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Great Discoveries Made by Radio Astronomers During the Last Six Decades and Key Questions Today

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1. Introduction

An important window to the Universe was opened in 1933 when Karl Jansky discovered serendipitously at the Bell Telephone Laboratories that radio waves were being emitted towards the direction of our Galaxy [1]. Jansky could not pursue investigations concerning this discovery, as the Laboratory was devoted to work primarily in the field of communications. This discovery was also not followed by any astronomical institute, although a few astronomers did make proposals. However, a young electronics engineer, Grote Reber, after reading Jansky's papers, decided to build an innovative parabolic dish of 30 ft. diameter in his backyard in 1935 and made the first radio map of the Galaxy in 1940 [2].

The rapid developments of radars during World War II led to the discovery of radio waves from the Sun by Hey in 1942 at metre wavelengths in UK and independently by Southworth in 1942 at cm wavelengths in USA. Due to the secrecy of the radar equipment during the War, those results were published by Southworth only in 1945 [3] and by Hey in 1946 [4]. Reber reported detection of radio waves from the Sun in 1944 [5]. These results were noted by several groups soon after the War and led to intensive developments in the new field of radio astronomy.

In Section 2 are summarized radio observations of the Sun and of the massive coronal mass ejections that disrupt satellites and terrestrial power grids. In Section 3 are described discoveries of the powerful radio galaxies and quasars that indicate the presence of supermassive Black Holes of millions of solar mass at the centre of galaxies. In Section 4 is described the great controversy that arose between the Steady State theory and the Big Bang Model in 1961, after Martin Ryle and colleagues noted excess counts of weaker radio sources in the catalogue made by them using radio interferometers. I then describe observations of angular size of a large number of weak radio sources made with the Ooty Radio Telescope using the method of lunar occultation; their statistics indicated the evolution of the radio sources with cosmic epoch, consistent with the Big Bang Model. In Section 5 are described the important discovery of the Cosmic Microwave

Background radiation (CMB) by Penzias and Wilson in 1965 and later its detailed observations with higher angular resolution by Mather *et al.* in 1990 with the COBE satellite and by Bennett *et al.* in 2003 with the WMAP satellite; these observations have given a firm support to the Big Bang Model, indicating that the Universe is dominated by 74% dark energy, 22% dark matter, and 4% ordinary matter. Observations of the HI emission from the spiral galaxies and attempts to measure the epoch of re-ionization are summarized in Section 6. The serendipitous discovery of the Pulsating Radio Sources (Pulsars) is described in Section 7. Observations of more than a hundred molecules in the interstellar medium and megamasers are summarized in Section 8. Developments of earth's rotation synthesis radio telescopes for high-resolution observations of celestial radio sources are described in Section 9. In Section 10 are discussed some of the Key Questions today concerning the Universe. Conclusions are given in Section 11.

In this brief review, pioneering observations and discoveries are described at first, followed by descriptions of the current status. The references are not exhaustive and only indicative.

2. Radio Studies of the Sun and Solar Wind

Soon after the end of the War in 1945, a few groups, particularly in Australia and the UK, started detailed observations of radio emission from the Sun, using existing radar equipment to begin with and later with interferometers. In 1946 and 1947, Pawsey and colleagues found that: (a) solar corona has a temperature of about one million degrees, (b) solar radio emission has a slowly varying component related to sunspot area and (c) there occur intense radio bursts associated with the flare activity [6]. Ryle and colleagues also measured angular sizes of solar emission associated with sunspots and also its circular polarization confirming the predictions by Martyn and by Appleton and Hey. These discoveries led to the development of two major facilities in Australia for investigating characteristics of the solar radio emission. Wild and colleagues [7] developed a swept frequency solar radio spectrograph that led to major classifications of solar radio bursts: (a) Type I, as noise storms, (b) Type II caused by outward ejections of matter with velocities of hundreds of km that cause plasma oscillations at successive higher levels of the solar corona and (c) Type III, caused by ejections of matter of ~1/3rd of the velocity of light. Type IV was later identified by French workers, Type V by Wild and colleagues and Type U by Maxwell and Swarup. In 1953, Christiansen and Warburton constructed an innovative grating array in order to make two-dimensional maps of the radio emission from the Quiet Sun [8]. During the last 60 years, these pioneering observations have been pursued in great detail by scores of workers and have provided very valuable information about the solar activity [9]. Of particular importance are the massive coronal mass ejections (CMEs) that derive their tremendous energy from the stressed magnetic fields by the sunspot activity on the Sun causing large disturbances on the earth. CMEs have also been associated with the coronal holes. Observations of the interplanetary scintillations of ~1000 compact components of distant radio galaxies and quasars are being done on a daily basis over a large part of the sky around the Sun by Manoharan and colleagues using the Ooty Radio Telescope in India [10]. These observations provide information about variations of the solar wind and also acceleration of the coronal mass ejections affecting the earth. During the last 15 years, X-ray and coronagraphic observations of the Sun by the SOHO satellite of NASA have provided valuable data about the quiet and active Sun. NASA's STEREO has revealed the 3D structure of the CMEs. Japanese and Russian agencies have also built solar observatories in Space.

