAT domestic communications spacecraft.

In addition to its unique situation 14,763 feet (4,500 meters) high in the western Himalayas, low sky brightness, low atmospheric absorption and low atmospheric turbulence makes the Indian Astronomical Observatory (IAO) at Hanle unique in the world. The 2-meter optical telescope of IAO enables the continuous studies covering half the globe, from the Canary Islands (20 degrees west longitude) to Eastern Australia at (157 degrees east Longitude).

Image 4: Hanle Observatory, one of the world's highest sites for optical, infrared and gamma-ray telescopes.

The Hanle telescope was designed by IIA scientists in association with EOS Technologies of Tucson, Arizona. The telescope has Ritchey Chretien optics and an altazimuth mount. The mirror of the telescope is made of special low expansion ceramic which can withstand extremes of the climatic conditions.

This telescope is expected to provide high-quality data that would lead researchers to study in greater depth diverse problems relating to various aspects of stars and stellar systems. They include star forming regions in remote galaxies, supernovae, high redshift radio galaxies, gamma ray burst sources, large scale structure of the universe and cosmology.

On another front, the IIA and McDonnell Center for Space Sciences of Washington University have set up an Antipodal Transient Observatory with two telescopes of 0.5-m aperture each, one at Hanle and the other at Arizona, nearly 180 degrees apart in longitude to monitor active galactic nuclei.

Swarup (2006) recapitulate his initiation into the field of radio astronomy during 1953-1955 at CSIRO, Australia; the transfer of thirty-two parabolic dishes of six-feet (1.8-m) diameter from Potts Hill, Sydney, to India in 1958; and their erection at Kalyan, near Bombay (Mumbai), in 1963-1965. The Kalyan Radio Telescope was the first modern radio telescope built in India. This led to the establishment of a very active radio astronomy group at the Tata Institute of Fundamental Researhc, which subsequently built two world-class radio telescopes during the last forty years and also contributed to the development of an indigenous microwave antenna industry in India.

The Ooty Radio Telescope, built during 1965-1970, has an ingenious design which takes advantage of India’s location near the Earth's Equator. The long axis of this 530 m × 30 m parabolic cylinder was made parallel to the Equator, by placing it on a hill with the same slope as the geographic latitude (11 degrees), thus allowing it to track celestial sources continuously for 9.5 hours every day. By utilizing lunar occultations, the telescope was able to measure the angular sizes of a large number of faint radio galaxies and quasars with arc-second resolution for the first time. Subsequently, during the 1990s, the group set up the Giant Metrewave Radio Telescope (GMRT) near Pune in western India, in order to investigate certain astrophysical phenomena which are best studied at decimetre and metre wavelengths. The GMRT is an array of thirty fully-steerable parabolic dishes of 45 m diameter, which operates at several frequencies below 1.43 GHz. These efforts have also contributed to the recent international proposal to construct the Square Kilometre Array (SKA).

Astronomical observations at radio wavelengths play a key role in the discovery and study of certain classes of astronomical objects and radio observations play a complementary roles in the study of nearly all objects in the Universe. Examples of the discovery role include pulsars, the cosmic background radiation, and complex molecules in space. More generally, radiowavelength observations provide insights into the very low temperature Universe (temperatures below 20 K), the highly obscured Universe (where dustobscures optical and even infrared wavelength emission) and the very high energy Universe of strong magnetic fields and relativistic particles associated with flares, neutron stars, and black holes.

3.4.3 Research at NCRA-TIFR

The National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research (NCRA-TIFR) is the premier institute for radio astronomy in India, and one of the best in this field in the world. Research activities at NCRA-TIFR are centered on low frequency radio astronomy, with faculty members carrying out research in a wide range of areas, including solar physics, pulsars, active galactic nuclei, the interstellar medium, supernova remnants, the Galactic Centre, nearby galaxies, high-redshift galaxies, fundamental constant evolution, and the epoch of reionization. NCRA-TIFR has built and operates the largest steerable radio telescope in the world, the Giant Metrewave Radio Telescope, as well as the Ooty Radio Telescope, and offers challenging opportunities to work at the frontiers of astronomy and astrophysics, as well as in instrumentation development.

The Radio Astronomy Centre (RAC) is a part of the National Centre for Radio Astrophysics (NCRA) of the well-known Tata Institute of Fundamental Research (TIFR) which is funded by the Government of India through the Department of Atomic Energy. The RAC is situated near Udhagamandalam (Ooty) in the the beautiful surroundings of the Nilgiri Hills and it provides stimulating environment for the front-line research in radio astronomy and astrophysics with its excellent and highly qualified staff and international reputations.

3.4.4 Giant Metrewave Radio Telescope (GMRT) at Pune

The NCRA has set up a unique facility for radio astronomical research using the metrewavelengths range of the radio spectrum, known as the Giant Metrewave Radio Telescope (GMRT). It is located at a site about 80 km north of Pune. GMRT consists of 30 fully steerable gigantic parabolic dishes of 45m diameter each spread over distances of upto 25 km. GMRT is one of the most challenging experimental programmes in basic sciences undertaken by the Indian scientists and engineers (TIFR, 2001).

Image 5: Giant Metrewave Radio Telescope (GMRT) at Pune

Goals of GMRT

Although GMRT will be a very versatile instrument for investigating a variety of radio astrophysical problems ranging from our nearby Solar system to the edge of the observable Universe, two of its most important astrophysical objectives are to:

- detect the highly redshifted spectral line of neutral Hydrogen expected from protoclusters or protogalaxies before they condensed to form galaxies in the early phase of the Universe and
- search for and study rapidly-rotating Pulsars in our galaxy.

