# Growth and Development of Radio Astronomy in India

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# Chapter 5
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## 5.1 Introduction

### 5.1.1 Early Years of Radio Astronomy

Radio astronomy is the study of the universe through naturally produced radio waves reaching us from a variety of celestial objects. Over the last 60 years, many extraordinary celestial objects and phenomena have been discovered by radio astronomers that have revolutionized our understanding of the universe. This new science was born when Karl Jansky (1933) serendipitously discovered that radio emission in the form of radio noise was being emitted from the direction of the Milky Way, our galaxy. This discovery remained unnoticed by optical astronomers and physicists for many years. In 1935 Grote Reber, a young amateur radio engineer, constructed a 10 m diameter parabolic dish in his backyard and succeeded to make a map of the Milky Way (Reber 1940). Development of radar during World War II resulted in the discovery of radio emission from the sun (Hey 1946a; Reber 1944; Southworth 1945). The publication of these results soon after the end of the war, led to the establishments of active radio astronomy groups mainly in Australia and UK, who investigated the nature of radio emission from the sun and also discovered several discrete radio sources associated with objects in our galaxy and distant galaxies. These remarkable discoveries led to worldwide interest in the great potential of the radio window of the electromagnetic spectrum for exploration of the universe, resulting in development of many outstanding radio telescope facilities in the world as well in India.

In 1945 Australian radio astronomers found that radio emission from the sun had two main components: (a) the radio emission from the quiet sun was estimated to have a temperature of $\sim 10^6 K$ and (b) that from active sun (solar radio bursts) exceeded $10^{11} K$. Ginzburg (1946) and Martyn (1946) independantly considered thermal emission to arise from the solar corona with kinetic temperature of $\sim 10^6 K$. Saha (1946) considered excitation of the energy levels of the nuclei and atoms and molecules by a strong field near sunspots but its contribution was not considered significant by observers (Pawsey 1950). Saha (1946) also postulated radiation at the gyro frequency but its escape was not permitted by severe attenuation at the plasma frequency layer at higher levels (Martyn 1947).

The discoveries of radio emission from celestial bodies were keenly noted by astronomers, physicists and students in India. M. K. Das-Gupta from the Institute of Radiophysics and Electronics (IRPE), Calcutta, went to work at the Jodrell Bank Observatory in UK and made a path-breaking discovery that the strong radio galaxy, Cygnus A, was a double radio source (Jennison and Das-Gupta 1953). M.R. Kundu after graduating from IRPE went to France and got the Ph.D. degree working on a high resolution radio interferometer operating at centimetre wavelengths. T.K. Menon went to Harvard in 1951.

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### *5.1.2 Growth of Radio Astronomy in India*

Monitoring of the solar radio emission was started at the Kodaikanal Observatory in 1952. In 1952, Sir K. S. Krishnan, Director of the National Physical Laboratory (NPL), New Delhi, attended the General Assembly of the International Radio Scientific Union (URSI) held at Sydney. He was very impressed by the discoveries being made by Australian scientists in the new field of radio astronomy. Krishnan arranged deputation of the author (G. Swarup) of NPL and R. Parthasarathy of the Kodaikanal Observatory for 2 years during 1953–55 under a Colombo Plan fellowship at the Radiophysics Division of the Commonwealth Scientific and Industrial Research (CSIRO), Australia. In 1955, CSIRO agreed to gift to NPL 32 parabolic dishes of 1.8 m diameter, which formed the grating array built by W.N. Christiansen in 1952 at Potts Hill, near Sydney, and were being dismantled as a new radio telescope was being built by Christiansen (Swarup 2006, 2008). On return from Australia, Swarup and Parthasarathy joined NPL in 1955. Since the transfer of the dishes got delayed, they went to USA in 1956. During 1956–58, NPL attracted N.V.G. Sarma and M. N. Joshi after their M.Sc., T. Krishnan after his M.S. from the University of Cambridge and M.R. Kundu after his Ph.D. in France. Later Kundu joined the University of Michigan, Krishnan went to work at the University of Sydney in Australia. Sarma went on deputation for 2 years to work on a radio telescope at the University of Leiden and Joshi to France for a Ph.D. degree in radio astronomy; both returned to NPL in 1962 or so. Later during 1963–1965, Swarup, Sarma, Joshi and Kundu joined the new radio astronomy group that was formed at the Tata Institute of Fundamental Research (TIFR), Mumbai, in 1963 (see Section 5.2). It may be noted that although NPL was not able to provide suitable support for the growth of radio astronomy therein, it nurtured a group that later joined TIFR. Over the last 45 years, two world class radio astronomy facilities have been built in India by TIFR at Udhagamandalam (Ooty) and near Pune as described in Section 5.2. Astronomy with the Glant Metrewave Radio Telescope (GMRT) is described in Section 5.3. The development of radio astronomy at the Indian Institute of Astrophysics (IIA), Bengaluru, is described in Section 5.4, at the Raman Research Institute (RRI), Bengaluru, in Section 5.5, and at the Physical Research Laboratory (PRL), Ahmedabad, in Section 5.6. Conclusions and future thrusts are discussed in Section 5.7.

## 5.2 National Centre for Radio Astrophysics of TIFR (NCRA/TIFR)

### *5.2.1 Brief History*

In September 1961, four radio astronomers working abroad, M.R. Kundu, T. Krishnan, T.K. Menon and the author (G. Swarup) wrote a ‘proposal for the formation of a radio astronomy group in India’ and sent it to several scientific organizations in India. Dr. Homi Bhabha, the great visionary and founder Director of TIFR met T.K. Menon in Washington DC in USA and “indicated outlays of Rs. 50–100 lakhs if the group fulfils the expectations”. He sent a telegram to the above four persons on January 20, 1962 stating that TIFR has decided to establish radio astronomy group, a prompt action indeed by any standards in the world (Swarup 1991).

The radio astronomy group got established after I joined TIFR in April 1963. Sarma and Joshi joined in 1964 and played a critical role in the development of the Ooty Radio Telescope (ORT). M.R. Kundu joined the group in 1965 and returned to USA in 1968; T.K. Menon joined in 1971, after $\sim$ 20 years in USA, and returned to join the University of Vancouver in Canada in 1974; contributions by both were very important in the growth of the radio astronomy of TIFR in its early years. In Section 5.2.2 are described four radio telescopes built by the group over the last four decades. Subsequent sections present some of the highlights of the group’s work, which spans a variety of topics in the fields of solar, galactic and extragalactic radio astronomy. Radio Astronomy Group was originally located at TIFR, Bombay (now Mumbai). The Radio Astronomy Centre (RAC) of TIFR was formed at Ootacamund (now Ooty) in 1966. The TIFR Centre at Bangalore for radio astronomy was established at Bangalore in 1977 and got shifted to the National Centre for Radio Astrophysics of TIFR at Pune that was formed in 1987. NCRA has now academic headquarters of the group at Pune with observational facilities at Ooty in Tamil Nadu and the GMRT centre $\sim$ 80 km north of Pune near Khodad in Maharashtra.

## *5.2.2 Research Facilities*

### 5.2.2.1 The Kalyan Radio Telescope

As a first step, the newly formed radio astronomy group of the TIFR, set up a grating-type radio interferometer at Kalyan near Bombay in 1965 for observing the sun at a frequency of 610 MHz (Swarup et al. 1966). The interferometer consisted of 32 parabolic dishes of 1.8 m diameter that were gifted by CSIRO, Australia to the NPL and later transferred to TIFR. Twenty-four dishes were placed along a 630 m east-west baseline and eight along a 256 m north-south baseline, giving an angular resolution of 2.3 arc-min × 5.2 arc-min (Figure 5.1). The telescope was used for studying the quiet and active regions of the sun during 1965–68. It was found that the quiet sun had considerable limb-brightening at 610 MHz and that the solar corona had a temperature of ∼ $10^6$K (Figure 5.2) (Sinha and Swarup 1967). Solar radio bursts were also observed at 610 MHz. The Kalyan Radio Telescope was disbanded in 1968 as the group got involved in the ambitious ORT described in the next Section.

**Fig. 5.1** Twenty-four dishes of the EW array of the Kalyan Radio Telescope at 610 MHz (Swarup et al. 1966)

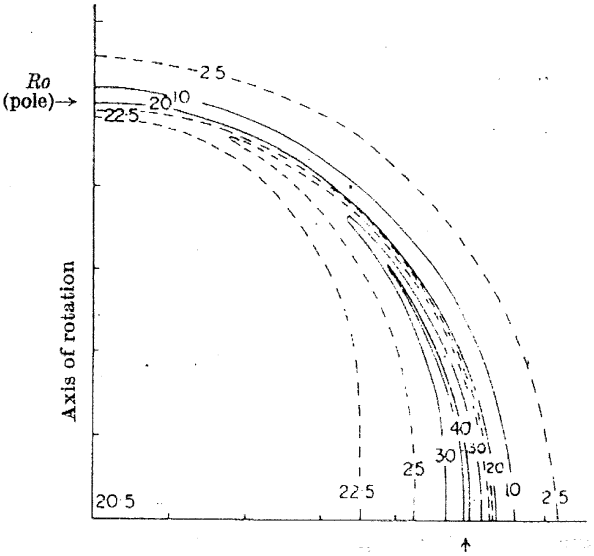

**Fig. 5.2** Brightness distribution of the solar radio emission at 610 MHz (Sinha and Swarup 1967)

#### 5.2.2.2 The Ooty Radio Telescope

As stated in the 1961 proposal that was sent to Bhabha and others (see Section 5.2.1), our initial idea for a major radio astronomy facility was to set up a large Mills Cross operating at a wavelength of about 2*m* in India. However, the ionospheric scintillations that are prominent in India due to its close location to the magnetic equator seemed a cause of worry. In early 1960s there was a great controversy between the Big Bang model and the Steady State model for explaining the origin and evolution of the universe. During late 1950s, Martin Ryle and colleagues at the University of Cambridge had plotted number versus intensity of $\sim 200$ radio sources discovered by them and found an excess of weaker radio sources. By assuming that the weaker radio sources are located far away, Ryle supported the Big Bang model. However, Fred Hoyle, proponent of the Steady State model, questioned the above assumptions. For distinguishing between the above models, measurement of angular sizes of a large number of weak radio sources seemed important but suitable radio interferometers providing arc-sec resolution were not available anywhere in the world at that time. Hence I proposed to exploit the lunar occultation method to measure angular structure of a large number of radio sources that required a large steerable radio telescope. This proposal resulted in the ORT. It was the first major facility in India which firmly established the country on the world map of radio astronomy.

The ORT consists of a 530 m long and 30 m wide parabolic cylinder (Figure 5.3) Its design makes full use of India's proximity to the geographical equator. The unique feature of this telescope is that its long axis is aligned in the north-south direction along a hill which has a natural slope of about $11^\circ$, the geographical latitude of Ooty. Thus the long axis of rotation of the telescope becomes parallel to the earth's rotation axis, enabling the telescope to track radio sources in the sky by a simple mechanical rotation of the parabolic frames in the east-west direction. The pointing in the north-south direction is achieved by electronic phasing of the 1056 dipoles placed along the 530 m long focal line of the parabolic reflector. A useful declination range of $\pm 60^\circ$ can thus be covered. The signals picked up by the dipoles are combined with suitable phase shifters to form 12 independent beams designed to cover the lunar disk. The reflecting surface is made up of $1,100$ thin stainless steel wires running parallel to each other for the entire length of the cylinder. The surface is supported by 24 parabolic frames on towers located 23 m apart. ORT operates at a frequency of 325 MHz (Swarup et al. 1971). It provides an effective collecting area of $\sim 8,500$ m$^2$. The receiver system was upgraded in 1993 by placing a RF amplifier and a phase shifter after every dipole, increasing its sensitivity by a factor of 4 (Selvanayagam et al. 1993). Recently a digital system has been installed by the RRI group (Prabu 2008). The RF bandwidth of the ORT is about 16 MHz.

**Fig. 5.3** ORT consists of a 530 m long and 30 m wide parabolic cylinder with its long axis parallel to that of the earth; the long white streak on right side is reflection of 1,100 stainless steel wires by the sunlight (Swarup et al. 1971)

#### 5.2.2.3 The Ooty Synthesis Radio Telescope

The resolution of a telescope, in units of radian, is given by the ratio of the wavelength of radiation divided by the size of its aperture. At a wavelength of $\sim 1$ m, we require the aperture size to be nearly 200 km to get a resolution of 1 arc-sec, that is available in fact for a mere 10 cm size of a lens of an optical telescope.

Alternatively, in order to achieve high resolutions at radio wavelengths, radio astronomers have developed radio interferometer systems over the last 60 years, starting from a simple 2-antenna interferometer to the complex synthesis radio telescopes built today. A synthesis radio telescope consists of several antennas located over a large area that measure the coherence pattern of the incoming wave front received from a distant celestial radio source. It is readily shown that a 2-antenna interferometer measures one Fourier component of the brightness distribution of the celestial source with its value depending on the separation of the antennas. With n antennas, we measure $n(n-1)/2$ Fourier components. With the rotation of the earth, the projected separations of the antennas change continuously and thus for an array of only 20 or 30 antennas millions of values are recorded. An inverse Fourier transform is carried out in powerful computers using sophisticated self-calibration algorithms that yields radio image over the entire field of view of the component antennas of the array. By 1980s, several powerful synthesis radio telescopes had been built in UK, Netherlands, and Australia. These were designed to work at cm and dcm wavelengths (at frequencies of $\sim 1,400$ MHz to over $10,000$ MHz), particularly to obtain high angular resolution for finding fine structure of celestial radio sources. Soon after the completion of the ORT it was decided to build the Ooty Synthesis Radio Telescope (OSRT) operating at 325 MHz (see next paragraph) and later the powerful GMRT operating in the frequency range of $\sim$ 130 MHz to $1,430$ MHz (see Section 5.2.2.5), thus complementing radio telescopes elsewhere in the world.