3. Radio Galaxies, Quasars, and Black Holes

3.1. Radio Galaxies

I describe firstly the remarkable story of the discovery of Cygnus A and its optical identification with a distant galaxy. In 1945 Hey, Parson and Phillips in the UK noted fluctuations in the intensity of cosmic radio noise towards the direction of the Cygnus constellation [11]. Their antenna had a very broad beam. In 1947 Bolton and Stanley determined its source size as ~8 arc-minute using a 'sea interferometer', consisting of an antenna placed on a hill at Dover Heights towards the Pacific Ocean in Australia that produced interference fringes as the source rose from the horizon [12]. In 1951, Graham-Smith measured its position to an accuracy of ~1 arc-minute using a radio interferometer [13]. Thereafter, Baade and Minkowski made observations in that direction with the 200 inch (5 m) Mt. Palomar telescope and identified Cygnus A with a perturbed galaxy having a recession velocity of 17000 km s^{-1}, corresponding to a redshift of 0.06 implying a distance of ~1000 million light years, much further than any other known optical galaxy at that time [14]. In 1953 using an intensity interferometer of about one arc-minute resolution, Jenison and Das-Gupta found that Cygnus A is a double radio source [15]. Since Cygnus A has a very high flux density, it became clear that it should be possible to detect much weaker radio sources up to large distances using sensitive radio telescopes and thus distinguish between various cosmological models, as discussed in the next Section.

At that time there was great controversy about the physical processes giving rise to the very powerful radio emission. Brehmstrahlung radiation by hot bodies was totally inadequate. It was concluded in 1954 that radio emission is caused by 'synchrotron radiation' when electrons with relativistic velocities spiral in the presence of magnetic fields resulting in radiation of extremely high power. Observations of the predicted polarization gave support to the theory.

By 1950, using rather modest equipment, Australian and UK radio astronomers had catalogued ~50 discrete radio sources. A few were associated with known galaxies such as Virgo A and Centaurus A. Later, Martin Ryle and his group constructed radio interferometers using parabolic cylinders with large collecting area at Cambridge in UK and catalogued more than 250 radio sources across the northern sky by 1960. By then, Bernie Mill and colleagues in Australia also catalogued a few hundred radio sources, mostly across the southern sky, using the Mills-Cross using dipole arrays. At first, there was great controversy concerning the overlapping portions of the two catalogues but it was resolved soon with better measurements by the Cambridge group, resulting in the well-known 3C catalogue.

Since the wavelength of radio waves is quite large, radio interferometers with spacing of many kilometers are required for making detailed radio images of celestial sources with arcsec resolution, as is now possible using synthesis radio telescopes that are described in Section 9. Today, thousands of radio galaxies have also been mapped with sub-arc second resolution. Very long baseline interferometers (VLBI) have provided even milli-arcsec resolution. About 13 years ago, Japanese astronomers placed a 10m diameter parabolic dish orbiting in space and combined it with ground radio telescopes on Earth in order to study a few compact radio sources with 0.0001 arcsec resolution. To date, millions of extragalactic radio sources have been catalogued by various workers. A major challenge has been to make optical identification, although it has become easier after the usage of CCDs on optical telescopes. Yet, a large number of radio sources have remained unidentified with galaxies, as most of the weaker radio sources are likely to have much higher redshifts, requiring large optical telescopes to observe fainter galaxies.

We next summarize the nature of radio galaxies. As described earlier, radio galaxies are millions of time more energetic than normal galaxies. A radio galaxy is generally a double or triple source, with two outer radio lobes and a central component associated with a supermassive Black Hole at the centre of the galaxy. The central active galactic nuclei (AGN) give rise to jets of relativistic electrons and positrons, and also slower protons, in two opposite direction that result in radio lobes at the two opposite extremities (see Figure 1, p. 357).

3.2. Quasars (QSO)

3C273 is a compact quasi-stellar radio source (quasar). In 1963, Martin Schmidt concluded from the known spectral lines of 3C273, which hitherto were found to be very puzzling as their occurrence could not be explained by any stellar process, that the spectra consisted of Balmer lines of hydrogen and were Doppler shifted corresponding to a redshift of 0.158, the highest known redshift at that time [17]. This conclusion indicated immediately the existence of a new class of celestial objects in the Universe. 3C273 is an optically bright galaxy with a magnitude of 13. It is a compact radio source having not only a radio jet but also optical and X-ray jets. Subsequently, a large number of quasars have been discovered, the brighter ones mostly by Australian radio astronomers using the Parkes Radio Telescope at 5GHz. Radio and optical surveys have indicated that quasars are associated with galaxies that have active galactic nuclei (AGN). Many AGNs are found only at optical wavelengths and are called Quasi Stellar Objects (QSO). A large number of QSOs have also been catalogued by optical surveys; a few have been identified even at redshifts > 6. Many QSOs are found to be radio loud but a large number are radio quiet. Many QSOs are also strong X-ray sources, with the X-ray emission arising close to the Black Holes located at the centre of AGNs. X-ray observations have provided important information about Black Holes, such as their spin and properties of the surrounding Accretion disks that feed matter into the Black Holes from the associated galaxies.

