Chapter 13: The Development of Radio Astronomy

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Radio astronomy has been a very instrument-driven science. The great discoveries of radio astronomy often happened soon after a new radio telescope was put into operation. Many of these discoveries have been serendipitous but contributed to the rapid progress in modern astronomy. Thus the question of what has happened to the historic instruments is a very relevant topic. In this article we sketch the history of the discoveries in radio astronomy and investigate the status of the heritage instruments that were involved in these discoveries.

The first detection of comic radio waves was made in 1932 by Karl Jansky, a physicist working for the Bell Telephone Laboratories in the USA. The detection was made in the frequency range around ~20 MHz (15m wavelength), where commercial telephone communications were carried out. Jansky was studying the causes of disturbances to radio telephone communications. The observations were made with a rotating 'Bruce array' that allowed the direction of the disturbances to be pinpointed. Jansky found that in addition to natural causes of disturbances such as thunderstorms, a hiss-type disturbance was changing with sidereal time, and he correctly identified this to be due the radio emission of the Milky Way. The next serious astronomical investigation of the radio emission was made by Grote Reber in 1944 (see Fig. 13.0.1) who surveyed the sky at ~160 MHz with a paraboloid reflector. The first maps of the radio Milky Way that were presented showed that the most intense radio emission came from a region some 30° away from what was the accepted position of the Galactic Centre, a spectacular radio astronomy discovery.

The development of radio astronomy followed the first steps taken by Jansky and Reber. At the outset, dipoles (known and used by Heinrich Hertz in the 1880s) made into arrays were generally used. These were suitable for observations at metre wavelengths. The paraboloid reflector radio telescope, first used by Grote Reber, became the mainstay of radio astronomy. Such reflectors were general-purpose instruments and could be constructed to operate at short centimetre and millimetre wavelengths, to which radio astronomy moved in later years. Neither of the historical instruments of Jansky and Reber exists on its original site. Jansky's original antenna was at the Holmdel New Jersey field station of the Bell Telephone Laboratories. A replica of this antenna can be seen at the entrance of the National Radio Astronomy Observatory in Green Bank, West Virginia, USA. Nearby stands the antenna used by Grote Reber on his private land at Wheaton, Illinois. This antenna was transferred to Green Bank but its wooden sections required considerable refurbishment.

Technological developments during the Second World War brought about a huge improvement in radio reception methods. New antennas and sensitive receivers were developed, albeit not for radio astronomy. A report about the detection of solar radio waves was published by J.S. Hey in 1946. Hey and his colleagues also observed fluctuations in the cosmic radiation and correctly interpreted them as being due to discrete radio sources. These new discoveries, added to the diffuse emission from the Milky Way that had already been observed by Jansky and Reber, laid the basis for radio astronomy. After the Second World War, trained radar experts quickly adapted their equipment to study cosmic radio emissions.

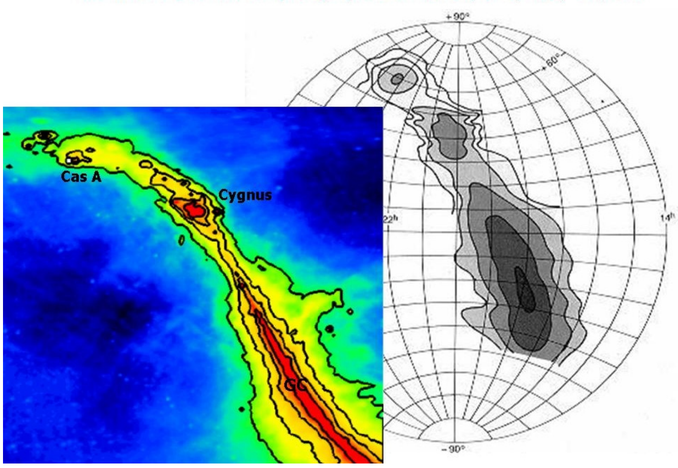


Fig. 13.0.1. Right: The first radio map of the Milky Way at 160 MHz. After G. Reber, *ApJ* 100 (1944), 279. **Left:** a recent 1400 MHz map of the same region by W. Reich. © Max Planck Institut für Radioastronomie

The discovery of discrete radio sources led to the need for ever-greater angular resolution and to the construction of more sensitive radio telescopes. The first optical identifications of radio sources, made by J.G. Bolton and others in 1948, showed that these were some of the most unusual cosmic objects with angular structure. The next step that was needed was to map the structures of these objects.