3.4.5 Ooty Radio Telescope (ORT)

The Ooty Radio Telescope (ORT, as it is known) is a cylindrical paraboloid of reflecting surface, 530 m long and 30 m wide, placed on a hill whose slope of about 11 degree in the north-south direction which is same as the latitude of the location of ORT. This makes it possible to track celestial objects for about 10 hours continuously from their rising in east to their setting in the west by simply rotating the antenna mechanically along its long axis. The antenna beam can be steered in the north-south direction by electronic phasing of the 1056 dipoles placed along the focal line of the reflector. The reflecting surface is made up of 1100 thin stainless steel wires, each 530 m long. It is supported by 24 parabolic frames separated by 23 m from each other.

The telescope is operated at 326.5 MHz (a wavelength of 0.92 m) with 15 MHz usable bandwidth. The large size of the telescope makes it highly sensitive. As an example, it is in principle capable of detecting signals from a mere 1 watt radio station located ten million kilo meter away in space.

Image 6: Ooty Radio Telescope (ORT) at Ooty

The Ooty Radio Telescope has been designed and fabricated fully indigenously. The ORT was completed in 1970 and continues to be one of the most sensitive radio telescopes in the world. The observations made using this telescope have led to important discoveries and to explain various phenomena occurring in our Solar system and in other celestial bodies.

3.5 Radio Astronomy Research in China

The astronomy of East Asia began in China. The solar term was completed in Warring States Period. The knowledge of Chinese astronomy was introduced to East Asia. Astronomy in China has a long history. The detailed records of astronomical observations were kept from about the 6th century BC until the introduction of Western astronomy and the telescope in the 17th century. Chinese astronomers were able to precisely predict comets and eclipses. Much of early Chinese astronomy was for the purpose of timekeeping. The Chinese used a lunisolar calendar, but because the cycles of the Sun and the Moon are different, astronomers often prepared new calendars and made observations for that purpose. The astrological divination was also an important part of astronomy. Astronomers took a careful note of "guest stars" which suddenly appeared among the fixed stars. They were the first to record a supernova, in the Astrological Annals of the Houhanshu in 185 A.D. Also, the supernova that created the Crab Nebula in 1054 is an example of a "guest star" observed by Chinese astronomers, although it was not recorded by their European contemporaries. The ancient astronomical records of phenomena like supernovae and comets are sometimes used in modern astronomical studies. The world's first star catalogue was made by Gan De, a Chinese astronomer, in 4th century BC.

3.5.1 Miyun Station

The Miyun Synthesis Radio Telescope (MSRT) is a linear array of 28 elements, 9-meter aperture telescope working on 232 MHz. The MSRT was officially opened in 1984, and dedicated to a Northern Sky Survey for 10 years and the result of a 232MHz radio map was publishe.

d in 1996. And then, the MSRT was upgraded into an adding system with sensitivity equivalent to a 47-m single dish. Completed in 2000, the adding system has been used for the IPS obsevation. As a further development, a project is undergoing for the construction of a 50-m single dish, operated up to S band, but the central part of 30-m, can be used for X band. The 50-m telescope is of multi-purposes, among those, pulsar timing for gravitational wave detection, a powerful element for the Chinese VLBI network, and also, a data receiving ground station for space mission will be on the prior list.

Image 7: Miyun Synthesis Radio Telescope (MSRT) in Beijing

3.5.2 The FAST Project

The MSRT team has been involved in the project SKA (Square Kilometer Array) since the very beginning of this huge international cooperation in 1993. An engineering conceptional investigation has been done under the support of the CAS since then. A proposal of a set of about 30 elements, large Arecibo-like spherical reflectors, each of which can be dynamically shaped to form local parabolic patches was set up by the team. In Guizhou province, near Guiyang city in the SW of China, there are hundreds of valleys which can be used to accommodate such kind of ground fixed radio telescope and become one of the candidates of the SKA. As a pioneer project, the design of a single dish of Five hundred meter Aperture Spherical Telescope (FAST) has been carrying out. In very good cooperation with some 20 groups in the institutes and universities in China, the FAST feasibility study has been finished and approved by the CAS in 2001. In comparison to the Arecibo telescope, a larger aperture, wider sky coverage, shorter wave length, faster motion, lighter weight radio telescope model is acceptable for further engineering design. The study is also highly marked by the SKA organization, and is accepted as one of the options of the SKA.

Image 8: Five hundred meter Aperture Spherical Telescope (FAST), China

3.5.3 Large Radio Telescope Laboratory

To fulfill the SKA and the FAST project, the Laboratory has been established in the National Astronomical Observatory at its center in Beijing. To perform the feasibility study and engineering test of the key technology of the FAST and SKA, new concepts and many simulation studies have been done in this Laboratory. The conceptional design of the 50-m telescope has also been done in this Laboratory.

3.5.4 Delingha Station

Delingha Station Being one branch of the Purple Mountain Observatory, the station located in Qinghai province is the only site for millimeter wave observation in China. A mmwave telescope of 13.7 m, protected by a radome, is situated near the Gobi, the wild desert in North-western China. Beginning from 13 mm, for water vapor sources detection, Delingha station has moved to 2.6mm band with a cooled Schottky receiver and an AOS (acoustic-optical spectrometer) system. Recently, an advanced 90—115 GHz super conducting SIS receiver has been developed and operated, and the sensitivity of the telescope improved immediately. CO line survey for about 2000 cold IRAS sources were observed, and many new CO sources were detected.