The OSRT used the principle that the effective area of a pair of antennas, A1 and A2 is given by $(2A_1A_2)^{0.5}$. Since ORT has a large area (500 m × 30 m), we built seven smaller antennas of size 23 m × 9 m and one of 92 m × 9 m in an array of $\sim$ 4 km in extent (Swarup 1984). Signals from three nearby antennas were brought to a central receiver system using coaxial cables and that from far away antennas by means of radio-telemetry. OSRT was equivalent to a 4 km radio telescope giving a resolution of about 1 arc-min at 92 cm wavelength. OSRT was used for studying many galactic and extragalactic radio sources. A few of the results obtained are described in Section 5.2.2.3. The OSRT project allowed the group to master complex UHF electronics and image processing techniques. It was dismantled in 1986 in order for the group to concentrate on a much more challenging GMRT project.

#### 5.2.2.4 Giant Equatorial Radio Telescope (GERT)

The success of the ORT led to the idea of building a much larger radio telescope quiet close to the earth's equator, say in Kenya or Indonesia, as a collaborative project between developing countries. The proposal was discussed with A. M. M'Bow, Director-General of UNESCO during his visit to TIFR in 1977. He was very enthusiastic about it and approved a grant of US$ 14,000 for holding an international workshop and visits to a few countries in Africa. Designs were developed and cost estimates were made for a steerable parabolic cylinder of 2 km long and 50 m wide and also 10 smaller cylinders of 100 $m \times 50$ $m$ to be placed up to 14 km away in order to form a synthesis radio telescope. A detailed report was prepared proposing the establishment of an International Institute of Space Sciences and Electronics (INISSE) and the Giant Equatorial Radio Telescope (GERT) by Swarup from India, Odhiambo from Kenya and Okoye from Nigeria (Swarup et al. 1979, 1984; Swarup 1981). During negotiations, Kenya's interest dwindled after President Kenyatta expired in 1978. In 1981 Dr. Hidayat of the Boschha Observatory, Indonesia, arranged a visit by an Indian team to W. Sumatra, where a site was located close to the earth's equator. In August 1983, President Suharto approved half of the estimated cost of US$ 20 million and India was to meet the other half. However, with the success of the VLA in 1980, development of the method of self-calibration and the newly developed optical fibre transmission technique for RF signals, it seemed to us that it should be possible to build a more flexible and powerful synthesis radio telescope at metre wavelengths in India. Therefore, the GERT became the GMRT! The Noble Laureate Tony Hewish, UNESCO Consultant, for GERT wrote to me in 1983 that his enthusiasm for the GERT decreased after Kenya lost interest.

#### 5.2.2.5 The Giant Metrewave Radio Telescope (GMRT)

Although most of the pioneering work in radio astronomy during 1940s and 1950s was done at metre wavelengths, many powerful radio telescopes were built subsequently at shorter wavelengths for obtaining higher angular resolution. *However, there are many outstanding astrophysical problems that can be studied only at metre wavelengths* ($\sim$0.2–10 m), such as observations of the redshifted $1,420$ MHz line emission of the neutral hydrogen (HI) from distant celestial objects. Many other phenomena can also be advantageously investigated at long wavelengths, such as studies of Pulsars or diffuse features in the radio brightness distribution of celestial radio sources. These considerations led to the GMRT proposal.

The GMRT consists of 30 fully steerable parabolic dishes, each of 45 m in diameter (Swarup et al. 1991). A noteworthy feature of the GMRT is its hybrid design. Fourteen antennas are located randomly in a compact array of ∼1 km × 1 km in size that allows mapping of the extended features of celestial radio sources with arc-min resolutions. Other 16 antennas are located along three Y-shaped arms for providing higher angular resolution (Figure 5.4).

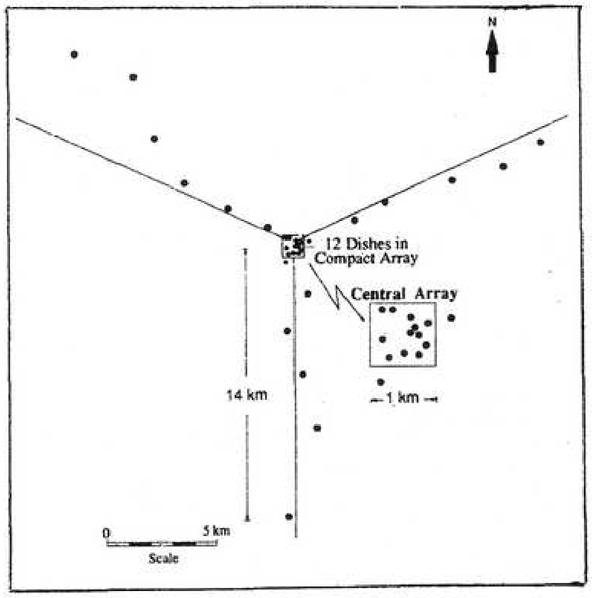

**Fig. 5.4** Array configuration of the 30 numbers of 45 m parabolic dish antennas of the GMRT (Swarup et al. 1991)

For parabolic dish antennas operating at microwave frequencies it is required to use aluminium sheets in order to get good reflectivity, but that are subject to large wind loads. For operation at decimetre and metre wavelengths, the reflecting surface of the dishes is often made of wire mesh panels in order to reduce wind loads than that for solid panels yet providing sufficient reflectivity. However, the supporting structure of wire mesh panels is often subject to large wind drag. A design breakthrough was made for the construction of the 45 m dishes. In order to obtain the required curved surface of parabolic dishes using wire meshes of a low solidity, specially developed for the GMRT, an innovative SMART concept (Stretched Mesh Attached to Rope Trusses) was used that also minimized the back up structure of the dishes (Figure 5.5). The wire rope network makes a mosaic of plane facets approximating a parabolic surface. The reflecting surface consists of stainless steel wire mesh of 0.55 mm diameter with a grid size of 10 mm × 10 mm in the inner one-third area, 15 mm × 15 mm in the middle part and 20 mm × 20 mm in the outer part of each of the 45 m dish. Thus it became possible to build 45 m dishes quite economically.

The primary antenna feeds of the GMRT are placed on a rotating turret near the focal point of each dish. The voltage signals received by the dual polarized feeds are amplified by low noise amplifiers and brought to a central point at intermediate frequencies and are applied to a digital correlator system that provides 256 frequency channels over a 32 MHz band. The correlator takes cross products of voltages received from all the 30 antennas, for each of the 256 channels that are finally stored in a computer system for image processing. The GMRT is currently operating in five frequency bands near 150 MHz, 235 MHz, 325 MHz, 610 MHz and 1000–1430 MHz . GMRT is now being upgraded to provide more or less continuous frequency coverage from ∼ 40 MHz to 1430 MHz and a bandwidth of ∼ 256 MHz or even ∼ 400 MHz The effective area of the GMRT antennas is 30,000 $m^2$ for the lower four frequency bands and $\sim 18,000\ \mathrm{m}^2$ near 1,430 MHz. GMRT is the most powerful radio telescope operating at metre wavelengths in the world.

**Fig. 5.5** A close view of a 45 m parabolic dish antenna of the GMRT. Ten far away antennas are seen in the background

## *5.2.3 Major Scientific Contributions by NCRA-TIFR*

The research contributions made by the radio astronomy group of TIFR during the last 45 years have been published in over 800 refereed papers. In Section 5.2.3.1 is presented contributions made during the years 1970 to 1998 mostly using the ORT, prior to the operation of the GMRT. In Section 5.2.3.2 are given interplanetary scintillation studies made with the ORT from 1970–2008. Research contributions made during the last 10 years using the GMRT are described in Section 5.2.3.3.

### 5.2.3.1 Highlights of Astronomy at Ooty

Although the ORT was conceived in 1963 for cosmological investigations (see Section 5.2.2.2), the radio astronomy group of TIFR has made many valuable contributions concerning cosmology, extra-galactic radio sources, galactic radio sources and interplanetary medium (see Sections 5.2.3.2–5.2.3.4 ). The contributions made during 1963–1988 are given in $\sim$ 250 papers and have been summarised by Swarup et al. (1991) During 1988–1998 there were about 200 papers and nearly 350 during 1999–2008 after the GMRT became operational. Here we give only a few highlights.

### 5.2.3.2 Radio Astronomy and Cosmology

In 1929, Hubble made a remarkable discovery that further a galaxy is located from us, faster it is moving away. This led to the Big Bang model for the origin and evolution of the universe. In 1948, Hoyle, Bondi and Gold proposed an alternate model, the Steady State model, in which the matter was created not just in the beginning but everywhere, say near the nuclei of galaxies, to explain the expanding universe.

Soon after World War II, a strong radio source was discovered towards the constellation Cygnus (Reber 1944), named later as Cygnus A. The observed flux density of radio waves from the Cygnus A nearly equaled that of the quiet sun, in contrast to the sun being millions of time brighter than stars or galaxies at optical wavelengths (Hey et al. 1946b). Based on its accurate position measured by Smith (1951), Baade and Minkowski (1954) identified it with a faint optical galaxy with a redshift of 0.06 that was several times more distant than that of any known galaxy at that time! The source was shown to be a double radio source with a separation between the two components of $\sim$ 1 arc-min (Jennison and Das Gupta 1953). By 1960 nearly 200 radio galaxies were catalogued using radio interferometers by English and Australian radio astronomers but only $\sim$ 30 could be identified with visible galaxies. It became clear that radio galaxies are located at cosmological distances and therefore their statistical properties could be used for distinguishing between cosmological models. As noted in Section 5.2.2.2, Martin Ryle from Cambridge plotted number counts versus flux density of $\sim$ 200 radio galaxies and concluded support for the Big Bang model. ORT was conceived to measure accurate positions and angular sizes of a large sample of radio galaxies as described below. These observations allowed us to study cosmological evolution of radio galaxies and other active galaxies.

Determination of the redshift of a rather compact quasi-stellar radio source (quasar) 3C 273 as 0.158 by Martin Schmidt (1963) indicated existence of a new class of celestial object in the universe. 3C 273 is optically bright with a magnitude of 13. By $\sim$ 1980s QSOs were identified up to redshift, z $\sim$ 4 and today beyond $z \sim 6$. Many of these sources are radio loud quasars (RLQ) but large numbers are radio quiet quasars (RQQ). High resolution observations made at metre wavelengths by the TIFR group have provided independent support to the unified models concerning radio galaxies and QSOs, as discussed below.

*Lunar Occultation Observations*: The ORT tracked the moon daily during 1970–1978, (except during 1972–73), for a general survey of the sky that provided one-dimensional brightness distribution along two or more directions across $\sim 1,000$ galactic and extragalactic radio sources of flux density >0.6 Jy. These observations provided high resolution of $\sim$ 1–10 arc-sec at 325 MHz. It was the best resolution achieved at that time for a large number of weak radio sources. Subrahmanya (1975) developed an innovative 'positivity constraint' for image restoration. The data was used for studies of galactic and extragalactic radio sources and cosmology.

*Cosmological Studies:* Using the occultation observations, Swarup (1975) derived a relation between angular size, $\theta$, and flux density, S, for radio galaxies for the first time. It was found that the median value of angular size, $\theta$m, varies from $\sim$ 100 arc-sec for the nearby strong radio galaxies with $S_m \sim$ 10 Jy to 10 arc-sec for $S_m \sim$ 0.6 Jy (Figure 5.6). Kapahi (1975) combined the radio source counts, N(S) and $\theta_m - S_m$ relation and concluded that not only the space density of radio sources was higher but also their angular size was smaller at earlier cosmic epochs. This result was not consistent with the Steady State model and indicated evolution of radio sources with cosmic epoch. It provided support to the Big Bang model, independently to the discovery of the cosmic microwave background radiation by Penzias and Wilson (1965). Subsequently $\theta_m - S_m$ relation has been investigated in detail by a number of workers using radio interferometers (Figure 5.7) (see Kapahi 1989 for a review). It was extended up to lower flux densities by Mark Oort with a median value of $\sim$ 1 arc-sec at 1 mJy.

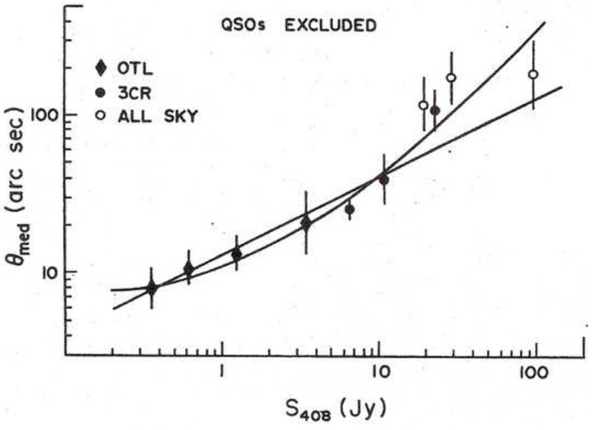

**Fig. 5.6** The curved line in the Figure shows a relation between the median value of angular size of radio galaxies versus their flux density (Swarup 1975)

*Angular Size-Redshift Relation*: Later when redshift estimates became available for a large sample of radio galaxies, it became possible to investigate the angular size-redshift relation directly (Figure 5.8). A steep evolution of linear sizes, $l$, with redshift $z$ was determined as $l \,\alpha\, (1+z)^{-3}$, and also a mild dependence on radio luminosity, $l \,\alpha\, P^{0.3}$ (Kapahi 1989). During 1976–1988 cosmological evolution of linear sizes and radio luminosity functions (RLF) were investigated in several papers indicating that the linear sizes were smaller on an average at higher redshifts (at earlier cosmic epochs), possibly due to higher density of the intergalactic medium at earlier cosmic epoch.