Unified models of active galaxies indicate that jets of energetic particles emanate from the AGNs moving outwards at relativistic velocities. If the jet is beamed towards the observer, the radio emission from the central component, that generally has a flat spectrum, gets relativistically beamed and thus AGN is observed as a quasar with flat spectrum. If one of two jets is at a larger angle to the observer, radio emission only from that jet is seen as shown in Figure 1 (see. page 357). The unified model also explains observed optical spectra of the AGNs, which depend on the orientation of the axis of tori around the central Black Holes.

3.3. Black Holes in the Universe

Although the presence of massive Black Holes at the centre of active galaxies was firstly established by radio astronomy observations, their existence has been firmly established by extensive radio, optical and X-ray observations. It has now been concluded that almost all galaxies have supermassive Black Holes of several millions, some even billions, of solar mass. Our Galaxy has a Black Hole of about one million solar mass. The matter from the outer parts of a galaxy spirals into the Black Hole, forming a torus and an accretion disk around the Black Hole. Although it is not yet clear as to how jets are created, it has been suggested that a large magnetic field near the centre of AGN gives rise to the jets of energetic particles. However, not all galaxies are powerful radio sources. Stellar-size Black Holes have also been discovered in our Galaxy.

OJ287 is the largest Black Hole observed to date. It is considered to be an object of ~100 million Suns in a binary orbit around a Black Hole of ~17 Billion Suns. OJ287 was first detected in 1970s in the Ohio Radio Sky Survey. From its radio and optical observations, it is classified as a BL Lac object (with featureless continuum emission). It is located 3.5 billion light years away. It has produced many quasi-periodic optical outbursts going back approximately 120 years, as apparent on photographic plates from 1891 (Wikipedia).

4. Radio Astronomy and Cosmology

In 1929 Hubble made a remarkable discovery that *the farther away is a galaxy from us, the faster it is moving away*. His observations indicated that the Universe is expanding and provided support to Father Lemaitre's 1927 paper that was based on the framework of the General Theory of relativity. These results gave rise to the Big Bang Model, according to which the Universe was extremely energetic and tiny in the beginning and has continued to expand thereafter. As an alternative to the Big Bang theory, in 1948 Hoyle, Bondi and Gold proposed the Steady State Theory, according to which new matter is created continuously as the Universe expands [18].

By 1960, Martin Ryle from Cambridge had catalogued ~250 radio galaxies. He concluded from the 'radio source counts' that weaker radio sources are much more numerous supporting the Big Bang model [19], (see Figure 2). However, Hoyle questioned the implicit assumption by Ryle that the weaker sources are located far away. The above arguments immediately led to a great controversy between the Big Bang model and the Steady State Theory.

In order to distinguish between the Big Bang and Steady State models, I decided in 1963 to measure angular sizes of a large number of weak radio sources, as radio sources located far away were expected to have smaller angular sizes. At that time, angular sizes of extra-galactic radio sources had been determined with sufficient accuracy for a few dozen sources only. Further, no suitable radio interferometers with sufficiently large sensitivity and arcsec resolution were in the offing. Hence, I decided to use the lunar occultation

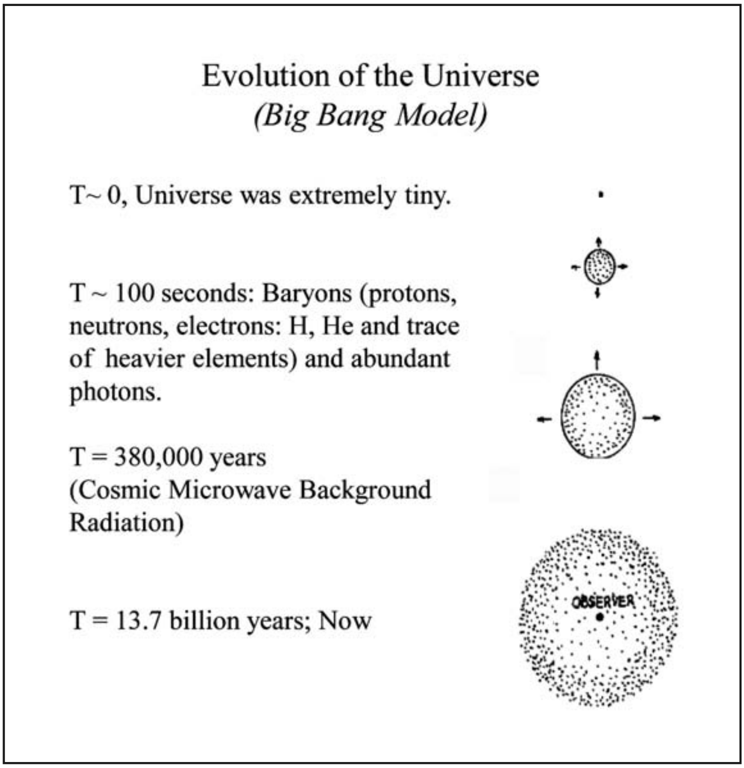

Figure 2. The sketch indicates evolution of the Universe according to the Big Bang Model. The Model predicts that weaker radio sources located far away would be much more numerous compared to those nearby (assuming no evolution of luminosities with cosmic epoch).