3.5.5 Mm and Sub-mm Wave Laboratory

This Laboratory is located in Purple Mountain Observatory in Nanjing. It supports the Delingha Station strongly with the research and development of mm wave technology, which also has been applied to other fields besides radio astronomy. Most of the radio instruments used in the Delingha Station have been developed in this Laboratory, a 3-channel receiver and back system to match the CO line observation around 115 GHz is under development recently. For sub-mm work, a 660— 720 GHz, with world standard performance high sensitivity SIS receiver has been built. This work offers the possibility of cooperation for receivers in the ALMA project and the SMA project. A portable sub-mm radio telescope POST, with aperture in 30 cm and working at 492 GHz has been developed jointly by the Laboratory with Japanese groups. The POST has been performed test observation in Delingha and Japan, and can be used for site selection and experimental observation.

3.5.6 Shanghai VLBI Station

Shanghai VLBI Station located in Shanghai, at the suburb SW to Shanghai city, the VLBI station was established in 1987. The 25-m radio telescope equipped with receivers on 92,18,13.6,6,3.6 and 1.3 cm, and Mk4, S2 VLBI terminals. The station is mainly performing VLBI observations and is a member of EVN, IVS, and also joined heavily in the observation of VSOP. APSG and domestic geodetic VLBI observations have been done every year. Shanghai station has been participating in some experiments for the Mars, Venus studies, and will join in the SELENE, VERA projects.

Image 9: Shanghai VLBI station

3.5.7 Urumqi Station

Urumqi Station located in Nanshan, at the suburb south to Urumqi city, was established in 1994. A 25-m telescope with receivers on 92, 18, 13, 13.6, 6, 3.6, 1.3 cm and Mk4, K4 VLBI terminals, the Nanshan station is a twin VLBI stations with the Sheshan station in Shanghai. Nanshan station being surrounded by mountains and forests, with small radio influence and good geographic distribution, has joined in many cooperative projects such as EVN, IVS, VSOP, APSG, and domestic geodetic VLBI experiments for radio observation on space debris, low-frequency VLBI and the VERA, SELENE projects.

Besides VLBI, the Nanshan station has been doing successful pulsar observation in multi-band, cooperating with Australia colleagues and good results have been achieved.

Image 10: Urumqi VLBI station

3.5.8 VLBI Laboratory

The Laboratory is located in Shanghai Observatory and supports VLBI technical developments for the Sheshan and Nanshan stations. Besides the VLBI terminals and receivers upgrading, now the laboratory is working on a 2-station VLBI correlator, planning for extending to a 4- station correlator as well as e-VLBI technique development.

A mobile VLBI station of 3.5-m aperture, S-2 terminal 13.6/3.6 cm receiver, was completed in recent years. This mobile is being used for domestic geodetic VLBI, located in Kunming and got good observations. A 10-m redio telescope for solar observation is located in Kunming Observatory.

3.6 Techniques used in Radio Astronomy

Radio astronomers use different techniques to observe objects in the radio spectrum. Instruments may simply be pointed at an energetic radio source to analyze its emission. To “image” a region of the sky in more detail, multiple overlapping scans can be recorded and pieced together in a mosaic image. The type of instrument used depends on the strength of the signal and the amount of detail needed.

Observations from the Earth's surface are limited to wavelengths that can pass through the atmosphere. At low frequencies, or long wavelengths, transmission is limited by the ionosphere, which reflects waves with frequencies less than its characteristic plasma frequency. Water vapor interferes with radio astronomy at higher frequencies, which has led to building radio observatories that conduct observations at millimeter wavelengths at very high and dry sites, in order to minimize the water vapor content in the line of sight. Finally, transmitting devices on earth may cause radio-frequency interference. Because of this, many radio observatories are built at remote places.

3.6.1 The Electromagnetic Spectrum

Radio is part of the Electromagnetic Spectrum (EM) along with Light. Whenever an electric charge changes speed or direction it gives off an electromagnetic (EM) wave. How fast the wave ‘wiggles’ determines what kind of EM radiation is created. EM can be placed in order from lowest energy to highest energy as follows: Radio, Infrared, Visible Light, Ultraviolet, X-Rays, and Gamma Rays. The chart below also shows Frequency and Wavelength as well as Energy. These three are related through two equations: $f=c/\lambda$ and $E=hf$ (f=Frequency; c=speed of light (~300,000km/sec); λ=wavelength; E=energy; h= Planck's constant (~6.626 × 10−34 Joules・sec)). The equations show that as the energy increases, the wavelength decreases and the frequency increases.