*Spectral Index-Flux Density ($\alpha$-S) Relation:* The flux density values of the Ooty occultation sources at 325 MHz were combined with measurements made at higher frequencies using other radio telescopes (Gopal-Krishna and Steppe 1982). This provided an additional constraint on the RLF. Miley and others have shown that radio sources with steep spectral index, say $\alpha >\sim 1.3$, $(S \propto \nu^{\alpha})$ are often located at higher redshifts, allowing to search for radio galaxies at earlier cosmic epochs and thus investigations of cosmic evolution of

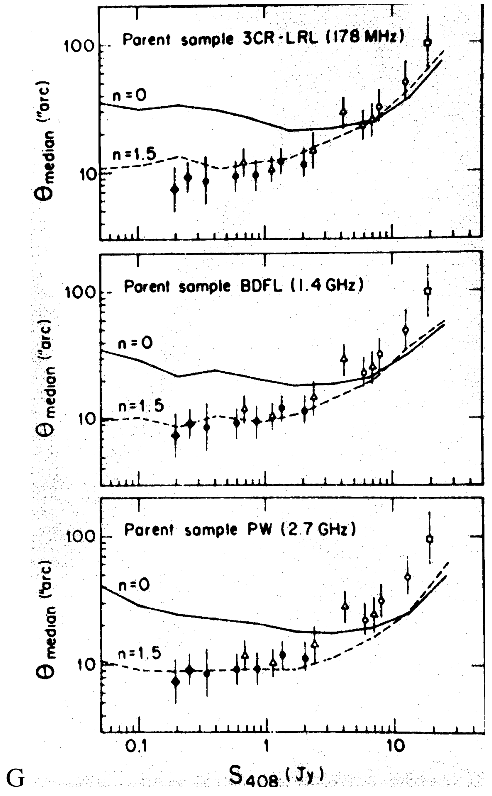

**Fig. 5.7** Shows a comparison between predictions of evolutionary models of radio luminosity function and the observed angular size-flux density relation (Kapahi et al. 1987)

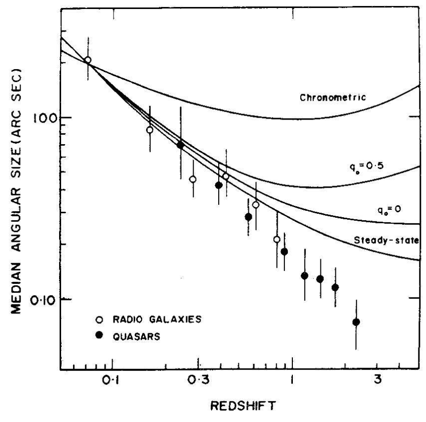

**Fig. 5.8** Open and filled circles show values of the observed median angular size of radio galaxies revealing a steep evolution of linear sizes with redshift z (Kapahi 1987)

radio galaxies. Interesting question and possible answer for the dependence of the steeper spectral index for high redshift radio galaxies has been investigated by Kapahi and Kulkarni (1986), Gopal-Krishna (1988), and Athreya and Kapahi (1998).

*Search for Primordial Hydrogen*: According to the Big Bang model, electrons, protons neutrons and sea of photons formed in the first few minutes after the origin of the universe at temperatures of tens of million degrees and thus constituted ∼ 74% of hydrogen ∼ 26% of helium and only a trace of other light elements such as lithium and deuterium. After a few million years the universe cooled and electrons and protons combined to form neutral hydrogen. Subsequently structure formed in the universe by gravitational collapse. Thus condensates of massive primordial neutral hydrogen (HI) are expected to occur in the universe prior to the formation of galaxies. Observations were made with the ORT at 325 MHz during 1980s and indicated that

Zeldovich Pancake with mass $5 \times 10^{15} M_0$ did not form at $z = 3.3$, as predicted by the hot dark matter models (Subrahmanyan and Swarup 1990). Observations made using the VLA by Subrahmanyan and Anantharamiah (1990) put upper limits to the HI mass of $\sim 10^{14} M_0$. The above studies and also stronger support to the Cold Dark Matter model by astrophysicists by mid 1980s indicated to us the requirement of a much larger radio telescope for exploring the era of galaxy formation and that led to the GMRT project described in Section 5.2.2.5.

*The Deuterium Abundance:* Deuterium is predicted to have been produced in the first few minutes after the Big Bang. The measurement of its abundance relative to hydrogen is of considerable cosmological importance. Observations by Sarma and Mohanty (1978) from the Ooty group and Anantharamiah and Radhakrishnan (1979) from RRI put an upper limit to the D/H ratio, in contrast to the positive detection reported previously by the Caltech group.

### 5.2.3.3 Radio Galaxies, Quasars and Active Galaxies

Radio galaxies and quasars are the most energetic celestial objects in the universe. The radio luminosity of the normal galaxies is $10^{37}$ erg $s^{-1}$, star-burst galaxies typically radiate $10^{40-41}$ erg $s^{-1}$ whereas that of radio galaxies and quasars is several magnitude higher up to $\sim 10^{45}$ erg $s^{-1}$. It is now well established that these highly energetic objects are associated with active galactic nuclei (AGNs) that are powered by massive black holes with masses of tens to hundreds of million solar masses. AGNs give rise to jets of relativistic particles that interact with the intergalactic gas and emit radio waves by synchrotron process (see e.g. Burke and Graham-Smith 1997). In recent years extensive observations have also been done of the AGNs and associated active galaxies at infrared, optical, ultraviolet and X-ray wavelengths. Observations at metre wavelengths have provided valuable complimentary information about these objects such as their age, cosmological evolution, etc.

While the occultation survey discovered mostly uncatalogued radio sources providing their accurate positions and structures, predicted occultation of several well known radio sources were used to compare the brightness distributions at 92 cm wavelength with that available from the aperture-synthesis observations made at shorter wavelengths (Gopal-Krishna and Swarup 1977; Gopal-Krishna 1977). It was found that diffuse features believed to be filled with energy-depleted features did not show the anticipated brightening at metre wavelengths, constraining the evolutionary model of the radio sources (Figure 5.9). However, many radio galaxies do show spatial variation of spectral index that provide estimates of the ages of the radio galaxies. Menon (1976) compared brightness distribution of a selected sample of sources from the occultation survey at 327 MHz with the observations made with the 3-element Green Bank array and derived spectra of various sub-components.

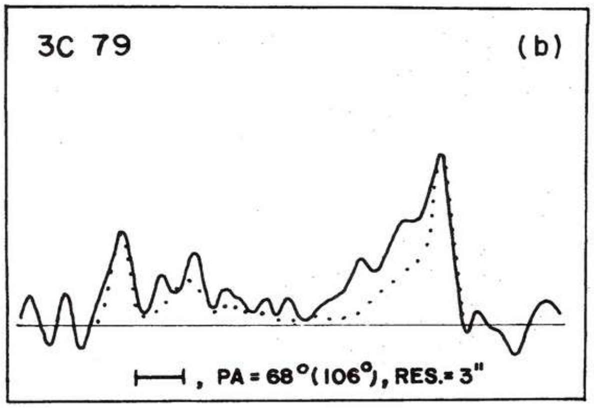

**Fig. 5.9** The solid curve shows brightness distribution derived from the Ooty occultation observations at 325 MHz; the dotted curve that derived from strip integration of the 5 GHz Cambridge map (Gopal-Krishna and Swarup 1977)

*Compact Radio Sources and Gigahertz Peak Radio Sources*: A new class of '*compact radio sources*' were identified by Kapahi (1981) from high resolution observations of a complete sample from a 5 GHz survey, made using the Westerbork Array. The much lower incidence of such sources in low-frequency surveys was attributed to a turnover in their spectrum at several hundred MHz. Gopal-Krishna et al. (1983) identified a large number of related and important class of '*gigahertz peaked spectrum (GPS) sources*'. Extensive work has been done on these interesting classes of radio sources by many workers during the last 25 years as they provide valuable information about the intergalactic medium and central regions of young active galaxies.

*Relativistic Beaming and Unification of Quasars and Radio Galaxies:* Some of the earliest tests to verify the possibility that the radio galaxies and quasars are related were done by Gopal-Krishna et al. (1980), Kapahi (1981b) and Kapahi and Saikia (1982). While radio galaxies are mostly extended double radio sources with relatively weak central component, quasars have prominent central components with prominent jets. Investigations showed that their differences arise due to the viewing angle with respect to the axis of their radio jets consistent with the predictions of the relativistic beaming model and the 'unified scheme' developed independently by Orr and Browne (1982). Observed asymmetries in double radio sources were investigated (Gopal-Krishna 1980; Saikia 1984).

*Gravitational Lens 1830–21:* This uniquely bright pair of flat-spectrum radio knots separated by just 1 arc-sec was discovered serendipitously in the course of a galactic Plane Survey of scintillating extragalactic radio sources using the ORT (Rao and Ananthakrishnan 1984; Rao and Subrahmanyan 1988). Subsequently, the source was observed with the VLA and was explained by the core of a distant radio quasar being lensed by an intervening galaxy (Figure 5.10) (Subrahmanyan et al. 1990). Jauncey investigated it further and considered it as the first example of Einstein's ring. Extensive studies have been made of this source by many workers.

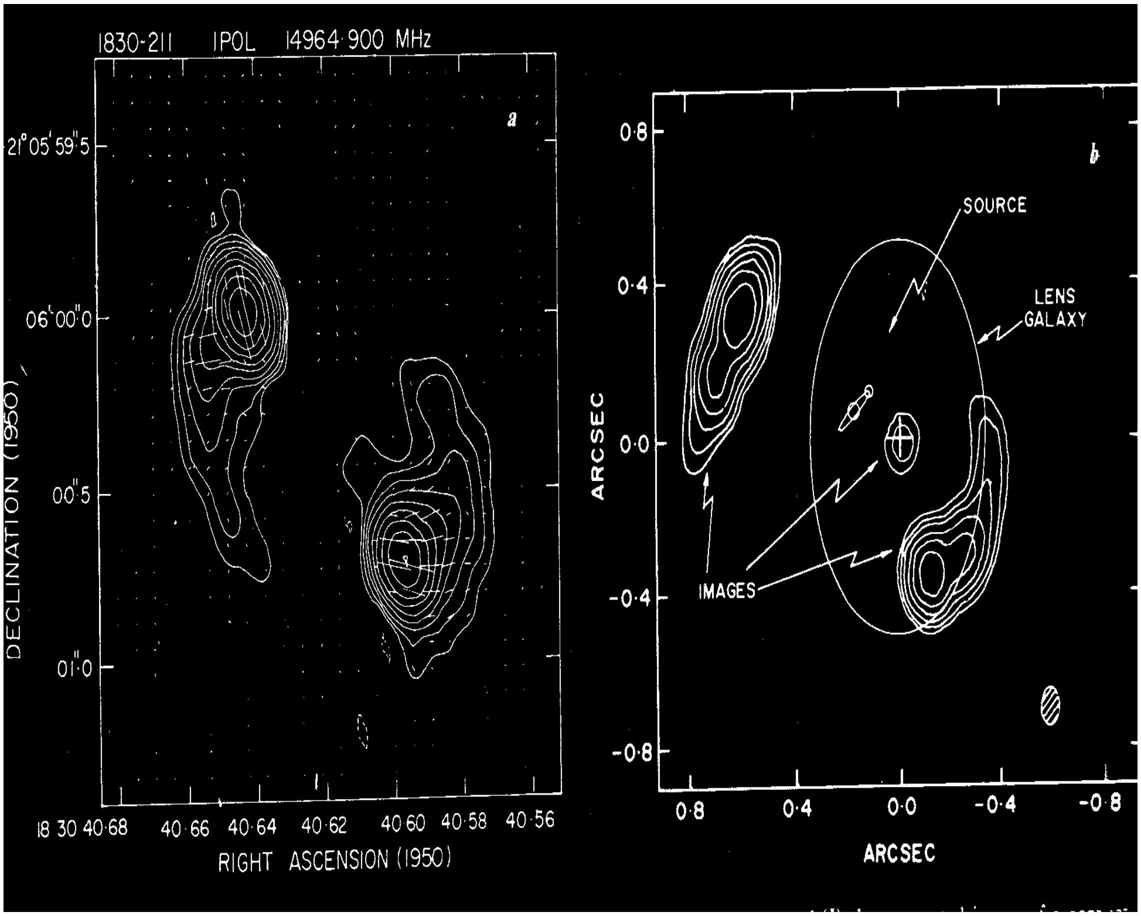

**Fig. 5.10** The left figure shows the observed map of the double flat spectrum radio source made with the VLA at 11 GHz. Right Figure shows a derived image of a distant radio quasar with a core and a jet lensed by an intervening galaxy (Subrahmanyan et al. 1990)

*The Giant Radio galaxy 0503-286:* This radio source with a size of 2.5 Mpc (Figure 5.11) is one of the largest known radio galaxy in the Southern Sphere and was independently discovered using the OSRT by Saripalli et al. (1986) and with the Molongolo Synthesis Telescope (Subrahmanya and Hunstead 1986) Observations of the Giant Radio Galaxies provide information about the luminosity of the nuclear regions of these galaxies, inverse Compton scattering and constraints on the physical properties of the intergalactic medium.

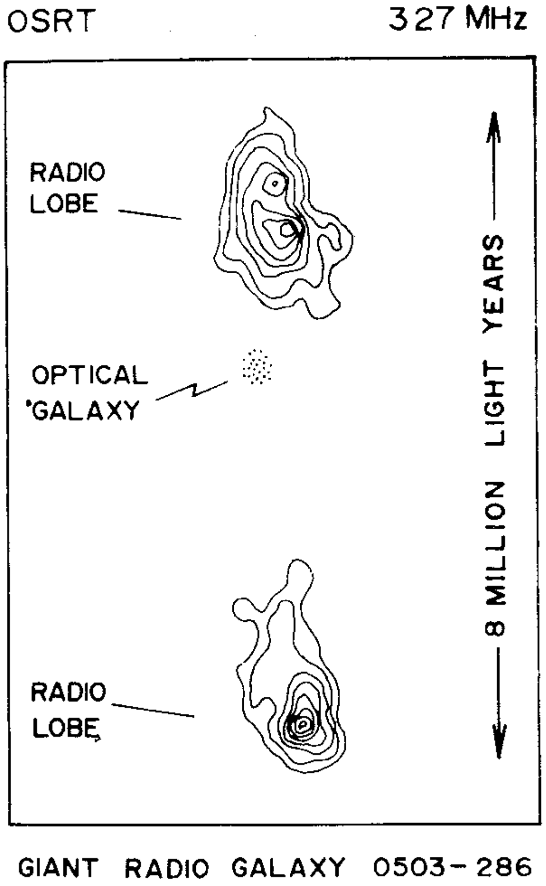

**Fig. 5.11** The Giant Radio galaxy 0503-286 discovered in 1986 is nearly 8 million light years across (Saripalli et al. 1986)

*Observations of Low Frequency Variables:* A well-defined sample of 100 flat-spectrum radio sources was monitored over several months at 325 MHz. It was found that the low frequency variability supported RISS model; a relation giving dependence of the variability with the galactic latitude was derived (Figure 5.12; Ghosh 1990).