The existence of line emission at radio wavelengths had already been predicted by Henk van de Hulst in 1944, and the discovery of the hyperfine line of neutral hydrogen, HI, from the Milky Way at 21cm wavelength was made by H.I. Ewen and E.M. Purcell in 1951. They used a horn antenna placed on a building of the Lyman Laboratory at Harvard University. This original horn antenna is also on display in Green Bank. Shortly after the initial discovery of the HI line, confirmatory measurements were made at the Leiden Observatory and the CSIRO Radiophysics Division in Sydney. In the following years these groups mapped the entire Galaxy in this spectral line, giving us information about the spiral structure of the Milky Way. Further discussion about possible radio line emissions led to the construction of powerful spectrometers that eventually brought about the rapid development of radio spectroscopy.

In 1945, military-disposals equipment became available for peaceful purposes. One of the most important disposal items in facilitating the rapid start of radio astronomy in Europe was the 7.5m-diameter 'Würzburg Riese' paraboloid antenna used in the German radar system. Numerous Würzburg dishes were transferred to various European observatories in the United Kingdom, the Netherlands, France, Sweden and Czechoslovakia where they were used in early radio-astronomy discoveries. Several of these dishes have now found their way into museums. Most of the Würzburg dishes required considerable maintenance work before their transfer to museums, since corrosion was active in the metallic sections. They can be seen in Deutsches Museum, München, at Douvres la Delvarne, France, Waaldorp, Netherlands, and the Imperial War Museum at Duxford, U.K. The last active use of Würzburg dishes was in Ondřejov, Czech Republic, for solar research.

In the USA many military laboratories became involved in radio astronomy research. The Naval Research Laboratory in Washington DC has a long record of radio-astronomy research. A 50ft dish on top of a building was used for early observations at high radio frequencies (up to 10 GHz, the first cm-wavelength observations). The thermal emission of planets, the free-free HII emission in the Milky Way and the polarization of the Crab Nebula were all discovered in the 1950s by the group using the 50ft dish. This radio telescope is still present and can be seen when landing at the Ronald Regan airport in Washington DC. Another important early instrument, which was used in the discovery of the first molecular emission (the OH line) in 1963, was the 84ft parabolic antenna of the Millstone Hill Observatory of the Lincoln Laboratory. This instrument is also still in use. One of the most unusual single radio telescopes, still standing on its original site, is the 20ft-aperture horn-reflector antenna used by Arno Penzias and Robert Wilson in 1964 in the discovery of the 2.7°K cosmic microwave background (CMB), for which they received the Nobel Prize in 1978. This telescope stands on the grounds of the former Bell Telephone Laboratories in Holmdel, New Jersey. The present owners are the Alcatel-Lucent company.

Single dishes could map the smooth extended emission of the Milky Way but did not have the angular resolution to locate the positions and determine the structure of discrete radio sources. The need for higher angular resolution to study the discrete radio sources led to the introduction of radio interferometry. Martin Ryle's group in Cambridge had been using interferometers from the very beginning in 1946. In addition to long-wavelength interferometers, two Würzburg dishes were used as an interferometer to make accurate positional determinations of radio sources and permit subsequent optical identification. Other antenna configurations used in the early days of radio astronomy in Cambridge were cylindrical paraboloid and corner reflectors placed on an east-west line. These antennas were structurally very simple and have not completely survived. In Australia a cliff interferometer was used first for solar research by J.L. Pawsey and colleagues in 1946; they also related interferometer measurements to imaging. Two years later J.G. Bolton and colleagues presented the first optical identifications of radio sources. The quest to improve the angular resolution led to the construction in 1953 of a grating interferometer with 32 small dishes for solar research. Radio telescopes of this type were built in Japan, Canada, the Soviet Union and India. Also in 1953, B.Y. Mills and A. Little in Australia invented an antenna system that became known as Mills Cross. This instrument synthesised a pencil in both Right Ascension and Declination, so that accurate positions could be determined and good maps made of the diffuse emission. None of the early antennas in Australia exist in full on the original sites. Mills Cross antennas were constructed in Italy, the Soviet Union, and most recently at Molonglo in Australia. All these antennas are still in use. The sites within the city of Sydney were taken over for building construction or reverted to public reserves. The Fleurs field station, which hosted the Chriss-Cross and the Mills Cross, was transferred from CSIRO to the University of Sydney. However, radio astronomy was also abandoned at this site and some of the instruments were transferred to the Australia Telescope National Facility headquarters in Epping. Most of the early antennas—many of which, built for low radio frequencies, used wood as construction material—have not survived. The early paraboloid dishes were also of a very light construction and were not maintained. Some antennas were ultimately moved to other locations.