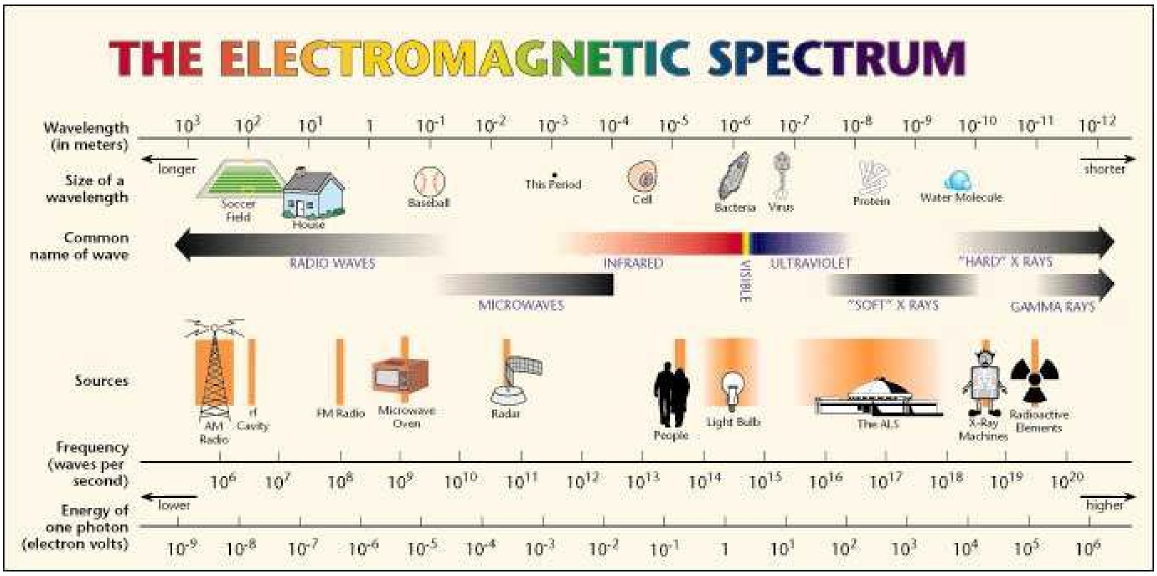

Image 11: Electromagnetic Spectrum
Source: http://son.nasa.gov/tass/images/cont_emspec2.jpg

EM vs. Sound

- Sound is longitudinal (travels with the wave direction) while light is transverse (travels perpendicular to the wave direction).
- Sound travels at about 1,100 ft/sec while light travels at about 186,000 miles/sec.
- Sound travels only in matter while light can travel through a vacuum.
- Sound is vibrating matter while light is vibrating electrons.