*An Ultra Steep Relic Source in Abell 85:* As part of an extensive study of clusters of galaxies, an ultra steep spectrum radio source without any obvious optical counterpart was discovered in Abell 85 (Figure 5.13) (Joshi et al. 1986). This source has evinced considerable observational and theoretical interest by several workers in the last few years.

### 5.2.3.4 Galactic Objects

Radio emission has been observed from a variety of objects in our galaxy, ranging from the Jupiter, sun, neutral HI gas in spiral arms, non-thermal emission, recombination lines from interstellar gas, ionized hydrogen HII regions, molecular clouds, pulsating radio sources (pulsars), micro-quasars, galactic centre, etc. Radio astronomers in India have made observations of most of the above objects using metre wave radio telescopes built in India and also used international facilities. Here we describe some of the results obtained with the ORT by the TIFR group. In Section 5.3 are given observations made with the GMRT and in Sections 5.4, 5.5 and 5.6 are some of the results obtained by IIA, RRI and PRL.

*The Galactic Centre:* The radio source Sgr-A associated with the centre of our galaxy is one of the strongest radio source in the sky. The Ooty occultation observations of Sgr-A at 325 MHz were combined with the

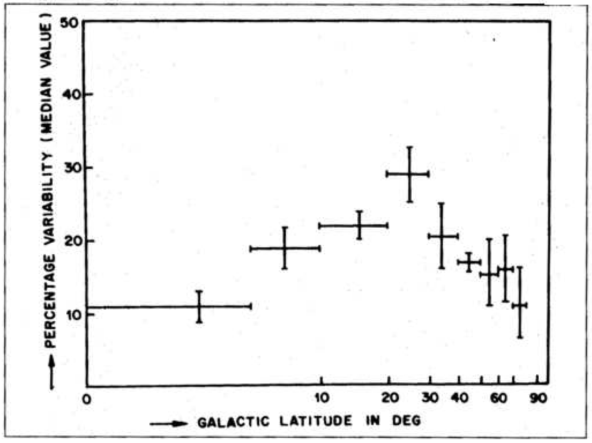

**Fig. 5.12** Dependence of percentage variability of radio sources on galactic latitude by RISS

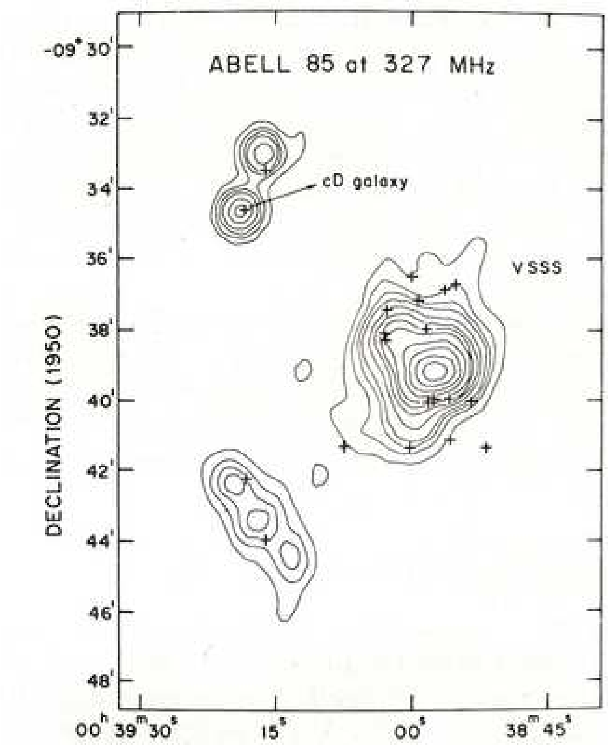

**Fig. 5.13** The relic source with very steep spectrum (VSSS) discovered in 1986 with the OSRT (Joshi et al. 1986) has been studied in detail by many researchers in recent years

WSRT observations at 1,420 MHz yielding separation of the thermal and non-thermal emission within Sgr-A and clarifying the properties of this important radio source for the first time. It was shown that the non-thermal emission traced a shell-like structure with a diameter of $\sim$ 8 pc, marked by several peaks superimposed on a broader non-thermal source of flatter spectra (Gopal-Krishna et al. 1972; Gopal-Krishna and Swarup 1976).

*Pulsar Research with the ORT:* Pulsars are rapidly rotating neutron stars in which the radio emission arises by curvature radiation in a narrow cone around the magnetic field lines. This cone sweeps past the observer like a lighthouse beacon. Thus the observer receives a narrow pulse of radio emission during each rotation of the neutron stars. Observations with the ORT during 1970s led to discovery of eight new pulsars, including a pulsar with unusually large pulse-width (Mohanty and Balasubramanian 1975). Detailed observations of several pulsars were made by Krishnamohan and Balasubramanian (1984) for separating the degree of intrinsic intensity variations of the pulsed emission from that due to fluctuations caused by the interstellar medium (ISM).

Using the upgraded ORT, detailed pulsar scintillation studies were carried out during 1993–1998. Propagation of pulsar radio signals through the turbulent plasma of the ISM can be used for a better understanding of the ISM. It was shown that scattering material in the local ISM (LISM) is not uniformly distributed in a region of about 1 km/sec around the sun. Instead, there is strong evidence for the presence of a low-density bubble around us, surrounded by a shell of enhanced scattering material (Bhat et al. 1998). This result was an important step in understanding the properties of the LISM, and has been included in electron density models of the galactic ISM. It was also shown that the Loop I bubble (which is believed to be a nearby supernova remnant shell) also produces enhanced scattering from the plasma associated with its shell boundary (Bhat and Gupta 2001).

Backer (1970) discovered that some pulsars occasionally show drop in their pulsed emission, called nulling. It provided very tight constraints for their emission physics. Using the ORT, pulse nulling was studied for 10 pulsars. Nulling fractions for PSRs B0149-16 and B0942-13 were determined in detail (Vivekanand 1995). A high sensitivity study of PSR B0031-07 was carried out to characterize its unique sub-pulse drifting. The ORT data showed that the average spacing between two sub-pulses increases monotonically with drift rate contrary to the belief held earlier (Vivekanand and Joshi 1997; Joshi and Vivekanand 2000).

#### 5.2.3.5 Interplanetary Scintillations (IPS) and Solar Weather Studies Using the ORT (1970–2008)

During the last 38 years, the Ooty group has made important contributions concerning fine structures of radio sources, solar wind and interplanetary medium based on interplanetary scintillation (IPS) observations of distant radio sources. The IPS technique exploits the scattering of radiation from compact components of quasars and radio galaxies by the solar wind density irregularities, which are moving radially outward from the sun.

An extensive IPS survey of the galactic plane ($b < 10$ degree) using the ORT showed absence of scintillating radio sources of size $<0.5$ arc-sec, indicating enhanced interstellar scattering towards the galactic plane. A two-component model for the distribution of scattering plasma was proposed (Rao and Ananthakrishnan 1984). Further, systematic measurements of IPS on individual sources have yielded information about the compact component of size $\leq 100$ mill-arc-sec (mas) for several thousand extragalactic radio sources at $\sim 1$ m wavelength.

Ooty IPS studies have also established the density turbulence spectrum to be of power-law form, $\Omega_{Ne}(q) \sim q^{-(3\text{to}3.5)}$ in the spatial-scale range 10–500 km (Manoharan et al. 1987, 1995 and 2000). Using the above power-law model, the speed of the solar wind was derived from single-station measurements that were consistent with the multi-station IPS system in Japan (Figure 5.14) (Manoharan and Ananthakrishnan 1990). *This is a very important result and has been accepted by the IPS observers who are using the single-station method for deriving solar wind velocity.*

The importance of the Ooty IPS measurements increased when the day-to-day monitoring of the heliosphere was made on a grid of large number of radio sources ($\sim$ 800–1,000 per day), whose lines of sight cut across different parts of the heliosphere. The image processing of the normalized scintillation indices ($g$-values) and the estimated speeds obtained from each line of sight provides the three-dimensional view of the ambient solar wind (Figure 5.15) as well as the turbulent regions associated with the propagating disturbances,such as coronal mass ejections (CMEs) in the IPS field of view (e.g. Manoharan et al. 1995; Janardhan et al. 1996).

The Ooty IPS studies have provided for the first time a complete coverage of the imaging of CME structures all the way from the sun to the earth (Manoharan et al. 2001). The velocity of the solar wind is found to have two-level deceleration: (1) a low decline in speed at distances within or about 100 $R_{\text{sun}}$, and (2) a rapid decrease at larger distances from the sun. Each CME tends to attain the speed of the ambient solar wind at 1 AU or further out of the earth's orbit (Manoharan 2006). The solar wind measurements at Ooty over the solar cycle 23 provided the large-scale changes of latitudinal features of the solar wind density turbulence and speed. Routinely imaging of solar wind disturbances at Ooty in the sun-earth distance has provided a capability to predict the adverse space-weather events before their arrival at the near-earth environment (Manoharan et al. 2001; Manoharan 2006).

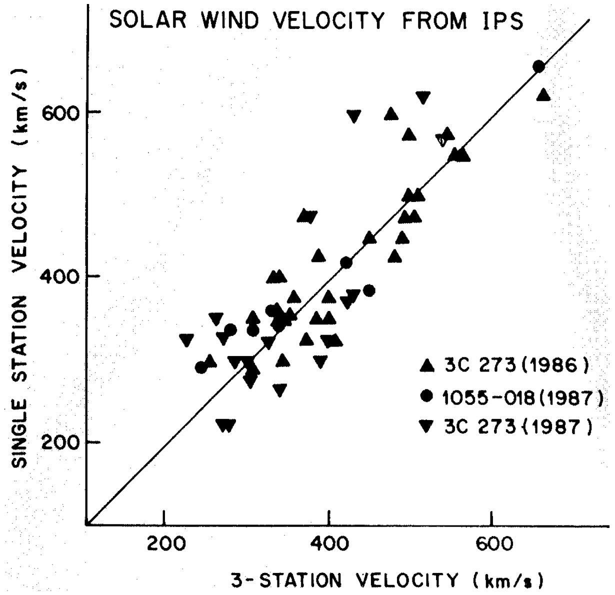

**Fig. 5.14** Plot of solar wind velocity derived from single station IPS power spectra observations made with the ORT versus 3-station IPS system in Japan (Manoharan and Ananthakrishnan (1990)

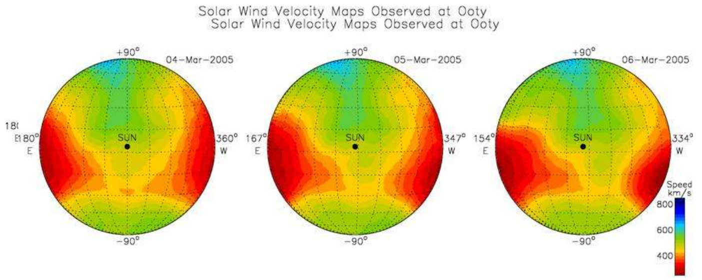

**Fig. 5.15** Speed of the solar wind (V-map) on three consecutive days (Manoharan 2006)

## 5.3 Astronomy with the GMRT during 1999–2008 (Some Highlights)

GMRT of the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research (NCRA-TIFR) started partial observations in 1999 and was fully commissioned in 2000 for use by astronomers in India. Since 2001, its usage is decided by a GMRT time allocation Committee against refereed scientific proposals submitted by the Indian and international astronomical community. GMRT is being used by astronomers from 22 countries. Based on refereed proposals, about half of time of the GMRT has been allocated each to Indian and international astronomers. Some of the highlights of the contributions made by the Indian astronomers during the last 10 years are described below. The broad categories are cosmology with the 21 cm line of neutral atomic hydrogen, pulsars, and low frequency probing of active galaxies.

### 5.3.1 Cosmology

*Damped Lyman Alpha Systems*: Even the partially complete GMRT had the sensitivity and frequency coverage to detect absorption lines produced by intergalactic clouds against background continuum sources. In fact, its unique frequency coverage allowed one to detect sources that were not observable at other observatories. The first of these studies started in 1999 when only eight of the 30 GMRT antennas were available (Chengalur and Kanekar 1999), and the GMRT continues to be one of the foremost instruments for such studies. Observations of these systems (the so-called "damped Lyman alpha" systems, which are believed to be the precursors of the large disc galaxies we see today) have established a broad trend of increase in gas temperature with increasing look back time (e.g. Chengalur and Kanekar 2000; Kanekar and Chengalur 2003). The GMRT was also one of the first telescopes at which surveys for absorption from the OH molecule at cosmological distances have been conducted. These studies (e.g. Kanekar and Chengalur 2002), have shown that the gas phase chemistry in cosmological distant galaxies is similar to that in our own. Further accurate comparison of the frequency of the redshifted OH spectral lines, with the frequencies measured in terrestrial laboratories has helped to place stringent limits on the evolution of the value of the fine structure constant and the electron to proton mass ratio (Chengalur and Kanekar 2003).