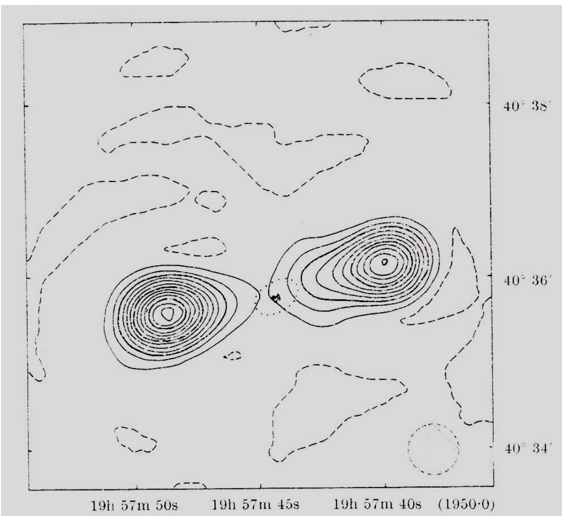
The beginnings of radio astronomy as 'big science' led to the foundation of new observatories and to the financing of new radio telescopes. Paraboloid telescopes of the ~25m-diameter class were constructed in numerous observatories including Dwingeloo, Netherlands (1955), Stockert, Germany (1956) and Pushino, Soviet Union (1959). The National Radio Astronomy Observatory, founded in the USA, began operations with the Tatel 85ft (26m) radio telescope in 1958. At the same time the construction of a 140ft-precision telescope begun in Green Bank (completed in 1965). This telescope is still standing on the original site, part of the NRAO organisation. While the construction of the 140ft dish experienced delays, a 300ft transit dish was built in Green Bank in 1962. This dish collapsed owing to metal fatigue failure in 1988. The Stockert and Dwingeloo telescopes are still standing on their original sites, protected by foundations that support historical objects. (The Stockert antenna is examined more closely in Case Study 13.1.) The construction of what was then the world's largest reflector, a 250ft (74m) radio telescope, was completed at Jodrell Bank, UK, in 1957. This radio telescope has been refurbished several times, and is still actively used in research, having been renamed the 'Lovell Telescope'. Single-dish antennas were used in the 1960s to measure linear polarization and the radio Zeeman effect, advances that led to the beginning of research in cosmic magnetic fields.

The construction the Giant Pulkovo Radio Telescope—a section of a reflector corresponding to an aperture of 130m × 25m, designed to operate in the centimetre and long millimetre wavelength range—was completed in 1956 in the Soviet Union. This telescope is still used for solar research. Experimenting with new types of antenna, J.D. Kraus designed a large reflector-director system. The first such radio telescope, later named the 'Big Ear' when used for the search of signals from extraterrestrial civilizations (SETI), was constructed for the Ohio State University. This type of radio telescope, which combines low cost with a large collecting area, was copied in several other observatories. The Kraus telescope became operational in 1960 but had to make way for real estate development and a golf course in 1998. A large decametre radio telescope of the reflector-director type at the Nançay Observatory, France, which was completed in 1965, is still operating today. The 64m Parkes radio telescope became operational in 1962. Owing to its position in the southern hemisphere it was a major contributor to many studies of the Milky Way. The Parkes radio telescope is still a fully operational instrument. The largest reflector, a spherically shaped, non-steerable 1000ft-diameter reflector, was built in 1963 at Arecibo, Puerto Rico. This instrument was used initially for ionospheric work and planetary radar but later the research was shifted to radio astronomy. The large collecting area of this instrument opened up a new dimension in single dish sensitivity. The Arecibo facility is still operational although subject to threats of closure owing to financial problems.