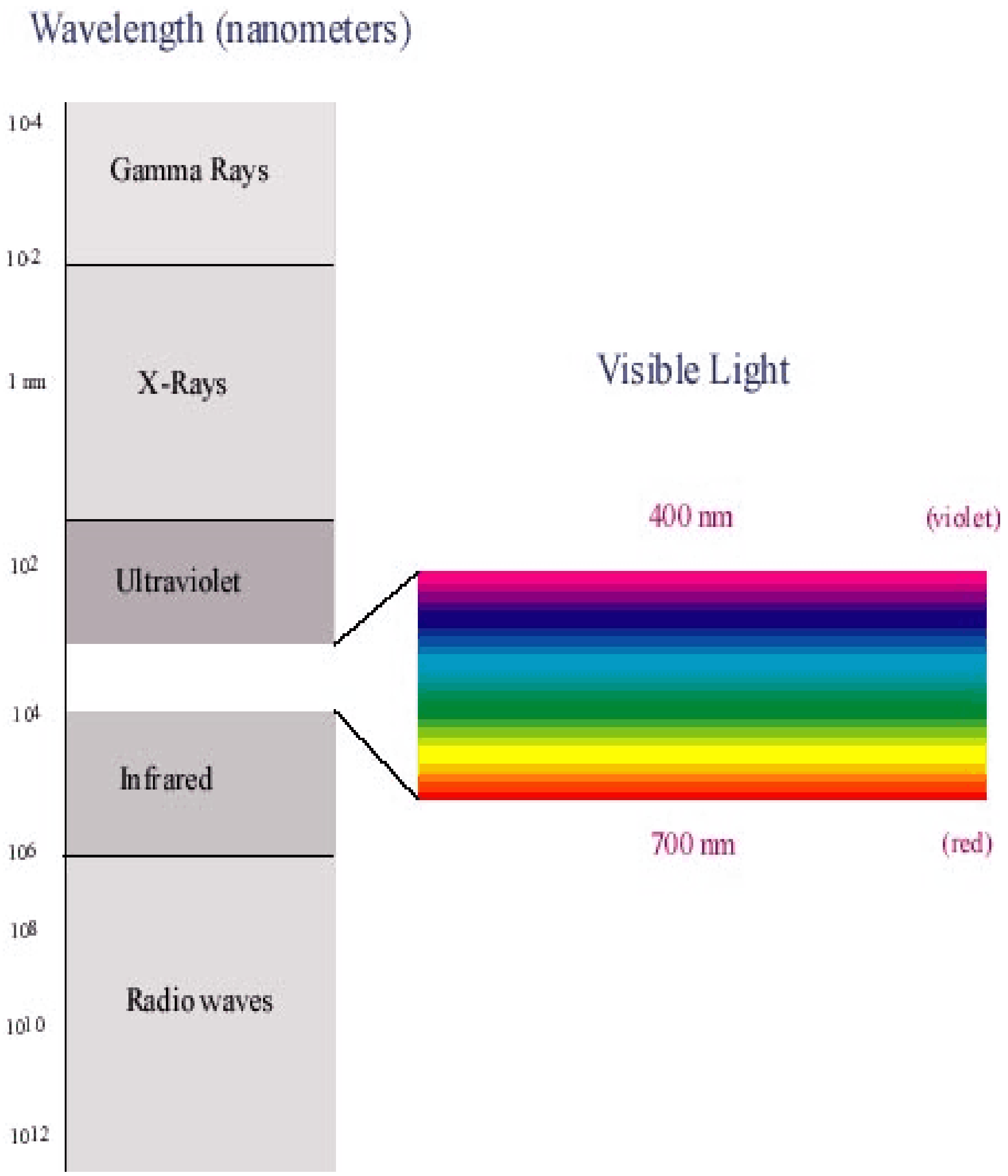

Image 12: Electromagnetic Spectrum Diagram

As the picture shows, many objects are viewed better in different types of electromagnetic (EM) radiation. Remember that the higher up in the picture you go, the more energetic the object has to be. Therefore, cooler objects will be near the bottom while really 'hot' objects will be near the top. Remember that all pictures that are not visible light are representations in false color (i.e.: made so we can see them as if we could see that frequency of the electromagnetic spectrum).

The different "types" of electromagnetic radiation are defined by their wavelengths:

Type	Wavelength Range
Gamma rays	<0.01 nanometers
X-rays	0.01 - 10 nanometers
Ultraviolet	10 - 300 nanometers
Visible	0.3 - 0.8 micrometers
Infrared	1 - 1000 micrometers
Radio	0.001 - 30 meters

3.6.2 Radio Telescopes

Radio telescopes are mainly either prime focus or Cassegrain reflectors. However, the radio telescope looks very different from the optical telescope; radio telescopes are much larger than optical telescopes. The reason for this is that the angular resolution (or the angular area of the sky from which the telescope can collect emission) of a telescope is proportional to the wavelength divided by its diameter. So in order for a radio telescope to be able to detect the same angular resolution as an optical telescope the radio telescope has to be much larger. In addition, the sensitivity of the telescope or the ability to detect weak emission is also related to the area of the reflecting surface.

There are four basic elements to a radio telescope, the reflector, the subreflector, the feed and transmission line and the receiver.

The reflector collects power from astronomical sources. The subreflector is a surface that directs the radiation to the feed at the center of the reflector. Behind the feed is the receiver system (at the cassegrain focus). The receiver amplifies the radio signal, selects the appropriate frequency range that detects the signal.

Radio telescopes use a large metal dish, usually parabolic, to reflect radio waves to the subreflector situated close to the prime focus. The signal from the antenna is sent to an amplifier, which magnifies the faint radio signals. The amplified radio signal is then processed by a computer. The receiver is configured in such a way that throughout the amplification process, the signal remains directly proportional to the strength of the incoming radiation. So the resulting image or spectrum is a true representation of the emission from the astronomical source. The following image is a schematic diagram of a radio telescope. (Chautauqua, 2000).