method for the purpose. I proposed and directed construction of a cylindrical radio telescope of a large size, 530m long and 30m wide that was located on a hill at Ootacamund (Ooty), with its long axis parallel to that of the earth, taking advantage of India's location close to earth's equator. Using the Ooty Radio Telescope (ORT), we measured angular sizes of ~1000 weak radio sources with arcsec resolution using the method of lunar occultation. We found that the weaker sources of smaller flux densities had smaller angular size, compared to angular size of stronger 3C sources with higher flux densities. Also, our results indicated cosmic evolution of radio sources, thus providing independent evidence of the Big Bang Model [20, 21].

5. Big Bang Model and the Cosmic Microwave Background (CMB)

5.1. Big Bang Model

According to Big Bang Model, the Universe originated from an extremely energetic state at a very early epoch. Based on the measured values of the fundamental constants, we can derive the Planck time of 5×10^{-44} seconds as a possible era of the Universe soon after its creation. It is considered that Space and Time originated at that epoch. Active areas of quantum mechanics, quantum gravity and string theories are attempting to answer the question as to what was before the Big Bang but this area of research is still at an early stage. In 1980 Guth proposed that soon after the Big Bang the Universe went to a very rapid inflation by a factor of 10^{120}. The inflationary model explained certain dilemmas such as the homogeneity of the Universe and the horizon problem. The inflationary model also predicted occurrence of small-scale irregularities with a flat power spectrum that have been measured by the Cosmic Microwave Background radiation, as described below. Certain predictions of the above cosmological model are constituents of the Grand Unification Theory of Particle Physics and are subject to experimental verification that is being done by the Large Hadron Collider and other large accelerators.

In the Big Bang Model, matter consisting of protons, electrons and neutrons formed in the Universe when its temperature decreased from $\sim 10^{11}$ to $\sim 10^{9}$ K at epochs of ~0.1 s to 100 s. The Model predicts abundance of ~0.76% of hydrogen and ~0.24% of helium-4, and a much smaller fraction of deuterium, helium-3 and lithium-7 with respect to the baryon density of the Universe. Many observations of abundance of these elements made over the last few decades are found to be consistent with the predictions of the Big Bang Model. The Model also predicts occurrence of a very large density of photons due to annihilation of electrons, positrons, etc. at the early cosmic epoch of tens of seconds. The Cosmic Microwave Background (CMB) Radiation originated after the photons stopped interacting with matter as the temperature of the Universe decreased to ~3000 K when electrons and protons combined. Detailed observations of the CMB have provided a strong foundation to the above Model as described below.

5.2. Cosmic Microwave Background (CMB)

In 1965, Penzias and Wilson made a serendipitous discovery that there exists an all sky Microwave Background Radiation (CMB), corresponding to blackbody temperature of ~3 K [22]. The Nobel Prize was given to them in 1978. This radiation had been predicted to occur in the Big Bang Model and therefore gave strong support to the Model. It could not be explained in the Steady State Theory.

During the 1990s the COBE satellite designed by John Mather and George Smoot showed that the CMB radiation corresponded to a perfect blackbody radiation of 2.7 K (Figure 2), with minute anisotropies as expected in the Big Bang Model (Figure 3) [23]. The Nobel Prize was given to them jointly in 2006.

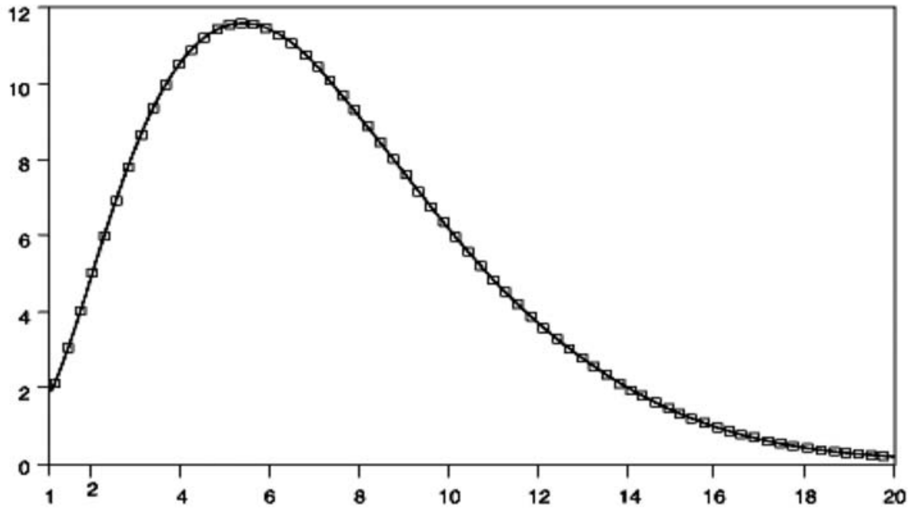

Figure 3. Vertical axis gives brightness (10^{-4} erg/sec/cm^{2}/steradian/cm^{-1}). Horizontal axis gives Frequency (cycles/cm) [23].