The decade 1960–1970 was marked by the development of the **aperture synthesis** method. A prerequisite of this method was high stability of amplifiers, local oscillators and cables. Computing power was also a necessity since data had to be Fourier transformed in order to produce images. The first practical aperture synthesis system was used by and Martin Ryle and A.C. Neville in Cambridge in 1962. This experiment used sections of the 178 MHz cylindrical paraboloid—some of the structures are still standing at the Lord's Bridge observatory. This development led ultimately to the discovery of **quasars**, the most distant sources in our universe, and allowed the nature of **radio galaxies** to be studied with the higher angular resolution. For their contribution to the development of aperture synthesis, Martin Ryle and Anthony Hewish were awarded the Nobel Prize in 1974.

Additional aperture synthesis telescopes were constructed in the Netherlands, USA, United Kingdom, India, Australia and Canada. Details are given in Table 13.0.1. They have been the driving force in present-day radio astronomy. In addition to radio continuum maps, line observation became feasible. At first, only HI maps were possible, but maps in many molecular lines were produced later. The consequent use of HI data on the rotation of galaxies, in combination with optical line data, led in the 1980s to the realization that galaxies contain considerable **dark matter**.

The scintillation method at lower radio frequencies offered an interesting way to study astrophysical plasmas. Several dedicated instruments were constructed for this purpose. One of the great discoveries, made at the low radio frequency of 85 MHz, was the detection of **pulsars** in 1967. The original antenna that detected pulsars was an array of dipoles on wooden posts constructed in Cambridge in 1962 and hence does not exist any more. The discovery of the **binary pulsar** at Arecibo in 1974 led to a revolution in gravitational physics and was recognised with the Nobel Prize in 1993. Another great discovery in the field of pulsar research was the detection of the first **millisecond pulsar** in 1982. The precise pulsar timing that became possible led to the detection of the first **extrasolar planetary system** in 1992.



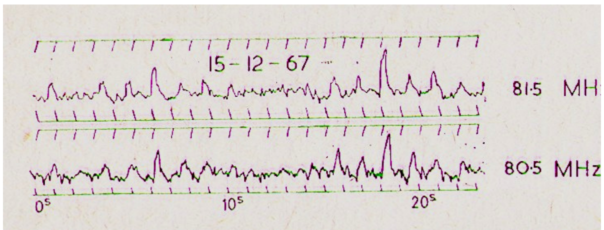


Fig. 13.0.2. Left: An early **aperture synthesis** map of the radio galaxy Cygnus A. After M. Ryle et al., *Nature* 205 (1965), 1259. See Fig. 13.0.4 for comparison. **Above:** The pulsar discovery record. After A. Hewish et al., *Nature* 217 (1968), 709.

Table 13.0.1. Interferometers in operation (2009).

Name	Country	Antennas	Array elements baselines	Operating frequencie
VLA, Soccoro	USA	27 × 25m	36.4 km Y-configuration	74 MHz – 86 GHz
WSRT, Westerbork	Netherlands	14 × 25m	2.8 km East-West	237 MHz – 6 GHz
Cambridge	UK	8 × 13m	4.6 km East-West	2.7 GHz – 15 GHz
ATCA, Narrabri	Australia	7 × 22m	6 km	1.4 GHz – 86 GHz
DRAO, Penticton	Canada	7 × 8.5m	604 m East-West	408 MHz – 1.4 GHz
Pune	India	30 × 45m	25 km irregular	50 MHz – 1.4 GHz
Merlin	UK	25m, 32m, 76m	233 km irregular	150 MHz – 23 GHz
Plateau de Bure	France	6 × 15m	North-South, East-West: 760m max.	90 GHz – 345 GHz
Nobeyama	Japan	6 × 10m	560-m T-base	24 GHz – 90 GHz
Carma	USA	6 × 10.4m, 9 × 6.1m	2.0 km max.	90 GHz – 230 GHz
SMA, Mauna Kea	USA	8 × 6m	500 m	230 GHz – 600 GHz

Table 13.0.2. Large single dishes in operation (2009).