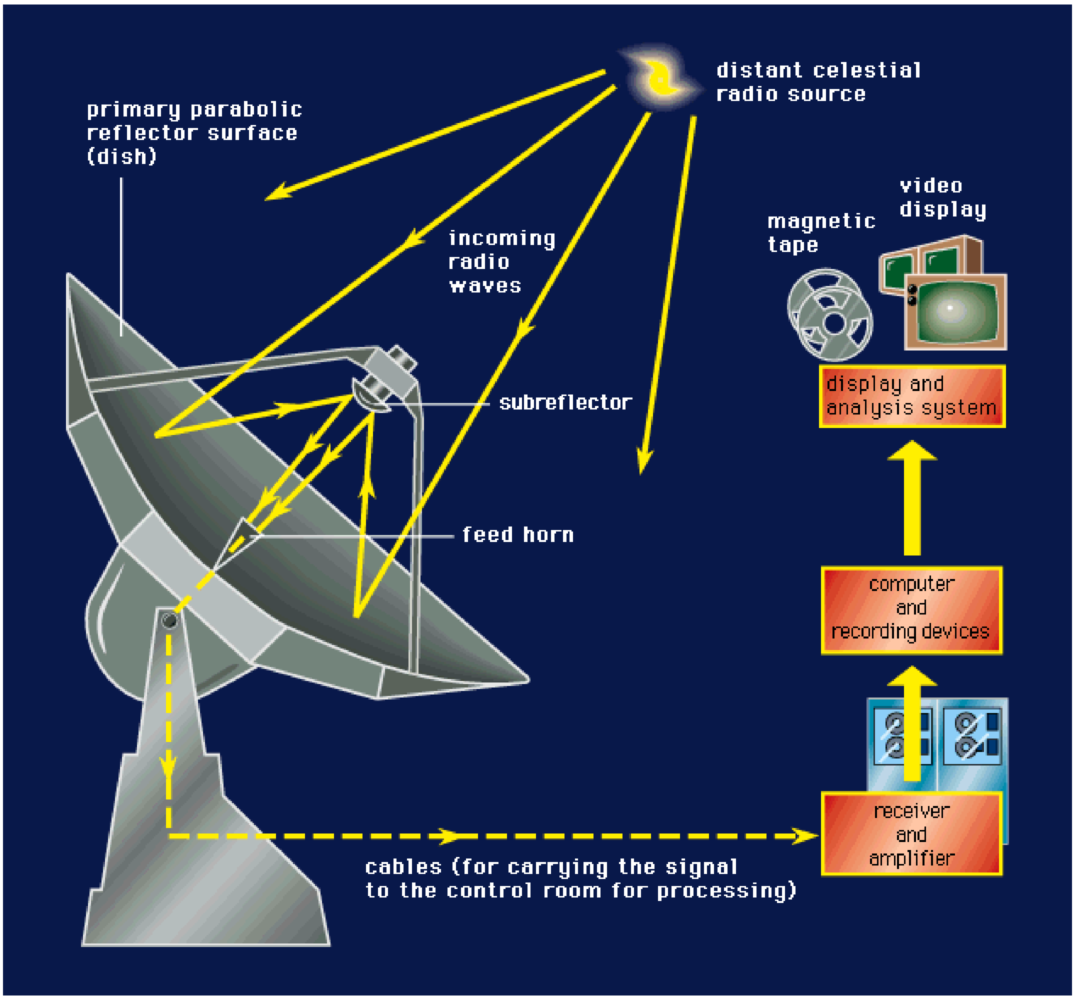

Image 13: Typical Radio Telescope

Source: http://abyss.uoregon.edu/~js/glossary/radio_telescope.html

The resulting images from the radio telescope are very different from the optical telescope. These differences are mainly due to the different mechanisms that cause the emission. For example, here is an image of the Milky Way using an optical telescope (photo courtesy of APOD). At visible wavelengths, the sky is dominated by thermal emission from the visible surface of the stars. Optical astronomers measure the brightness of objects by measuring the apparent magnitude, or the flux density of the object. The flux density is a measure of the power received from the object per unit frequency, per unit area.

3.6.3 Differences between Optical and Radio Astronomy

There are many differences between optical and radio astronomy. The three main differences are the design of the instruments, the resulting data that is found, and the different sources that are seen.

Both optical and radio astronomy use telescopes; however, there is a big difference in the design between an optical telescope and a radio telescope.

Optical astronomy is the study of the visible part of the electromagnetic spectrum that is wavelengths of approximately 400 nm (purple) to 700 nm (red).

Radio wavelengths are much longer; the radio spectrum ranges from approximately one millimeter to hundreds of meters. This means that optical photons have much higher energies than radio photons. This property of photons affects the way one would detect them.

Image 14: Milky Way using a radio telescope tuned to 408MHz.

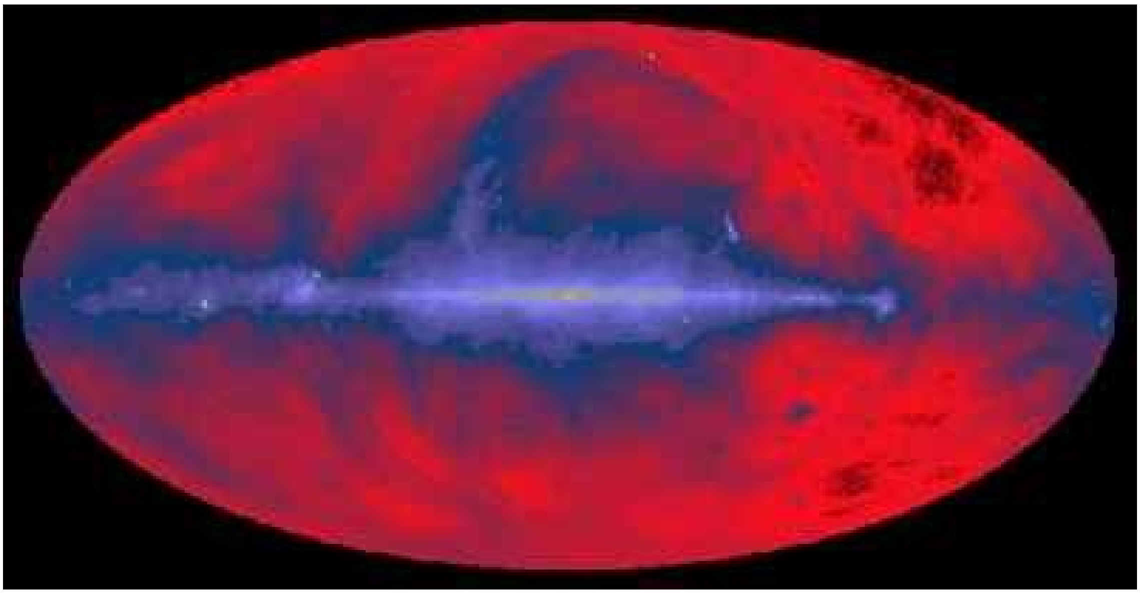

Image 15: Optical image of the galaxy M87 (HST)

An optical image of the galaxy M87 (HST), a radio image of same galaxy using Interferometry (Very Large Array-VLA), and an image of the center section (VLBA) using a Very Long Baseline Array (Global VLBI) consisting of antennas in the US, Germany, Italy, Finland, Sweden and Spain. The jet of particles is suspected to be powered by a black hole in the center of the galaxy.

Image 16: First 7-metre ESO/NAOJ/NRAOALMA Antenna.

Radio telescopes may need to be extremely large in order to receive signals with high signal-to-noise ratio. Also since angular resolution is a function of the diameter of the "objective" in proportion to the wavelength of the electromagnetic radiation being observed, radio telescopes have to be much larger in comparison to their optical counterparts. For example a 1 meter diameter optical telescope is two million times bigger than the wavelength of light observed giving it a resolution of roughly 0.3arc seconds, whereas a radio telescope "dish" many times that size may, depending on the wavelength observed, only be able to resolve an object the size of the full moon (30 minutes of arc).