Soon after observations of the CMB made by Penzias and Wilson, a question arose as to what are the seeds of structure in the CMB that gave rise to the formation of galaxies later by gravitational collapse. A major support to the Big Bang Model came after the detections of predicted fluctuations in the CMB of about 1 part in 100,000 by the COBE data, as described by Smoot *et al.* [24]. The WMAP observations described by Bennett *et al.* have a much higher resolution of ~0.3 degrees that show detailed structure up to sub-horizon scale as shown in Figure 4 [25] (see p. 358).

5.3. Standard Cosmological Model

Evidence for the occurrence of dark matter in the Universe was first postulated by Zwicky in the 1930s by measuring velocities of galaxies in galaxy clusters. Its occurrence became established from the Flat Rotation curves that were observed optically by Rubin and Ford in 1970 [26], and by HI observations made by Robert and Whitehurst in 1975 [27] and Bosma in 1978 [28]. The presence of dark matter in the Universe is supported independently from observations of gravitational lensing of distant sources by the intervening clusters. Further, detailed observations of the velocities of various galaxies in clusters have provided an estimate of the dark matter density.

Based on observations of distant supernovae, a surprising conclusion was made about a decade ago, by Riess *et al.* [28] and Perlmutter *et al.* [29] that the Universe is accelerating, indicating the presence of dark energy (with negative pressure). From a detailed analysis of the WMAP observations, also using some of the earlier measurements, Spergel *et al.* [31] concluded that the Universe is dominated by 74% dark energy, 22% dark matter, and 4% ordinary matter as observed in stars and galaxies. The WMAP data provides accurate estimates to ~ ± 10% of several fundamental parameters, such as H_0, Ω_0 etc. of the cosmological model. Thus, it has been suggested that we have now entered an era of 'Precision Cosmology'. The recently launched Planck satellite will provide more precise measurements of the CMB concerning the cosmological model. Polarization measurements of CMB may test predictions of inflation.

6. The 21 cm Emission Line of Neutral Hydrogen (HI)

After reading the 1940 paper by Reber giving the radio map of the Galaxy, Professor Jan Oort wondered whether there were any spectral lines in the radio window (he got a copy of the paper even though the Netherlands was occupied during the World War II). His student, van de Hulst, made a path-breaking calculation in 1944 that the two closely-spaced hyperfine energy levels in the ground state of the neutral hydrogen atom (HI) emit radiation at a frequency of 1420.4058 MHz. Emission of the predicted HI line was observed in 1951 towards the Galaxy by Ewen and Purcell [32], and was soon confirmed by Australian and Dutch astronomers. Subsequently, its high-resolution observations delineated the spiral structure of the Galaxy for the first time. It may be noted that optical observations of the spiral structure are limited to close distances only, due to the presence of dust in the Galaxy. HI observations have now been carried out for a large number of spiral galaxies and dwarf galaxies. HI observations also provide information about the formation and evolution of galaxies, as hydrogen is the basic ingredient of stars and galaxies that are formed by its gravitational collapse. All the heavier elements are formed at the centre of stars by fusion. Their subsequent collapse leads to supernova and also interstellar clouds where molecules are found.

Observations of HI from very distant galaxies provide important clues about the evolution of galaxies. The most distant galaxy detected so far has a redshift of 0.18. By co-adding HI emission of a large number of galaxies in a cluster with measured redshifts, average content of HI in distant galaxies up to z ~0.8 has been estimated. With the Square Kilometer Array (SKA), it would be possible to measure HI of individual galaxies up to z ~3. HI absorption studies towards distant quasars have also been very fruitful. An important area of research is to search for the epoch of reionization of HI that is expected to occur prior to the redshift of about 6, soon after formation of first stars and galaxies. LOFAR, MWA and SKA described in Section 9 may determine this epoch.

7. Pulsars

In 1967 Antony Hewish and his student Jocelyn Bell were observing interplanetary scintillations of compact components of radio sources at Cambridge in the UK using a recently constructed array for that purpose. They discovered serendipitously that pulsed radio emission with a highly accurate periodicity occurred in the direction 1919+21 (right ascension and declination) [33]. Soon a few other pulsed radio sources were found and were called Pulsating Radio sources (Pulsars). The Nobel Prize was given to Anthony Hewish for the discovery of Pulsars in 1974; also to Martin Ryle for developing innovating radio techniques and for studies of radio galaxies, as described in Sections 3 and 9.