Name	Country	Size	Maximum frequency
Arecibo	Puerto Rico	305m	8 GHz
GBT, Green Bank	USA	110m × 100m	86 GHz
Effelsberg	Germany	100m	86 GHz
Lovell Telescope, Jodrell Bank	UK	76m	8 GHz
Goldstone, Robledo, Tidbinbilla	USA, Spain, Australia	70m	24 GHz
Yevpatoria	Ukraine	70m	6 GHz
Parkes	Australia	64m	43 GHz
Kalyazin, Ussurijsk, Bear Lakes	Russian Federation	64m, 70m, 64m	6 GHz
Miyun	China	50m	8 GHz

Spectroscopy became a major driving force in radio astronomy as a result of the detection of more than 150 molecular species. The beginning of molecular radio spectroscopy was the detection of the OH molecule in 1963, which was followed by the detection of ammonia in 1968 and water and formaldehyde in 1969. It became clear that there was a huge potential for spectroscopic discoveries in the millimetre wavelength range. Millimetre wavelength sources were difficult to measure at first since water vapour (also N_2 and O_2) in the Earth's atmosphere reduces astronomical signals and the early mm-wave receivers had low sensitivities. In the early 1960s, the typical single-dish size was 5m and these were located at sea-level sites. The first impressions were that there was little to be added to the measurements conducted at centimetre wavelengths. This changed as a result of two factors related to instruments. The first was the construction of a 36ft (later rebuilt to 12m) dish at 2500m elevation, started in 1965 at the Kitt Peak site in Arizona. Since water vapour has a scale height of 2000m, this high site and larger collecting area brought about a large improvement in sensitivity. The second factor was the introduction of more sensitive receiver systems. A far-reaching discovery made immediately was that of carbon monoxide (CO) at 115 GHz. This spectral line is widespread and rather intense, so it allowed mapping similar to the mapping done in the 21cm line of atomic hydrogen, HI. In addition, it was later shown that there is a rather simple relation between the abundance of molecular hydrogen and CO, so molecular cloud masses could be determined. The Kitt Peak 12m millimetre telescope is still operational under the auspices of the Steward Observatory of the University of Arizona. Surveys using 1.2m telescopes at 3 mm have allowed the distribution of CO in our galaxy to be determined from data collected in both the northern and southern hemispheres. The 1.2m dish is still operated by the Center of Astrophysics and the University of Chile. The molecular hydrogen distribution is strongly correlated with the distribution of HII regions, and thus with high-mass stars. In addition, CO measurements of nearby molecular clouds showed that stars are associated with these regions, and thus form in molecular clouds. It follows that to understand star formation one must study molecular clouds. In this respect, both the higher line transitions and the various isotopic species are a great help in determining the temperature and the density in these regions.

The next step in the development of radio telescopes was the inauguration of the Westerbork Synthesis Radio Telescope (WSRT) in 1970. This array consisted originally of 12 (now 14) 25m dishes on an east-west line. The Ooty radio telescope, a parabolic cylinder 530m long, was built in India in 1970. This telescope was originally designed for observing lunar occultations of radio sources but became a more general-purpose telescope in later years. It is still actively used in research. The inauguration of the 100m-precision radio telescope in Effelsberg (Germany) took place in 1971. For this telescope a new construction method named 'homology' was employed. Homology allows deflections in a structure but ensures that a paraboloid shape is maintained. This meant that high-frequency use of the 100m Effelsberg telescope, up to 86 GHz, was possible. The new radio telescopes allowed considerable progress in our knowledge: giant radio galaxies were discovered (WSRT), magnetic fields in nearby galaxies could be mapped (Effelsberg), and sensitive spectral observations could be made. Thus, for example, weaker atomic hyperfine lines from ionized 3-helium were observed in 1982, and a special facility was built for the detection of deuterium in 2007. In the Soviet Union, the Ratan 600 radio telescope was constructed in the Caucasus region, a 600m circle of reflecting panels that can be used particularly in multi-frequency mode. The Very Large Array (VLA), an array of 27 antennas 25m in diameter on a 27km Y-shaped line of tracks, was constructed near Soccoro, New Mexico and started full operations in 1980. The Giant Metrewave Radio Telescope (GMRT) near Pune, India has been operational since 1999. In addition, interferometers with radio links, rather than cables, became operational (Merlin, UK) giving increased angular resolution, and leading to the discovery of **gravitational lensing** in 1979.