4.6.4 Radio Interferometry

The process of separating two or more antennas by a certain distance and using them as one effective antenna is called interferometry. This process can be done with the antennas all connected by cables which carry the observed radiation to a processing center (called a correlator) - this is called connected element interferometry (Chautauqua, 2000).

The VLBI combines observations at multiple radio telescopes to form extremely high resolution images of astronomical radio sources. These telescopes are not connected by cables and can sometimes be on different continents. The data are collected on high density magnetic tapes which are then brought to a central correlator after the experiment is conducted. The results are observations with resolutions of milli and micro arcseconds. The VLBI continually challenges the limits of both telescopes and observers, while fostering international collaboration on the frontiers of astronomy. Current Haystack-led VLBI projects study the lives of stars from formation to senescence, and probe the violent physics of Active Galactic Nuclei (AGN).

3.6.5 Very Long Baseline Interferometry

Beginning in the 1970s, improvements in the stability of radio telescope receivers permitted telescopes from all over the world (and even in Earth orbit) to be combined to perform Very Long Baseline Interferometry. Instead of physically connecting the antennas, data received at each antenna is paired with timing information, usually from a local atomic clock, and then stored for later analysis on magnetic tape or hard disk. At that later time, the data is correlated with data from other antennas similarly recorded, to produce the resulting image. Using this method it is possible to synthesise an antenna that is effectively the size of the

Earth. The large distances between the telescopes enable very high angular resolutions to be achieved, much greater in fact than in any other field of astronomy. At the highest frequencies, synthesised beams less than 1 milliarcsecond are possible.

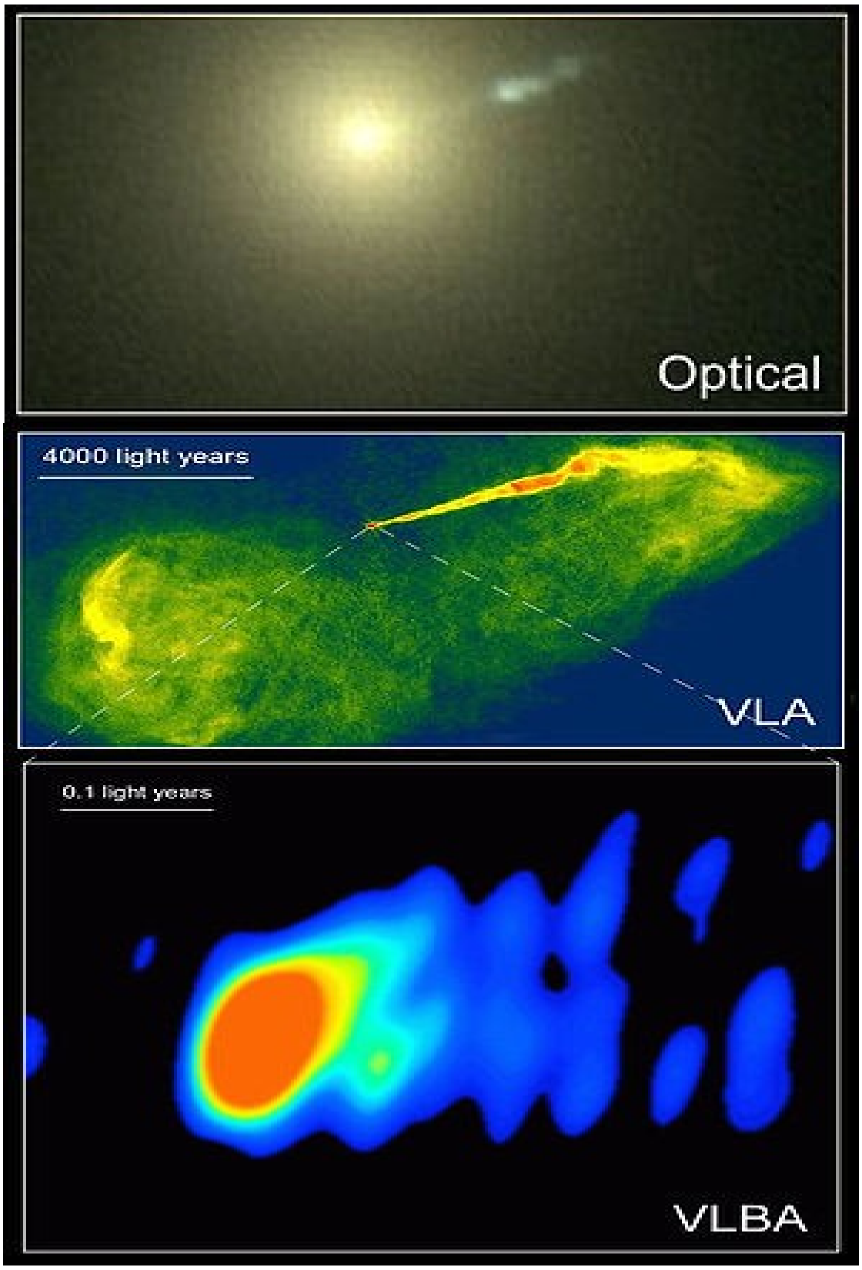

Image 17: An optical image of the galaxy M87 (HST), a radio image of same galaxy using Interferometry (Very Large Array-VLA)

An optical image of the galaxy M87 (HST), a radio image of same galaxy using Interferometry (Very Large Array-VLA), and an image of the center section (VLBA) using a Very Long Baseline Array (Global VLBI) consisting of antennas in the US, Germany, Italy, Finland, Sweden and Spain. The jet of particles is suspected to be powered by a black hole in the center of the galaxy.