*HI Absorption from Cold Gas at Intermediate Redshifts*: The Damped Lyman alpha systems (DLAs), with log N (HI) $>20.3$, are a major reservoir of HI at high z and possibly the progenitors of present-day galaxies. At high z, despite many attempts, only a handful of DLA galaxies have been detected based on line and/or continuum emission. A GMRT survey to search for 21 cm absorption in a representative and unbiased sample of 35 DLA candidates at $1.10 < z < 1.45$, drawn from the strong MgII systems in SDSS DR5, has resulted in discovery of nine new 21 cm absorbers. Prior to this survey, only one 21 cm absorber was known in the redshift range of $0.7 < z < 2$ (Gupta et al. 2006b). GMRT observations of two relatively weak, radio loud, but very dusty QSOs resulted in the detection of 21 cm absorption in both cases. The spin temperature of the gas is of the order of or smaller than 500 K (Srianand et al. 2008).

*Search for HI Emission*: Observations of neutral hydrogen in individual galaxies at different cosmic epochs provide a unique probe of star formation and the assembly of galactic discs. However, this is severely limited even for telescopes with a large collecting area like the GMRT. In a statistical study, however, one can add the signals for many galaxies and gain information on the average behaviour of the population, and begin to examine dependence on environment and galaxy type. The GMRT is uniquely suited to such studies, and indeed the highest redshift existing constrains come from GMRT observations (Lah et al. 2007). The observations of field galaxies give measurements that are consistent with those obtained via other techniques. However, measurements of the gas content of galaxies in clusters indicate a rapid evolution of the gas content of galaxies in clusters.

*Dwarf Galaxies:* It is currently believed that galaxies formed hierarchically, that is, small objects collapsed first, and these in turn merged to form the large galaxies that we see around us today. This process is inherently inefficient, leaving every large galaxy surrounded by a host of unmerged smaller (or "dwarf ") galaxies. The nearby dwarf galaxies can hence be regarded as representative of the primordial galaxy population and can be studied in exquisite detail. As some of the most un-evolved systems in the nearby universe, observations of dwarf galaxies are relevant in a host of cosmological contexts, ranging from testing predictions of cold dark matter models, the influence of cosmic reionization on the baryon content of galaxies, to understanding the parent populations of quasar absorption line systems. Further, dwarf galaxies also provide unique sites for understanding the processes which govern the conversion of gas to stars. This is because, (i) as opposed to large spiral galaxies, dwarf galaxies are dynamically simple systems and (ii) the relatively pristine chemical composition of gas in dwarf galaxies is closer to what one would expect in primordial galaxies. The largest such study is based on a GMRT survey of FIGGS, (the Faint Irregular galaxy GMRT Survey by Begum et al. 2008, and references therein). The GMRT studies have revealed ordered kinematics with dark matter profiles that do not match the expectations of cold dark matter that are substantially different from that observed in large galaxies simulations (e.g. Begum et al. 2003), and star formation rates. The GMRT map of the HI of the dwarf irregular galaxy NGC 3741 (Figure 5.16) extends to a record 8.3 times the Holmberg radius (Begum et al. 2005).

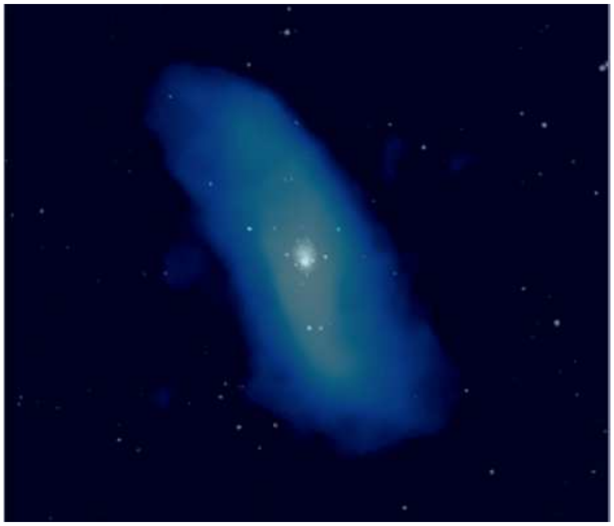

**Fig. 5.16** The GMRT map of the HI, overlaid on the optical image of the dwarf irregular galaxy NGC 3741 ($M_B \sim -13.1$). HI disk extends to a record 8.3 times the Holmberg radius. The rotation curve is measured up to 38 optical scale and remains flat; with a dynamical mass-to-light ratio of 107, this is one of the darkest dwarf irregulars (Begum et al. 2005)

### 5.3.2 *Active Galaxies*

Active galaxies could be broadly classified into those which harbour an AGN or exhibit an intense burst of star formation, called the starburst galaxies. The AGNs were amongst the first to show strong radio emission and are now understood to be due to accreting supermassive black holes pouring out energy in the form of jets, whose origin and formation remain enigmatic, into their host galaxies and beyond, into the intergalactic medium. Low-frequency data with the good sensitivity and resolution provided by the GMRT has led to both interesting individual objects and statistical information about the population. In both cases, the multi-frequency capability has provided valuable information.

*Double-Double Radio Galaxies*: One of the important issues concerning galaxies is the duration of their AGN phase and whether such periods of activity are episodic. For the radio-luminous objects, an interesting way of probing their history is via the structural and spectral information of the lobes of extended radio emission. A striking example of episodic jet activity is when a new pair of radio lobes is seen closer to the nucleus before the 'old' and more distant radio lobes have faded. Such sources have been christened as 'double-double' radio galaxies (DDRG). Observations made with the GMRT have led to the discovery of a new and interesting DDRG (J1453+3304, Figure 5.17), (Saikia et al. 2006), while observations of a number of DDRGs over a large frequency range have led to estimates of spectral ages and hence time scales of episodic activity (e.g. Konar et al. 2006).

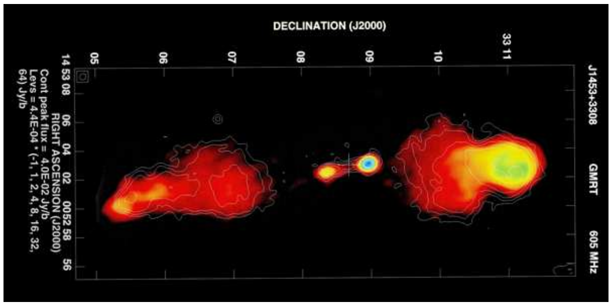

**Fig. 5.17** Brightness distribution across the double-double radio galaxy J1453+3304

*Giant Radio Galaxies*: The discovery of the largest giant radio galaxy, which are defined to be over a Mpc in size, has been reported from observations made with the GMRT and other telescopes (Machalski et al. 2008), and also one of the largest one-sided radio jets (Figure 5.18) (Bagchi et al. 2007). Multi-frequency matched-resolution observations of such giant radio sources (e.g. Konar et al. 2008), X-shaped radio sources (Lal and Rao 2007), relic lobes of radio sources have led to spectral and age information about different parts of the source, constraining models of radio sources.

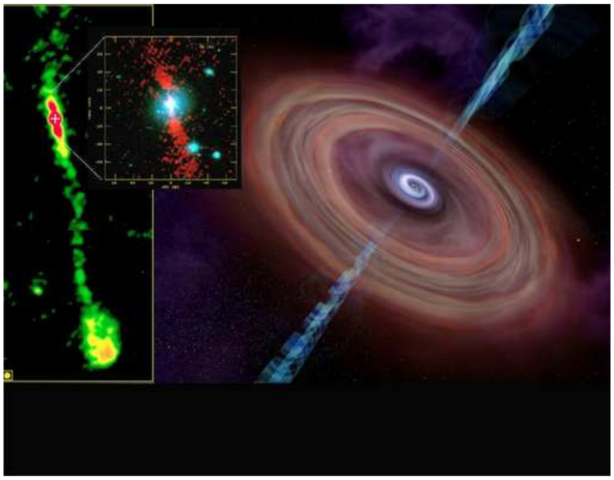

**Fig. 5.18** Radio image of a very large one-sided jet discovered by Bagchi et al. (2007)

*Radio Relics and Halos in Clusters of Galaxies*: Radio halos and relics are low-surface brightness sources with steep radio spectra, and sizes which can extend to over a Mpc.

While radio halos are usually located near the centre of a cluster and have a reasonably regular structure, the relics are located in the periphery of the clusters and exhibit a wider variety of structures. Besides understanding the physics of these structures these could provide useful insights towards understanding formation and evolution of clusters of galaxies. GMRT observations have helped identify several new relics and halos, and low-frequency GMRT observations of these have helped constrain models of these objects (e.g. Brunetti et al. 2008; Venturi et al. 2009).

*Interacting Galaxies and Superwinds:* In active galaxies, the gaseous ISM of disk galaxies are affected by various energetic and violent phenomena such as supernovae, stellar winds, jets driven by AGN, winds from accretion-disk and ram pressure stripping. Superwinds from starburst galaxies are important in supplying metal-enriched gas to the halo of the disk galaxy as well as to the intergalactic medium or the intracluster medium. Several such systems have been studied in detail using the GMRT providing important and useful constraints on the models of these sources, such as the superwind galaxy NGC1482 (Hota and Saikia 2005); in the Seyfert galaxy NGC3079 a large-scale halo has been imaged with the GMRT (Irwin and Saikia 2003); also the highly disrupted Seyfert galaxy in the Virgo cluster NGC4438 (Hota et al. 2007). The member galaxies in Holmberg 124 display signatures of tidal interwction and ram pressure stripping in the GMRT radio continuum and HI images (Figure 5.19) (Kantharia et al. 2005). These lower-luminosity galaxies also harbour black holes, somewhat more massive than in our own galaxy.

*Gamma Ray Bursts:* GMRT has played key role in identifying radio counterparts of very high energy gamma ray sources at high redshifts. Deep GMRT radio observations of these energetic sources have for the first time revealed presence of extended, diffuse and compact radio sources which are positionally coincident with the X-ray and optical/IR sources (Paredes et al. 2007).

*HI Absorption Studies*: An understanding of the properties of the gaseous environments of radio galaxies and quasars could provide valuable insights towards understanding the phenomenon of radio activity associated with these objects and their evolution. Such studies also enable us to test consistency of these properties with the unified schemes for these objects. An important way of probing the neutral component of this gas over a wide range of length scales is via 21 cm HI absorption towards radio sources of different sizes. As part of a study of HI absorption towards the central regions of active galaxies using the GMRT, HI absorption lines have been discovered towards compact sources, the core of a radio galaxy and a rejuvenated radio source,

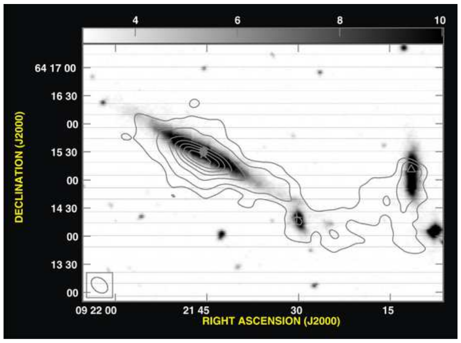

**Fig. 5.19** GMRT image of three galaxies in the group Holmberg 124, NGC2820, NGC2814 and Mrk 108, superimposed on optical image in grey scale. The radio bridge with a very steep spectrum ($\alpha$ = -1.8) is likely to be due to interactions of the galaxies, whereas the displaced radio disk of NGC2814 is likely due to ram pressure stripping (Kantharia et al. 2005)

consistent with the suggestion that supply of fresh gas restarts the radio activity (Gupta et al. 2006a; Gupta and Saikia 2006; Saikia et al. 2007).

*Deep Low Frequency Surveys*: Radio sources stronger than a few mJy are usually associated with AGN, while at lower flux densities the radio source counts are dominated by the radio-quiet objects in early-type galaxies, low-luminosity AGN and contributions from starbursts in late-type galaxies. In the last few years, the capability of doing deep low frequency imaging has been greatly improved by careful study of systematics and elaborate data processing. The deep surveys of specific fields at 610 MHz (Garn et al. 2008), 325 MHz (Sirothia et al. 2009a, 2009b) and 150 MHz (George and Ishwara-Chandra 2009) have reached depth and resolution unprecedented in these bands. Comparisons with existing high frequency surveys now become meaningful and they are already revealing interesting classes of objects with steep, curved, or peaked radio spectra, and unusual morphologies, for further follow-up. In many cases, extensive information at other wavebands is also available, allowing for a multi-wavelength approach to modeling the population of active galaxies. The surveys carried out so far represent the tip of what is possible and quite likely in the immediate future.

## 5.3.3 Our Galaxy

Many investigations have been done concerning objects in our galaxy over the last 8 years by research workers in India and abroad. Only a few of the results are described here.

*Galactic Centre region*: The lowest frequency detection of the black hole radio source, Sgr A* at the centre of our galaxy at $\sim$ 620 MHz with the GMRT indicated that it is located in front of the Sgr-A west complex (Figure 5.20) (Roy and Rao 2004). Scatter broadening has been found to occur towards the galactic centre region from the GMRT observations of 26 compact extragalactic radio sources at 255 MHz and 154 MHz. It was also inferred that the 7’ halo in Sgr A complex is a non-thermal source rather than a mixture of thermal and non-thermal electrons (Roy and Rao 2006).

*Micro-quasars and Gamma-ray Sources:* Micro-quasars in our galaxy have been monitored regularly using the GMRT since 2002. Mini flares were observed from one of the famous micro-quasar GRS1915+105, using which a new method to obtain radio spectral index from single frequency radio observation was evolved through modeling of evolution of flare under adiabatic expansion (Ishwara-Chandara et al. 2002). Further observation of GRS1915+105 during the flare also showed that the radio emission is optically thick at low radio frequencies in the initial stages of the flare. This was the first extensive monitoring of a micro-quasar at metre wavelengths. The flare peaks at metre wavelengths with a delay of a few days from its peak at cm wavelengths (Pandey 2006). Forty newly discovered gamma-ray sources by INTEGRAL were observed with the GMRT that led to the discovery of four new micro-quasar candidates (Pandey 2006).