Due to their highly accurate periodicities, Gold [34] suggested that pulsars are associated with neutron Stars, being the end product of stars when their nuclear fuel runs out (giving rise to a supernova remnant and a neutron Star). Due to the collapse of the parent stars and conservation of their angular momentum, neutron stars start spinning at a fraction of second. Their magnetic field becomes tens of billions of Gauss, resulting in coherent beamed radiation in the direction of their magnetic poles. If the rotation and magnetic axes are misaligned, periodic pulsed emission is observed on each rotation, analogous to that observed from a lighthouse. About 1700 pulsars have been catalogued so far. Many pulsars with millisec (ms) periodicities have also been discovered. Their precise periods correspond to highly accurate clocks, matching or exceeding atomic clocks, and therefore provide important tests of the General Theory of Relativity. A set of millisecond pulsars may allow detection of the primordial gravitational radiation, which is predicted by the inflationary model. An emission mechanism of Pulsars was suggested by Goldreich and Julian in 1969 soon after their discovery [35], but it has not been able to explain many observations. Many attempts are being made to find a satisfactory emission mechanism.

The first Binary Pulsar, 1913+16, was discovered by Hulse and Taylor in 1975. According to the General Relativity theory, a binary star system should emit gravitational waves. The loss of orbital energy results in shrinkage of its orbit. From accurate timing of the pulse period of the binary pulsar 1913+16, Weisberg and Taylor concluded in 1983 that the orbit of the pulsar is shrinking due to the gravitational radiation as predicted by the Einstein's General Theory of Relativity [36]. Recent observations have confirmed that its orbit continues to shrink as expected. The Nobel Prize was given to Hulse and Taylor in 1993 for this discovery.

8. Molecules and Megamasers

In 1963 Weinreb *et al.* discovered absorption lines of the interstellar molecule OH at 1665 and 1667 MHz [37]. The NH_3 molecule was found in the interstellar medium by Townes and collaborators in 1968. Over 140 molecules have been discovered till now in interstellar and circumstellar clouds in the Galaxy, including some with 13 atoms. The molecule CO has also been detected in nearby galaxies and in faraway galaxies including the distant quasar at z = 6.42. A recent finding by Iglesias-Groth *et al.* (MNRAS in Press) suggests that some of the key components in terrestrial prebiotic chemistry are present in the interstellar matter.

The OH maser in emission was discovered towards HI regions in the Galaxy in 1965. The first OH megamaser was observed in 1982 towards the nearest ultra-luminous infrared galaxy, Arp 220 [38]. Radiation occurs close to galactic nuclei. Their measurements have provided mass of the central Black Hole. Due to their powerful emission, OH megamasers have now been observed in many faraway galaxies. Megamasers of water (H_2O), formaldehyde (H_2CO) and methane (CH) have also been observed. Recently, Kanekar, Chengalur and Ghosh have made accurate measurements of the OH transition lines in galaxies at higher redshifts to investigate whether Fundamental Constants, such as the fine structure constants, change with cosmic epoch. Their results are suggestive but require further investigations.

9. Radio Telescopes

I list here only some of the major radio telescopes in order to indicate the type of instruments that have allowed frontline research in radio astronomy.

9.1. Synthesis Radio Telescopes

Since the wavelength of radio waves is quite large, it becomes necessary to use radio interferometers with large spacing in order to map radio sources with adequate resolution. In the 1940s Australian radio astronomers led by Pawsey used firstly a sea interferometer and later spaced interferometers. It was recognized that a pair of interferometer measures one Fourier component of a radio source and by using many spacings its map can be obtained by inverse Fourier transform. In the 1950 Christiansen built a grating interferometer for mapping the Sun. Mills and Little built a cross-type antenna, known as Mills Cross. Ryle and colleagues also started to build radio interferometers soon after 1946. During the late 1950s the Cambridge group, led by Ryle, built several sensitive interferometers and later employed for the first time the principle of earth's rotation synthesis radio interferometer for carrying out radio surveys [39] (Nobel Prize 1974). This technique has been exploited by a number of radio telescopes built in the world over the last 6 decades. Currently, the prominent radio telescopes using this principle are: (1) Westerbork Synthesis Radio Telescope in the Netherlands in 1971; (2) Very Large Array in USA in 1980; (3) Australia Telescope Array in 1990 and (4) Giant Metrewave Radio Telescope in India in 1999.

Several major synthesis-type radio telescopes with large sensitivity, high resolution and wide frequency coverage are being built now using new technologies, particularly, ALMA in Chile, LOFAR in Europe, LWA in USA, MeerKat in South Africa and ASKAP in Australia. MWA being developed by MIT, RRI and others is also likely to be located in Australia. Most ambitious is the international SKA radio telescope likely to be built by 2020 with contributions by more than 17 countries. SKA will provide extraordinary capability, with a collecting area up to 1 million sq. km, baselines of several hundred km and a wide frequency range.