The aperture synthesis method required that all antennas should be connected by cables or radio links. The development of highly stable clocks and of magnetic tape recorders led to the invention of 'independent oscillator-tape recorder interferometry'. In this method the antennas could be distributed widely over the whole world so that in the end this technology came to be

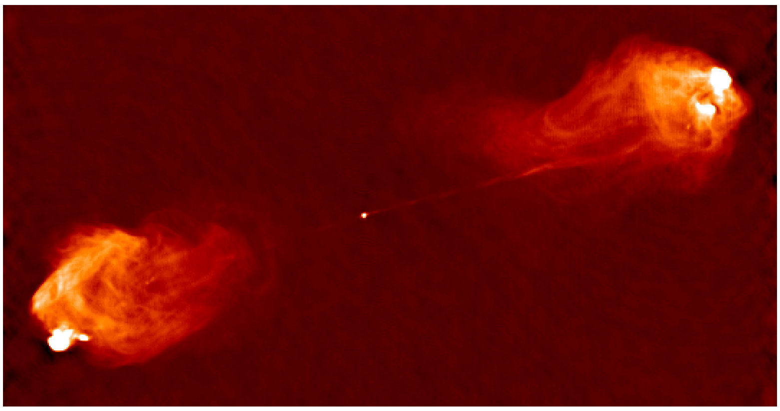


Fig. 13.0.3. A VLA map of Cygnus A. © National Radio Astronomy Observatory

known as 'very-long-baseline interferometry' (VLBI). VLBI was first mooted in the Soviet Union and implemented in 1967 in Canada and the USA. Progress in this area was dependent on better atomic clocks and wider-bandwidth tape recorders. It also required international cooperation and the setting of standards. VLBI networks were set up with the data correlated and processed centrally. The European VLBI network co-opted telescopes in China. A dedicated network in the USA, the Very Long Baseline Array (VLBA), replaced ad-hoc agreements. The VLBA often operate together with radio telescopes in Europe, and in particular with the 100m Effelsberg radio telescope. A separate network grew up in Japan and another one in Australia. The final extension of VLBI occurred when a radio telescope was placed in orbit by the Japanese space agency—this is known as the HALCA project. Numerous dishes in the 25m to 64m class were constructed with the dedicated aim of working in one of the VLBI networks. One of the spectacular discoveries of VLBI was that of the **superluminal motions** made in 1970. For masering spectral lines of OH and water vapour, VLBI provided source sizes and positions. Water masers have been used to estimate the mass of the centre of NGC 4258 and to estimate the Hubble constant, using the Nobeyama 45m radio telescope at first and later VLBI. The extension of VLBI to a wavelength of 1.3 millimetres will inevitably lead to the imaging of the event horizon of the source Sgr A*, the centre of our Galaxy. The centimetre emission from Sgr A* is likely to be optically thick synchrotron emission which becomes optically thin at short wavelengths. Thus images to the edge of the Schwarzschild radius require millimetre VLBI. Sgr A* is thought to be a supermassive black hole, so with millimetre VLBI we can study strong-field general relativistic physics close to home.

Space radio astronomy had its beginnings with the launch of the Ariel III cosmic radio experiment in 1967. In this simple experiment the cosmic noise was to be measured in the frequency range 2 MHz to 4 MHz, a frequency region not normally accessible to ground-based observations owing to the Earth's ionosphere. Later radio satellites concentrated on measurement at higher frequencies. The most prominent satellite in the mid-1980s was the ESA-NASA Infra Red Astronomy Satellite (IRAS) that provided a 1-arc-minute-resolution survey of the sky. The Soviet Union launched the satellite Relikt-1 in 1983 to study the CMB radiation at 37 GHz. Since this radiation peaks at a wavelength of about 1 mm, accurate measurements from the ground are difficult. IRAS was followed by the Infrared Space Observatory (ISO), which was used to study specific sources. With the NASA Cosmic Background Explorer satellite COBE it was shown that the spectrum is indeed black-body. This established that the 2.73 K background is most likely the remnant of the Big Bang, so that alternate theories are highly unlikely. The two principal investigators of COBE, G. Smoot and J. Mather, received the 2006 Nobel Prize. The continuation of COBE was the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, a NASA project that gave excellent results in high-frequency bands from 23 GHz to 94 GHz. PLANCK, a European Space Agency (ESA) satellite, is now at the Lagrangian 2 point and will progress this field of research. The Herschel Satellite Observatory, which was launched together with PLANCK in May 2009, is the most ambitious radio-infrared satellite project yet launched. The Herschel observatory is equipped with a 3.5m-diameter telescope that has three detector systems. The PLANCK satellite will survey the sky in 9 bands, from 30 GHz to 857 GHz, most of them with polarization data. Satellites use cooled detector systems and hence have a finite lifetime. They become space debris once their useful life comes to an end, usually owing to a lack of coolant. Hence we have no durable and authentic heritage satellites in space. Some pre-engineering models or copies do find their way into museums.