*Novae:* GMRT has been used to study the radio emission from galactic cataclysmic binaries known as novae which consist of a white dwarf accreting matter from a star with a large envelope. (i) The classical nova GK Persei was imaged at 325 and 610 MHz (Anupama and Kantharia 2005) Its flux density was found to follow a spectrum with index $-0.85$ whereas the higher frequencies had a flatter spectrum ($-0.7$) indicating an

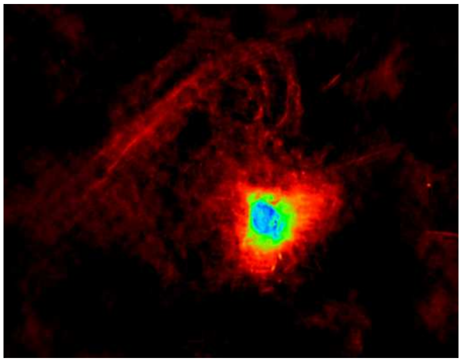

**Fig. 5.20** A radio image of the galactic centre and surroundings made with the GMRT at 610 MHz (Roy and Rao 2007)

adiabatic expansion of the nova remnant. (ii) RS Ophiuchi, a recurrent nova which recorded its latest outburst in February 2006 was observed at frequencies of 240, 325 and 610 MHz (Kantharia et al. 2007). This was the first detection of a recurrent nova at frequencies below 1 GHz and clearly demonstrated the presence of non-thermal synchrotron emission of index $-0.8$ in this system at very early times.

*Sun*: High dynamic range snapshot images of the solar corona were made by combining visibilities from the GMRT and Nancay radio heliograph in France. The technique allowed obtaining images of the sun at 327 MHz with a resolution of 49 arc-sec up to the size of the whole sun (Mercier et al. 2006).

### *5.3.4 Pulsars*

Due to their steep spectrum, pulsars have higher flux densities at lower frequencies. Further, the large collecting area of the GMRT allows observations of individual pulses with good sensitivity. Observations of individual pulses in nearly aligned pulsars have revealed details of drift and polarization patterns that provide important clues to the still enigmatic emission mechanisms. A few notable pulsars have also been discovered using the GMRT.

*Emission Geometry of Radio Pulsars:* From detailed analysis of high quality single pulse data taken primarily with the GMRT, new results have been obtained about the detailed distribution of emission components in the profiles of several pulsars (Gangadhara and Gupta 2001; Gupta and Gangadhara 2003). These results support the model of concentric conal rings of emission around a central core component of emission (Figure 5.21). Further, slight asymmetry in the locations of the conal components can be interpreted as being due to retardation and aberration effects in the pulsar magnetosphere. The main conclusions are (i) pulsars with multi-component profiles have multiple (two to three) concentric, hollow cones of emission, (ii) the typical emission heights for these cones in the pulsar magnetosphere range from $\sim$ 100 km to $\sim$ 1000 km, (iii) emission height for or a given cone is a function of the radio frequency, being lower for the higher frequencies, (iv) the magnetic field lines associated with these emitting cones are not located at the edge of the open field line region, but lie in the range $\sim$ 0.2–0.7 of this boundary, (v) there is some evidence that the wider cones originate further out on field lines.

*Multi-frequency Pulsar Observations:* Detailed studies of pulsars have been carried out using multi-frequency observations, simultaneous or otherwise, done at the GMRT in combination with other radio telescopes. These have yielded interesting results in diverse topics such as (i) estimation of pulsar dispersion measures (Ahuja et al. 2005), (ii) emission geometry of the drifting pulsar PSR B0031-07 (Smits et al. 2007), (iii) wide-band nulling properties of radio pulsars (Bhat et al. 2007), (iv) frequency dependence of pulse broadening due to interstellar scintillations (Loehmer et al. 2004). Furthermore, when combined with polarization information, extra insight into the emission process has been achieved, as in the case of the emission from the central core region of PSR B0329+54 (Mitra et al. 2007).

*Study of Drifting Pulsars:* Sensitive data from the GMRT on a few pulsars with wide emission profiles has provided interesting new insights (Gupta et al. 2004; Bhattacharyya et al. 2007). PSR B0826-34, a pulsar with emission over almost the whole pulse period, has been shown to have as many as seven drift bands in the main pulse window with highly correlated variations over durations of tens of pulse periods. This is

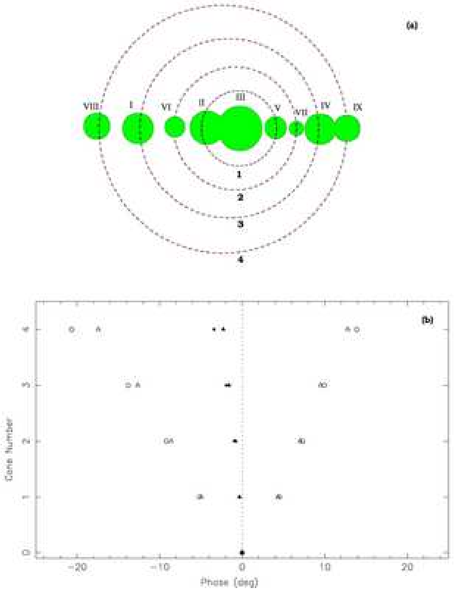

**Fig. 5.21** Location of nine emission components detected for PSR B0329+54 at 610 MHz, shown in the form of four conal rings around a central core component (top panel). The core component is labeled as cone. Lower panel illustrates the increasing asymmetrical locations of the four conal component pairs, with respect to the core, for 610 MHz (triangles) and 325 MHz (circles), (Gupta and Gangadhara 2003)

first direct evidence for such a large number of sparks and provides strong support to the model of rings of circulating sparks on the polar cap, resulting in conal emission beams. The unique drift pattern in the wide profile pulsar, B0818-41, is modeled as being created by two conal rings. Both the rings have the same values for the pattern rotation period (18.3 pulsar periods) and the number of emission sparks (about 20). GMRT has also allowed unraveling of the sub-pulse modulation characteristics of the five component pulsar B1857-26 (Mitra and Rankin 2008). The outer conal components exhibit a modulation periodicity of 7.4 pulsar periods, and there is evidence to indicate that there are 20 sparks and the pattern rotation period is 147 periods.

*Studies of the Double Pulsar:* The double pulsar system PSR J0737-3039, discovered by Lyne et al. (2004), provides an excellent laboratory for relativistic physics and studies of pulsar emission mechanism. The system is unique due to sharp pulses of this msec pulsar, the detection of its long period companion as a pulsar and an almost edge-on orbit. The line of sight to the msec pulsar passes through the magnetosphere of the long period pulsar giving a unique probe of the pulsar magnetosphere. Multi-epoch observations with GMRT at 325 MHz of the long period pulsar in this double pulsar system showed a change in the intensity, duration, and separation of its two bright phases, which provides a unique probe for the geodetic precession of this pulsar, with implications for theories of relativity (Joshi et al. 2004; Joshi 2006).

*Discovery of Some Interesting New Pulsars Using the GMRT:* Although more than thousand pulsars are now known, some of those discovered with the GMRT are of special interest. (i) The first pulsar PSR JO514-4002A discovered by the GMRT was found to be a 4.99 msec period neutron star, in the globular cluster NGC 1851 (Freire et al. 2004). Detailed follow-up studies revealed it to be a very interesting binary pulsar, with a white dwarf companion, an orbital period of 18.8 days and an orbital eccentricity of 0.9 - *the most eccentric orbit of a pulsar in a binary system.* The formation of such systems points to significant three body interactions *in the dynamics of dense globular clusters.* (ii) The second pulsar discovered by the GMRT was a very young pulsar, second *youngest pulsar in our galaxy. It is* located at the centre of the supernova remnant G21.5-0.9. The PSR J1833-1034, has a spin period of 61.8 msec, a characteristic age of about 5,000 years and a spin-down luminosity that is the second highest amongst all the known pulsars in our galaxy (Gupta et al. 2005): *given that most work on young pulsars in supernova remnants was done with statistics of two, one more is a welcome addition*; follow-up studies of this pulsar have revealed very interesting glitching behaviour (Roy et al. in preparation). (iii) An unbiased survey for long period pulsars carried out with the GMRT at 610 MHz (Joshi et al. 2008) covering 106 suare degrees has yielded its first results: three new pulsars (PSR J0026+6320, PSR J2208+5500, PSR J2218+5729 with periods of 0.318, 0.933 and 1.06, respectively). Results from this survey should improve our understanding of aging and death of these objects.

### 5.3.5 *Astronomy with the GMRT: General Remarks*

It is important to note that the above account has focused on selected highlights mostly by NCRA astronomers and is only a small subset of a much more extensive body of work, amounting to more than 300 publications done with the GMRT since it was commissioned. In particular, a large body of work on radio galaxies, quasars, cluster of galaxies, nearby galaxies, transients, ISM of our galaxy, supernova remnants, HII regions and sun is not represented. The proceedings of a recent international conference held at NCRA in December 2008 on "low frequency radio universe" (Saikia et al. 2009) describe in detail many studies carried out by Indian and international astronomers using the GMRT and other radio telescopes.

## 5.4 Radio Astronomy at the Indian Institute of Astrophysics

### 5.4.1 *Solar Physics*

The main focus of the radio astronomy facilities at the IIA concerns observations of sun at low frequencies, viz. 30–150 MHz. The early observations date back to 1950s at the Kodaikanal observatory, forerunner of the institute. Continuous recording of solar radio noise flux was commenced under A. K. Das in 1952 using a 100 MHz interferometer with twin Yagi type antennas (Kodaikanal Observatory report 1952). A 20-foot equatorially mounted paraboloid for observations at decimetre and metre wavelengths was set up in 1961 after M. K. Vainu Bappu took over as the director of the observatory. Under the Kodaikanal-Yale Project, recording of radio radiation from Jupiter at a frequency of 22.2 MHz was started using a phase switching interferometer (Kodaikanal Observatory report 1962). The custom-built 3 GHz wavelength radio receiver from the CSIRO, Australia, was put to use in 1965 for regular solar monitoring (Kochar and Narlikar 1995). In the early 1970s, an antenna array operating at 25 MHz was used to obtain information on radio bursts from the outer solar corona, with high temporal and frequency resolution (Sastry 1973). The above radio telescopes were discontinued after the Kodaikanal group moved to Bangalore in mid-1975 on the establishment of the autonomous IIA with the Kodaikanal Observatory as one of its constituent.

During the mid-1970s, a large radio telescope operating at 34.5 MHz was jointly set up by the IIA and the RRI, Bangalore at Gauribidanur, 80 km north of Bangalore. As described in Section 5.5.2, the telescope consists of 1,000 dipoles arranged in a 'T' configuration, with a 1.4 km east-west arm and a 0.5 km south arm (Figure 5.22), (Sastry et al. 1981; Dwarkanath et al. 1982). It has been engaged in the study of radio waves emanating from sun and various galactic and extragalactic objects (see Section 4.3 for non-solar observations). The notable solar observations with the array are: two-dimensional images of radio emission from the slowly varying discrete sources in the outer solar corona; radio brightness temperature of the outer solar corona is $<10^6$ K (Sastry et al. 1983).

**Fig. 5.22** An aerial view is shown of a section of the east-west arm of the Gauribidanur radio telescope operating at 34.5 MHz

Not many white light coronagraphs to probe the outer solar corona were in operation during the early 1980s and also the interest in the study of coronal mass ejections (CMEs) had just begun. Further both the Culgoora radioheliograph in Australia and the Clark Lake radioheliograph in USA had closed down operations. So the IIA decided to build a radioheliograph for dedicated observations of the solar corona, simultaneously at

**Fig. 5.23** Shows a section of the south arm of the Gauribidanur radioheliograph

different frequencies in the range 30–150 MHz. The Gauribidanur radioheliograph (GRH, see Figure 5.23) is in operation since 1997 (Ramesh et al. 1999). In the above frequency range the GRH provides information on the solar corona in the height range ∼0.2–0.8 $R_s$ above the solar surface, which is difficult to probe using ground based and space borne white light coronagraphs. Moreover no other radio telescope is presently operating in the above frequency. Some of the notable observations made with the GRH are:

Density and temperature of the pre-event structure of CMEs (Kathiravan and Ramesh 2005); velocity/acceleration of CMEs close to the solar surface (Ramesh et al. 2003); 'true' speed of CMEs in the three-dimensional space (Kathiravan and Ramesh 2004); estimation of parameters of the CMEs at large distances $\sim (5-40\ R_s)$ from the sun by observing angular broadening of distant cosmic radio sources (Ramesh et al. 2001); coronal electron density gradient in the $\sim 0.2-0.8\ \ R_s$ height range above the solar surface (Ramesh et al. 2006); radio noise storms and CMEs (Kathivaran et al. 2007); onset of CMEs and occurrence of transient dimming in the solar corona (Ramesh and Sastry 2000); plasma characteristics of radio emission associated with emerging magnetic flux from sub-surface layers of the solar photosphere (Shanmughasundaram and Subramanian 2004).

A high resolution radio spectrograph is used in conjunction with the GRH for obtaining a dynamic spectrum of transient burst emission from the solar corona. The antenna system consists of 8 log periodic dipoles. A commercial spectrum analyzer is used as the back end receiver to obtain spectral information with an instantaneous bandwidth of $\sim$ 250 kHz. The temporal resolution is $\sim$ 43 ms. The radio spectrograph and GRH together provide spectral and positional information on eruptive activity in the solar atmosphere. The observations so far have provided clues to the location of a source region of a CME through observations of transient 'absorption' bursts (Ramesh and Ebenezer 2001) and occurrence of radio bursts associated with magneto-hydrodynamic shocks in the solar corona (Subramanian and Ebenezer 2006).

Recently an interference radio polarimeter has been built at the Gauribidanur observatory to understand the polarization characteristics of various solar phenomena. Based on theoretical formulations for the response of a correlation telescope to polarized radiation, an east-west one-dimensional array of 32 log periodic dipoles has been set up to probe the coronal magnetic field in the height range $\sim 0.2-0.8\ \ R_s$ above the solar surface. The dipoles are arranged as four groups and they are oriented at $0^\circ$, $45^\circ$, $90^\circ$ and $135^\circ$ with respect to the terrestrial north. This helps in capturing the polarization state of the incident radiation with good accuracy. The idea is to get information on the coronal magnetic field through observations of circularly polarized radio emission from discrete sources in the corona (Figure 5.24). The spectral dependence of the observed emission in the above height range can also be obtained through multi-frequency observations. Instrumental calibration is carried out through observations of the randomly polarized sidereal radio sources (Ramesh et al. 2008).