9.2. Large aperture single radio telescopes

Single radio telescopes with a large collecting area allow special observations, such as spectral line observations, pulsar research etc. A major breakthrough was the construction of a 76 m diameter parabolic dish in 1957 conceived by Bernard Lovell. A 64 m diameter parabolic dish became operational at Parkes in 1961. A 100 m diameter dish was built at Bonn in 1972. A 100 m diameter dish with 2000 servo controlled panels to allow operation at mm wavelengths was built at Green Bank in the USA in 2002. The Arecibo Telescope built in 1971 has the largest collecting area amongst single aperture radio telescopes. It consists of part of a sphere of 300 m diameter fixed on the ground, with a steerable dish of about 25 m diameter placed near its centre allowing pointing in different directions over ~ ± 20 degrees of the zenith. A similar radio telescope of 500 m diameter, called FAST, is under construction in China.

10. Some Key Questions Today

I list below five key questions that are amongst the major objectives of the proposed SKA. The document 'Science with the Square Kilometer Array' gives extensive details of a wide number of astronomical objectives of the SKA [40].

Q.1: What is ultra-strong field limit of relativistic gravity?

Increased sensitivity of radio telescopes will discover many more pulsars and may find a pulsar in orbit around a Black Hole and near the galactic centre. Accurate timing of a large number of milli-second pulsars may detect primordial gravitational radiation as has been predicted to occur during very rapid inflation of the Universe in the Big Bang Cosmology.

Q.2: What is origin and evolution of the Cosmic Magnetism?

Radio Astronomy is uniquely placed to determine the evolution of a magnetic field from early times to now, through studies of Faraday rotation of polarization of synchrotron radiation in distant radio galaxies, and also observations of Zeeman splitting. As an example, the radio map of the nearby galaxy M51 at a wavelength of 6 cm show distribution of a large-scale magnetic field along the spiral arms. Observations of Faraday rotation of synchrotron emission of radio halos in distant clusters at high redshifts could become possible with SKA and thus may give a clue about the origin and evolution of cosmic magnetism.

Q.3: What are the processes about the formation and evolution of galaxies in the Universe?

The measurements of the unique 21 cm (1420 MHz) radiation of neutral hydrogen (HI) from a large number of galaxies up to large distances would provide important information about the formation and evolution of galaxies and of cosmology.

Q.4: When did the first stars form and neutral hydrogen get reionized?

Theoretical predictions, computer simulations and WMAP measurements indicate that the first stars and galaxies collapsed gravitationally from the primordial neutral hydrogen (HI) at redshifts of about 30. Later, neutral HI got ionized by UV by about redshift of ~6. Details of the epoch of Reionization are of great importance for studies of structure formation in the Universe, requiring measurements of emission and absorption of HI in the frequency range of about 50 to 200 MHz.

Q.5: Is there intelligent life search elsewhere in our Galaxy?

The proposed Square Kilometer Array (SKA) will allow studies of radio emission from extra-solar planets and Search for Extraterrestrial Intelligence (SETI) towards millions of stars.

10. Conclusion

Radio astronomy observations have revealed occurrence of truly violent phenomena in the Universe such as those occurring in radio galaxies and quasars, indicating the presence of supermassive Black Holes in the nuclei of the galaxies. One of the greatest discoveries of the last century was that of Cosmic Microwave Background Radiation which provided support to Big Bang cosmology. Its detailed observations combined with other astronomical data have indicated that visible matter is only 0.04%, dark matter 0.26% and dark energy 0.7% of matter density in the Universe. Discovery of line emission of neutral hydrogen (HI) allows investigations of the formation and evolution of galaxies and their dynamics. Observations of a binary Pulsar by Hulse and Taylor have provided evidence of gravitational radiation predicted by the General Theory of Relativity. Over 140 molecules have been discovered in the interstellar medium of our Galaxy. These molecules are ingredients of life on earth and raise the question of whether life exists elsewhere. There are many major questions today for which the ambitious SKA project that is likely to materialize by 2020 may provide a clue.

Over the last few decades, additionally to the radio window, sensitive observations made at X-Rays, UV, optical and infrared parts of the electromagnetic spectrum have provided important information about the physical processes in stars and galaxies. This multi-wavelength astronomical research may give us further insight into the mysteries of the Universe.