The development of millimetre-wavelength astronomy in the 1970s progressed with the construction of 14m- to 20m-diameter telescopes in radomes, but then progressed further with the construction of millimetre and sub-millimetre observatories at high and dry sites. The Institute for Radio Astronomy in the Millimetre Wavelengths (IRAM), a French-German-Spanish organization with headquarters in Grenoble, operates a 30m telescope at the 2850m-high Pico Veleta site in Spain and a millimetre interferometer on the 2552m-high Plateau de

Bure in France. The Caltech Sub-millimeter Observatory (CSO) built a 10m dish and a UK-Dutch-Canadian consortium built the 15m James Clerk Maxwell Telescope (JCMT) on the 4200m-high Mauna Kea site in Hawaii. The 15m Swedish-ESO Sub-millimetre Telescope (SEST) was erected at ESO's La Silla site in Chile. The National Astronomy Observatory of Japan constructed a 45m telescope and a millimetre interferometer in Nobeyama. The 10m Heinrich-Hertz-Telescope on a 3200m-high site at Mount Graham, Arizona, became operational in 1998. At Green Bank, as a result of the collapse of the 300ft transit telescope in 1988, a replacement was constructed, named the Robert C. Byrd Green Bank Telescope. The GBT, a 100m × 110m offset paraboloid reflector, became operational in 2000. In the quest for even better sites the 12m dish for the APEX sub-millimetre telescope was constructed on the 5105m-high Chajnantor plateau in Chile. In addition, the Japanese 10m telescope project ASTE became operational on a high site in Chile. A sub-millimetre interferometer (SMA) came into operation on Mauna Kea. Nearing completion is the Large Millimetre Telescope (LMT) on a 4600m-high site in Mexico. At the best sites, measurements can be made from ground-based telescopes up to a frequency of 1.3 THz, a wavelength of λ ~300µ. At the very best sites on Earth, it may be possible to extend measurements to somewhat higher frequencies. One of the sites now being extensively tested is Dome C in Antarctica. An intermediate between ground-based observatories and satellites is the airborne observatory SOFIA (Stratospheric Observatory for Infra-Red Astronomy). SOFIA is a US-German project that uses a 747 aircraft. It has a 2.5m telescope with an optical quality. It should begin science operation in 2010.

Until recently, ground-based radio astronomy relied on national incentives or the cooperation of a small number of individual nations. Examples of smaller cooperations are IRAM (France-Germany-Spain) and the JCMT (UK-Netherlands-Canada). The first global project that has brought together Europe, North America and East Asia is the ALMA millimetre project on the Chanjantor site in Chile. ALMA will have at least 66 antennas of 12m diameter and some of 7m diameter, making it the largest such facility on Earth. At low radio frequencies the goal is to build a Square Kilometre Array (SKA). The SKA will be preceded by smaller pathfinder projects such as the Low-Frequency-Array (LOFAR) in Europe, the Allen Telescope Array in the USA, the Australia-SKA-Precursor (ASKAP) in Australia and the Karoo Array Telescope (KAT) project in South Africa. In China, radio astronomers have now embarked on the construction of a 500m spherical radio telescope in the Karst region of Guizhou province. This can be thought of as a larger version of the 1000ft (305m) Arecibo design.

The history of radio astronomy has been marked by startling discoveries. From the first measurements, it was clear that radio and optical astronomy produced very different views of the sky: from this beginning came the discovery of synchrotron radiation, then quasars, pulsars, molecules and molecular clouds, the CMB gravitational lenses, and so on. The implications of these discoveries are still in the process of gestation. From the CMB, it is clear that our universe began about 13.7 billion years ago in an explosive process. From the newest WMAP results, it appears that baryons make up only 4% of the matter in the universe, with the rest being Dark Matter and Dark Energy. In addition to studies related to fundamental aspects of physics, we hope to learn from studies of star formation how our solar system was formed and perhaps how life on earth began. The early radio telescopes that made these discoveries possible are now heading for 'heritage instrument' status. However, it is surprising to see how many of these old instruments are still in full operational mode. It will require considerable determination to secure the necessary funds to preserve old radio telescopes.

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