### 5.4.2 Pulsars

Based on the data of PSR B1133+16 at three temporal resolutions (1160, 500 and 150 microseconds), it was found that orthogonal polarization modes are better resolved at higher temporal resolutions, and the pulses show a higher degree of polarizations. Further, the linear polarization is higher when the circular polarization has a minimum value (Gangadhara et al. 1999).

It was shown that the controversy whether the beam of the pulsar emission is conal or patchy has arisen because of incorrect identification of pulsar emission components in the average pulse profiles. Single pulse

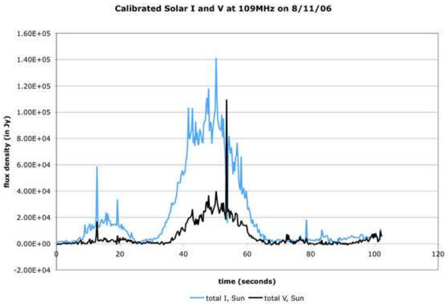

**Fig. 5.24** Observations of circularly polarized radio emission from the sun at a height of about 0.4 *Rs* above the surface with the Gauribidanur radio polarimeter

observations of PSR B0329+54, one of the strongest known pulsar, with the Jodrell Bank radio telescope at 606 MHz indicates that the weaker components seen in single pulses hardly show up in the average pulse profiles. Using the Window-Threshold technique for identifying the weaker emission components, nine emission components were detected in PSR B329+54 (Figure 5.21). This is the highest number of components ever detected among all the known pulsars. To make a multi-frequency estimate of the results, 325 MHz data of PSR B0329+54 from GMRT was used. The results were found to be consistent at the two frequencies. Further, it was found that the conal components on either side of the core are asymmetrically distributed with respect to the rotation phase (Gangadhara and Gupta 2001; Gupta and Gangadhara 2003).

### *5.4.3 Active Galactic Nuclei*

Polarization was detected on parsec scales in the nuclei of four Fanaroff-Riley type I (low-luminosity) radio galaxies. Observations with VLBI at $\lambda = 3.6$ cm reveal the presence of ordered magnetic fields within $\sim$ 1650 Schwarzschild radii of the putative central supermassive black hole. The relatively high fractional polarization in the parsec-scale jets of these galaxies is consistent with the unified scheme for low-luminosity radio galaxies and BL Lac objects. This result also suggests that these radio galaxies lack the obscuring tori that apparently depolarize the nuclear emission in the more powerful FR II type radio galaxies, and that their supermassive black holes are poorly fed and/or inefficient radiators (Kharb et al. 2005).

Investigation was made of the point-like optical nuclei in the centres of the host galaxies of a majority of radio galaxies by the Hubble Space Telescope. Simple model-fitting of the data suggests that the emission may be coming from a non-thermal relativistic jet. The results are broadly in agreement with the unified scheme for radio-loud AGNs (Kharb and Shastri 2004). Milli-arc second scale resolution was obtained using very long baseline interferometry (VLBI) images of the Seyfert 1 and Seyfert 2 galaxies at 5 GHz to test rigorously predictions of the unified scheme (Lal et al. 2004).

## 5.5 Radio Astronomy at the Raman Research Institute

Radio astronomy at the RRI, Bangalore was initiated in the late 1970s, and has now grown to form a major part of the institute's activity. By this time the ORT had already been established by the TIFR group. RRI involved itself in the use of the ORT primarily for spectral line observations. One of the first results of this was an upper limit to the average interstellar Deuterium abundance. Using a frequency-switched filter bank receiver at ORT, Anantharamaiah and Radhakrishnan (1979) determined that the interstellar Deuterium to hydrogen ratio is less than about 58 parts per million.

### *5.5.1 Radio Recombination Lines*

The spectral line activity gradually grew into a major enterprise at RRI in the early 1980s, and the focus shifted to Radio Recombination Lines (RRL). These lines originate in transitions between highly excited states of hydrogen and metal atoms. Typically such states are populated in the presence of an ionizing photon field. The atom is first ionized, and the high Rydberg states are populated as electrons recombine with the ions, and hence the name “recombination lines”. Radio recombination lines can be excellent probes of density and temperature of these ionized regions.

An extensive survey of the galactic plane for recombination line emission around 327 MHz was undertaken by RRI using the ORT. The typical transition observed was between Rydberg levels of 273–272 of the hydrogen atom. Observations were carried out for over 3 years, using a 128-channel one-bit autocorrelation spectrometer built at RRI and installed at Ooty (Antharamaiah 1985a). The result of this survey showed that the distribution of the RRL emission is quite ubiquitous over the inner galaxy (galactic ridge), and not just associated with the known, discrete ionized hydrogen regions. As the high Rydberg level atoms can exist in only relatively low-density regions, one way to explain the widespread distribution of the RRL was that ionized hydrogen regions had hitherto unseen low-density envelopes that give rise to these lines (Anantharamaiah 1985b, 1986). Correlation of the line intensities with those of background continuum indicated significant contribution of stimulated emission caused by population inversion at these energy levels. A survey of recombination lines in the longitude range $l = 330°$ to $89°$ by Roshi and Anantharamaih (2001) constrained the density of gas in the range 1–10 $\text{cm}^{-3}$.

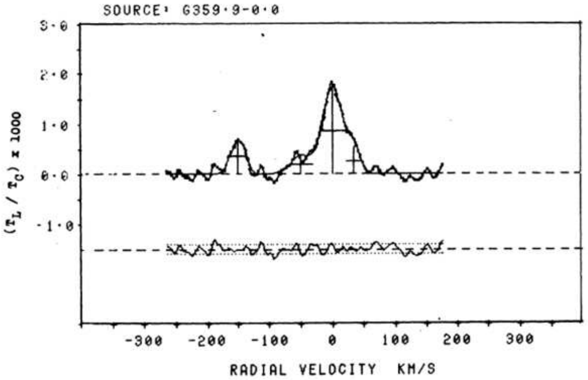

**Fig. 5.25** Radio recombination lines towards the galactic centre source Sgr A detected using the ORT. The height and the width of the fitted Gaussian components are indicated using the vertical and horizontal lines, and the post-fit residuals are also shown. The feature located near −150 km/s is a recombination line of carbon while the other features belong to hydrogen (Anantharamaiah 1985a)

The strong RRL detected towards the galactic centre allowed detailed analysis and modeling of the emitting gas, and resulted in placing a lower limit to the filling factor of the warm ionized medium (Anantharamaiah and Bhattacharya 1986).

The work on radio recombination lines was later extended to many other contexts, including starburst galaxies and AGN (Anantharamaiah et al. 1995; Phookun et al. 1998; Mohan et al. 2002). Almost all major radio telescopes in the world were used for such studies. A survey of the galactic plane for carbon recombination lines at the low radio frequency of 34.5 MHz was undertaken some years later with the T-array at Gauribidanur (Kantharia et al. 2001).

### *5.5.2 The Gauribidanur T-array Radio Telescope*

A large, fixed radio telescope operating at the decametric radio frequency of 34.5 MHz was set up in the early 1980s at Gauribidanur, about 80 km away from Bangalore. This was a collaborative effort of RRI with the IIA see Section 5.4.1). The telescope consisted of two fixed dipole arrays arranged in the form of a “T”. The east-west arm was 1.4 km long, at the middle of which joined a southern arm of 0.45 km length. The dipoles were arranged in east-west rows with an inter-dipole spacing of 8.6 m and an inter-row spacing of 5 m in the north-south direction. The east-west arm had four rows of dipoles, each row containing 160 dipoles. The south arm had 90 rows, each containing four dipoles. Signals from these 1,000 dipoles were electrically phased and combined to form a beam of 26 arc-min × 40 arc-min at zenith (Sastry et al. 1981; Udaya Shankar and Ravi Shankar 1990).

One of the major projects undertaken with the Gauribidanur T-array (Figure 5.26) was an all-sky survey at 34.5 MHz (Dwarakanath and Udaya Shankar 1990). Data was collected in interferometric mode using a 128-channel 1-bit correlator system built at RRI, recording visibilities by correlating individual rows in the south arm with one of the rows in the east-west arm. The result of the survey provided maps of the non-thermal galactic background emission, along with other emitting and absorbing sources. Ionized hydrogen regions showed up as strong absorption features, while large non-thermal loops and spurs stood out in emission.

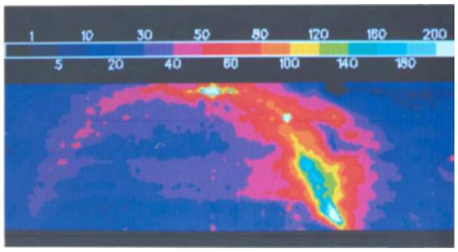

**Fig. 5.26** The sky map at 34.5 MHz made using the Gauribidanur T-array. The colour key represents the scale of brightness temperature in units of 1000 K. Right ascension increases from right to left and declination from bottom (-36 deg) to top (+64 deg). Image courtesy K.S. Dwarakanath and N. Udaya Shankar

The T-array has also been used for a spectral line survey as mentioned above, and for extensive pulsar observations, which will be described in a later section.

### *5.5.3 The Mauritius Radio Telescope*

RRI and IIA carried the experience gathered with the Gauribidanur T-array to establish a similar observatory in the southern hemisphere, on the island of Mauritius during the 1990s. In this Indo-Mauritian joint venture, a non-coplanar array of 1,024 fixed broadband helices was installed in an east-west arm of 2,048 m in length. The south arm here is 880 m long, and consists of 16 movable trolleys, with four helices on each. Visibilities are measured using a 512-channel 2-bit 3-level correlator system. At least 60 days of observations are required to cover all the spacings in the south arm up to 880 m, giving a synthesized beam size of about 5 arc-min (Golap et al. 1998). A survey of the southern sky at 150 MHz has been carried out with this telescope. The data collection was completed over several years. Preparation of maps using this data is ongoing; full resolution maps covering about 25% of the survey area, along with a source catalogue, are now available (Pandey 2006, see also http://www.rri.res.in/surveys/MRT/Download.html).

### *5.5.4 Instrumentation for the GMRT*

The GMRT set up by NCRA-TIFR near Pune has received major contributions from the RRI. RRI undertook to equip all antennas of the GMRT with feeds and receivers covering the 21 cm hydrogen line band. Installation of these large (∼500 MHz) bandwidth, dual linear polarization front ends on the GMRT was completed by 1999. The receiver developed in this connection has also been used in a stand alone experiment to make measurements of the temperature of the Cosmic Microwave Background radiation at 1,280 MHz (Raghunathan and Subrahmanyan 2000).

Another valuable contribution of RRI to the GMRT is the user-configurable digital GMRT Array Combiner (GAC) which allows the GMRT to be operated as a single phased or incoherent array. Signal from all antennas are combined to produce a single voltage (phased array) or power (incoherent array) data stream for each of

**Fig. 5.27** An aerial view of the Mauritius Radio Telescope, as seen from the south. A part of the east-west arm with fixed helices is visible in the upper part of the figure. Sixteen trolleys with four helices each are seen in the south arm.

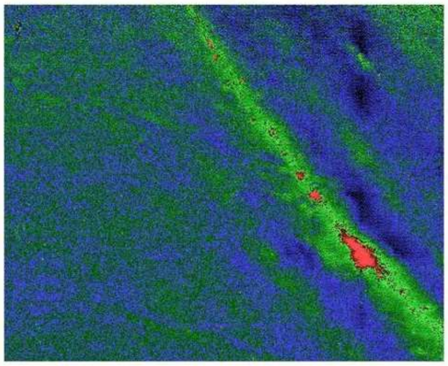

**Fig. 5.28** An image of the region RA18 to 19 and Dec -40 to -5 deg at 150 MHz obtained using the Mauritus Radio Telescope (Pandey 2006)

the spectral channels in each of the two polarizations (Prabu 1997). This instrument is particularly useful for pulsar studies, allowing time series analysis to be carried out on a single set of data streams rather than for each antenna separately. For pulsar studies at GMRT, RRI also built a versatile real time signal processor intended to act as a pulsar polarimeter. This processor applies on-line corrections for dispersion, Faraday rotation, Doppler acceleration and parallactic angle variations of the pulsar signal and records the stokes parameters, folding the pulses at a given period (Ramkumar and Deshpande 2002).

### 5.5.5 *Pulsar Studies*

The study of radio pulsars has been a sustained activity at RRI. Other than the GMRT, special instrumentation was also developed for the Gauribidanur T-array. Limited tracking using electrical phasing in the east-west direction was implemented; a swept-frequency local oscillator was employed for dispersion compensation (Deshpande 1992), and later a portable pulsar receiver was built and used, which recorded baseband voltages and allowed for a variety of offline processing.

A 1024-channel digital spectrometer with postdetection dedispersion facility designed and built at CSIRO, Australia (McConnell et al. 1996) was used in collaboration between RRI and CSIRO at the ORT for some time. This machine was later shifted to the Mauritius Radio Telescope. Among the notable results obtained during the Ooty run were the observations of intense radiation spikes from the nearby millisecond pulsar J0437-47, which were interpreted as diffraction patterns arising due to coherent emission over $\sim$100 m lateral extent in the pulsar magnetosphere (Ables et al. 1997). Accurate measurement of scattering delay of a sample of pulsars was also carried out using this instrument (Ramachandran et al. 1997).