The pre-eminent VLBI arrays operating today are the Very Long Baseline Array (with telescopes located across North America) and the European VLBI Network (telescopes in Europe, China, South Africa and Puerto Rico). Each array usually operates separately, but occasional projects are observed together producing increased sensitivity. This is referred to as Global VLBI. There is also a VLBI network, the ALBA, Australian Long Baseline Array, operating in Australia.

Since its inception, recording data onto hard media has been the only way to bring the data recorded at each telescope together for later correlation. However, the availability today of worldwide, high-bandwidth optical fibre networks makes it possible to do the VLBI in real time. This technique (referred to as e-VLBI) was pioneered by the EVN (European VLBI Network) which now performs an increasing number of scientific e-VLBI projects per year.

3.6.6 Astronomical sources

A radio image of the central region of the Milky Way galaxy. The arrow indicates a supernova remnant which is the location of a newly discovered transient, bursting low-frequency radio source GCRT J1745-3009.

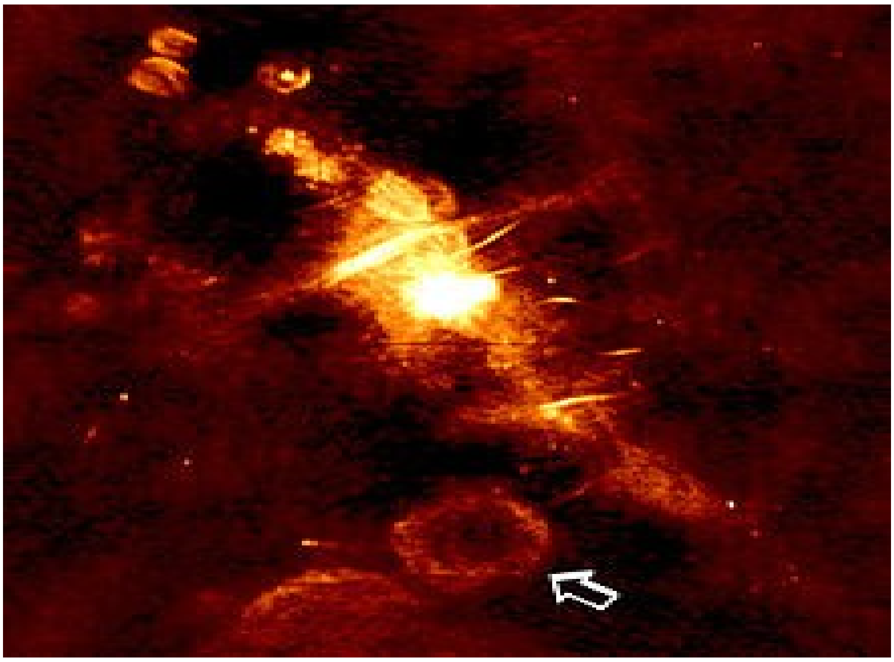

Image 18: A radio image of the central region of the Milky Way galaxy

The arrow in the image indicates a supernova remnant which is the location of a newly discovered transient, bursting low-frequency radio source GCRT J1745-3009.

The cosmic microwave background radiation was also first detected using radio telescopes. However, radio telescopes have also been used to investigate objects much closer to home, including observations of the Sun and solar activity, and radar mapping of the planets.

Sources of Radio Emission

- Solar system – sun, planets
- Milky way – star forming regions, old stars, supernova remnants
- Extragalactic – quasars, radio jets
- Molecules

- Active galactic nuclei and pulsars have jets of charged particles which emit synchrotron radiation
- Merging galaxy clusters often show diffuse radio emission
- Supernova remnants can also show diffuse radio emission; pulsars are a type of supernova remnant that shows highly synchronous emission.
- The cosmic microwave background is blackbody radio/microwave emission

None of the bright stars in the night sky are prominent radio emitters. The emissions that are measured in radio astronomy come not from the stars, but from the gasses, etc. It can be seen that these views are very different from one another. The radio sky is not dominated by the light from stars and, depending on the wavelength, may not be dominated by thermal radiation. At short radio wavelengths, the thermal emission sources dominate the sky, and at long radio wavelengths the sky is dominated by non-thermal emission sources. In the radio sky there are also sources of both continuous emission and line emission. An example of radio line emission is the 21-cm line of neutral atomic Hydrogen. At long wavelengths the emission occurs primarily from synchrotron emitting sources such as pulsars, supernovae remnants, radio galaxies, and quasars. At short wavelengths, the emission is dominated by thermal sources. Small, hot sources such as stars can be detected but are not an important part of emission. Large, cold sources such as the gas and dust clouds of interstellar medium and hot, large sources such as HII regions are important sources of emission.

3.6.7 Commonly used units in Radio Astronomy

- 1 Astronomical Unit (AU) = 150,000,000 km (Average distance between Sun and Earth).
- 1 Parsec (pc) = 3.26156378 light years (~206265 AU)
- 1 kpc = 1000 pc (kpc is used for measuring distances within our galaxy and neighboring galaxies).
- 1 Mpc = 1,000,000 pc (Mpc is used for measuring distances in cosmology)
- 1 jansky = 10-26 W m-2 Hz-1 (used for measuring flux density in Radio Astronomy)

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