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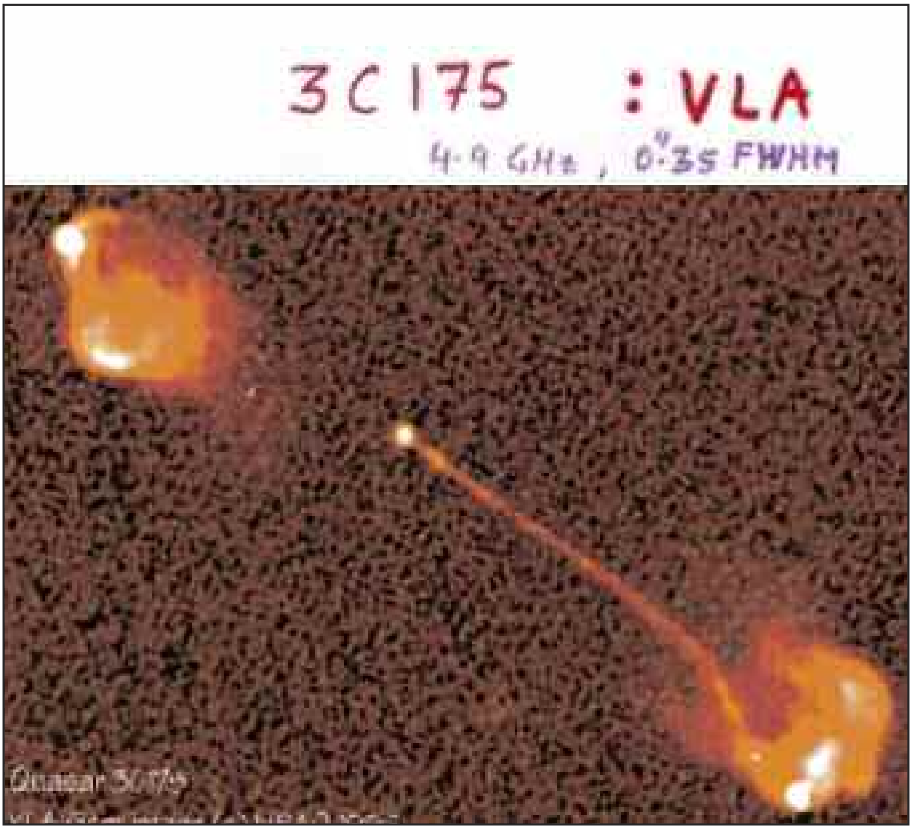

Figure 1. A radio map of the Quasar 3C175 made by Bridle *et al*. [16] with a resolution of 0.35 arc-sec, using the Very Large Array (VLA), showing a central compact radio source coincident with an optical galaxy at a redshift z =0.768, a jet of radio emission on one side (most likely towards the observer) and the two outer radio lobes. The lobes occur as the relativistic plasma ejected by the central active galactic nuclei in two opposite directions suffers shock by the intergalactic medium. The overall linear size of 3C175 is about 1 million light years.

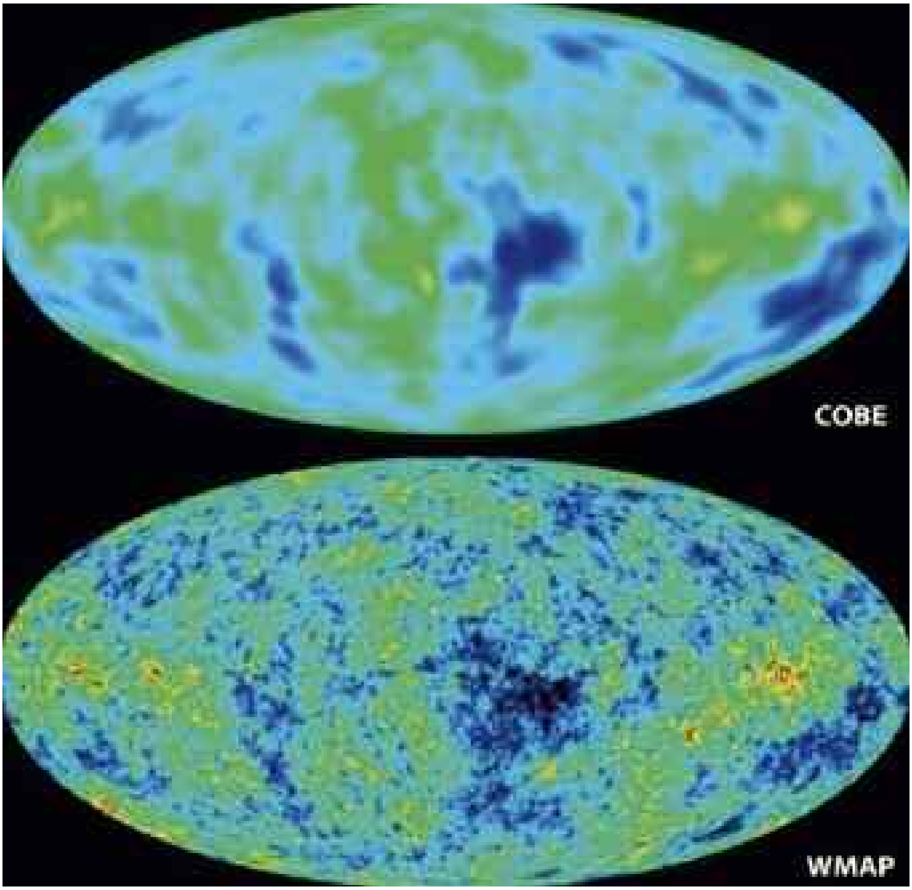

Figure 4. Fluctuations were detected in the Cosmic Microwave Background Radiation of about 1 part in 100,000 by the COBE satellite in 1992, as shown in the upper panel with an angular resolution of ~10 degree [24]. The WMAP observations shown in the lower panel have sufficient angular resolution of ~0.3 degree that clarifies detailed structure up to sub-horizon scale [25].