A cartographic transformation to map the pattern of observed subpulse drift to a rotating pattern of sparks in the pulsar magnetosphere was devised at RRI (Deshpande and Rankin 1999). While initially applied to the data obtained from the Arecibo telescope, this technique was employed also to the observations carried out using the Gauribidanur T-array (Asgekar and Deshpande 2005); (Figure 5.29)

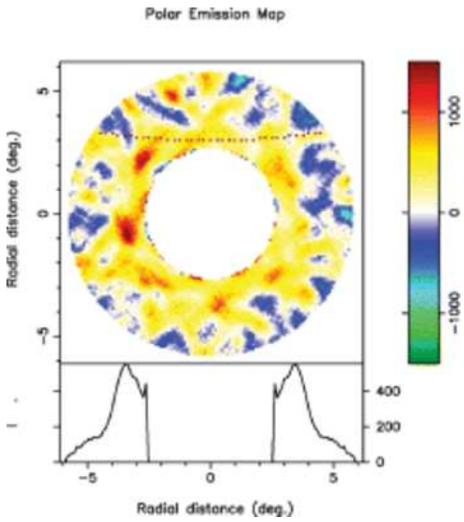

**Fig. 5.29** Average polar emission map (colour coded intensity) of the pulsar PSR 0834+06 obtained via cartographic transform from the data collected using Gauribidanur T-array at 34.5 MHz. The line of dots show the traverse of the sight line through the emission beam (from Asgekar and Deshpande 2005)

The ORT continues to be in use by the RRI pulsar group. At present a long-term pulsar timing programme is ongoing.

### 5.5.6 *Observations of Neutral Hydrogen Gas*

Study of the kinematics of interstellar gas and of galaxies in clusters and groups using the 21 cm hyperfine transition of neutral hydrogen has been a sustained theme at RRI, and has been pursued using the VLA (USA), WSRT (Netherlands), ATNF (Australia) and the GMRT. Parkes telescope observations of the neutral hydrogen absorption spectrum towards the galactic centre were used to determine the velocity distribution of cold clouds. A population of high-velocity clouds was discovered this way (Radhakrishnan and Sarma 1980), and was studied later in greater detail with the GMRT and the VLA (Dwarakanath et al. 2004). An extensive study of neutral hydrogen absorption by diffuse clouds at high galactic latitude was carried out using the GMRT (Mohan et al. 2004). Large imaging surveys of neutral hydrogen emission undertaken by RRI with the GMRT include those of galaxies in the Eridanus group (Figure 5.30) (Omar and Dwarkanath 2005) and of galaxies in X-ray bright groups (Sengupta et al. 2007).

### 5.5.7 *Millimetre Wave Astronomy*

RRI initiated the effort of millimetre wave astronomy in India, starting in the early 1980s. A 10.4 m diameter millimetre wave dish antenna was indigenously built following the design of similar antennas in use at the Owens Valley Radio Observatory operated by CalTech. The dish is constructed out of individually adjustable hexagonal panels made of lightweight aluminium honeycomb material sandwiched between aluminium skins. The surface accuracy is 100 microns, in order to enable operation at 2.6 mm wavelength corresponding to the spectral line generated by rotational transition of the CO molecule, the primary tracer of diffuse molecular gas in the universe.

Large observational programmes carried out at the 115 GHz (2.6 mm) band with this telescope include a study of Cometary Globules in the Gum Nebula, which led to a measurement of the expansion of the system of globules (Sridharan 1992), and a survey of molecular clouds in the Gould's belt, which reconstructed a

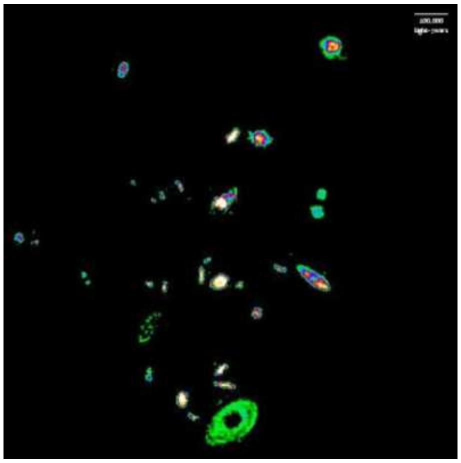

**Fig. 5.30** A collage of the galaxies in the Eridanus group imaged in the 21 cm wavelength of the hyperfine transition of neutral hydrogen. The colour coding represents the neutral hydrogen column density (from Omar and Dwarakanath 2005).

**Fig. 5.31** A picture of the 10.4 m diameter millimetre wave dish located at the RRI campus. The 10.4 m dish was installed in RRI campus and has been in operation since 1988. At the highest operating frequencies, a closed cycle 4K helium cryogenic system has been used.

3-dimensional structure of the distribution of molecular gas in this region (Ramesh 1994). However, due to restrictions placed by the local weather, the available time for observations at 115 GHz was quite limited. The telescope has thus spent a significant fraction of its time observing at lower frequencies. An extensive survey of SiO maser sources in the galaxy has been carried out at 86 GHz band over several years (Patel et al. 1992), and a methanol maser survey at 6.7 GHz band is currently ongoing. New receivers at 40–50 GHz band are now being installed on this telescope for a spectral line survey of star forming regions. Along with the 10.4 metre telescope, RRI also installed a smaller millimetre wave telescope made using a 1.5 metre diameter dish moulded out of synthetic material. This was used as a test bed for various technology developments before deployment at the 10.4 m dish. In addition, a study of atmospheric ozone was carried out with this telescope, deriving the height distribution of ozone over Bangalore (Vivekanand and Arora 1988).

### *5.5.8* Recent Developments

Radio astronomy continues to be an area of major research and development at the RRI. Some of the recent projects RRI has been engaged in are as follows:

A reconfigurable FPGA-based digital back-end has been built and installed at the ORT. This digitizes the signals from 22 modules of the telescope at the intermediate frequency (IF) stage and allows for either recording of the raw voltages or to combine them to form beams. This receiver will significantly enhance the versatility of the telescope.

RRI is currently engaged in the design and fabrication of a 40–90 MHz feed and receiver system for the GMRT. Four GMRT antennas have been equipped with the designed system and tests are in progress.

A wideband pulsar receiver capable of simultaneously sampling multiple frequency bands with dual polarzation is being developed. This can be used at the prime focus of any large aperture telescope, the current aim being the Green Bank Telescope in the USA.

A 12 m preloaded parabolic dish of a novel design developed and patented by Swarup and Tapde (2000) of NCRA has been constructed and installed by RRI at Gauribidanur. The characterization of the dish is currently in progress. Extensive photogrammetry measurements have been performed to provide feedback to structural analysis.

RRI has entered into a major partnership with the Murchison Wide-field Array telescope located in Western Australia. This telescope will eventually consist of 512 individual tiles of 16 dual-polarization dipoles each, optimized for operation over 80–300 MHz frequency range. Signals from these tiles will be combined at a central station. RRI has fabricated the first phase digital receiver for eight tiles, which digitizes the 16 analog signals, breaks each of them up into 256 spectral channels, selects 25 channels each (about 32 MHz bandwidth) and transmits them to the central station over fibre links.

## 5.6 Radio Astronomy at the Physical Research Laboratory

### *5.6.1 Interplanetary Scintillations, Solar Wind and Solar Studies*

*Introduction:* The radio astronomy work was initiated at the PRL by Bhonsle and colleagues in mid 1960s who built a 10.7 cm receiver for monitoring solar activity. Later dipole arrays were built at three stations for measuring the velocity of solar wind by observing interplanetary scintillations (IPS) at 103 MHz (Alurkar et al. 1989). The arrays were used for scintillation studies of compact extragalactic sources. The three IPS arrays have been shut down since 2000 due to intense interference from nearby TV transmitters. Subsequently the radio astronomy group at PRL has been using national and international facilities.

*The Three Station IPS Network at PRL:* The locations of the three arrays are shown on the right in (Figure 5.32). The average baseline separation between the three telescopes was $\sim$ 200 km, the size of the first Fresnel zone near the sun at 103 MHz. While the arrays at Rajkot ($22^\circ$ $18^\circ N; 70^\circ$ $44'$ E) and Surat ($21^\circ$ $09^\circ N; 72^\circ$ $47'$E) had a collecting area of 500 $m^2$ each, the array at Thaltej near Ahmedabad, ($23^\circ$ $18'; 72^\circ$ $29'$), had a collecting area of 20,000 $m^2$. The primary objectives of this network was to study the structure and distribution of plasma density inhomogeneities in the interplanetary medium between 0.3 and 1 AU, to study the angular structure of compact radio sources and to make systematic and regular measurements of solar wind velocities. (Figure 5.32) shows a portion of the dipole array at Thaltej.

*IPS Studies of Cometary Ion Tails:* The phenomenon of IPS can be used to study the plasma in the cometary ion tails along the sight lines of radio sources. Observations were carried out with the Thaltej radio telescope on two occasions, when comets Halley and Austin (1989c1) occulted compact radio sources (Alurkar et al. 1986; Janardhan et al. 1992). Estimates were made of the rms electron density fluctuations ($\Delta$N) in the cometary ion tails.

*Studies of Interstellar Scattering Using IPS:* The IPS observations of extragalactic radio sources provide estimates of the angular size of their compact components. A comparison was made between IPS observations using the Thaltej array at 103 MHz and measurements made using an array at Cambridge at 151 MHz. It was found that appreciable enhanced scattering occurs in the plane of the galaxy (Janardhan and Alurkar 1993). The interstellar scatter broaening at 103 MHz was estimated to be 0.07 arc-sec for galactic latitudes $|b| > 20^\circ$.

*Ulysses Solar Corona Experiment (Solar Wind Studies Close to the sun and at High Latitudes):* While the phenomenon of IPS at metre wavelengths can be exploited to study the solar wind at distances beyond ap-

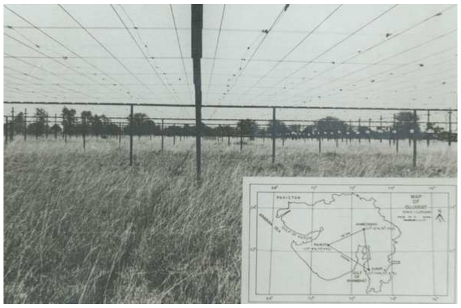

**Fig. 5.32** On top is seen a view of the dipole array at Thaltej, showing the reflecting plane and the individual dipoles loaded on open wire transmission lines; the inset shows the locations of the three IPS telescopes

proximately 40 solar radii, the plasma properties and structure of the solar wind at high latitudes and at distances <40 solar radii could be studied using dual-frequency Doppler sounding data from the Ulysses satellite's Solar Corona Experiment (SCE). The sounding data yielded solar wind velocities and measurements of columnar electron densities at southern solar latitudes between the pole and the equator in the distance range 4–40 solar radii (Janardhan et al. 1999). The Ulysses SCE was performed at the spacecraft's two solar conjunctions in summer 1991 and winter 1995.

*Study of Solar Wind Disappearance Events:* An extensive study of the extremely rare low-density solar wind anomalies at 1 AU, now known as "solar wind disappearance events" (e.g. Balasubramanian et al. 2003; Janardhan et al. 2008a) has shown that these events originate at the boundaries between large active regions and coronal holes located at central meridian and are caused by a process of interchange reconnection at the coronal hole and active region boundary. It has been shown that all disappearance events are characterised by extended periods of abnormally low densities at 1 AU, sometimes lower by two orders of magnitude from the average, and highly non-radial solar wind outflows. The azimuthal velocities can be as high as 100 km $s^{-1}$. Further, Janardhan et al. (2008b) showed that with the exception of co-rotating interacting regions, disappearance events provide the first link between the sun and space weather effects at 1 AU, arising from non-explosive solar events.

### 5.6.2 Solar Radio Emission and Space Weather

*Space Weather:* The rotation of the sun and its atmospheric disturbances are extremely complex phenomena and are likely to contribute to space weather. Vats (2007) has used 2.8 GHz solar radio emission over a period of several solar cycles to study the coronal rotation both on temporal and spatial scales. Mehta (2005) found that the coronal rotation has large temporal variations that correlate with the variability observed by optical methods, though there are differences in the radio and optical estimates of the coronal rotation. The first two components may be related to solar activity and Hale periodicities, respectively. The multi-frequency radio investigations reveal that the solar corona exhibits a differential rotation as a function of altitude (Vats et al. 2001).

### 5.6.3 Quasar and Pulsars

The giant quasar J1432+158 discovered using the GMRT is the largest single object known beyond a redshift of one (Singal et al. 2004). Using the Rajkot radio telescope at 103 MHz, a large number of giant pulses from the pulsar PSR 0950+08 were detected (Singal 2001). A possible detection was made of radio pulses from Geminga, a well known X-ray and gamma ray pulsar (Singal et al. 1999).

## 5.7 Conclusion

During the last 40 years several radio telescopes have been built in India, being amongst the best in the world. These have yielded many important results concerning a variety of radio sources in the universe. Successful design of the GMRT has played a role in the promotion of the ambitious Square Kilometre Array (SKA), as suggested by Swarup (1991) and Wilkinson (1991).

The indigenous design and construction of radio telescopes in India have also led to many spin offs. The design and construction of the ORT has contributed to growth of industries that have built a large number of antennas for satellite and microwave communication in the country. Many of the scientists and engineers who got trained in the radio astronomy groups later joined dozens of public and private institutes and industries. Four became professors in the Indian Institute of Technology at Bombay, Guwahati, Kharagpur and Madras.

The Indian radio astronomy groups have also contributed significantly to the construction of radio telescopes in Brazil and Mauritius.

Important scientific contributions and discoveries have been made by Indian radio astronomers in a wide variety of topics such as radio emission from the sun, pulsars, HII regions, recombination lines, supernova remnants, centre of our galaxy, dwarf galaxies, nearby galaxies, supernovae, radio galaxies, quasars, HI studies and cosmology. The relatively lower radio noise environment in India compared to that in the western countries, has allowed construction of several large facilities for operation at metre wavelengths.

The future of radio astronomy in India seems very bright. The GMRT is being upgraded to increase its capability very significantly. RRI is also adding several new facilities. It is proposed to initiate Very Long Baseline Interferometry (VLBI) between the GMRT and radio telescopes in Australia and elsewhere. Since the GMRT has a large collecting area, I suggest that it would also be advantageous for training of students to develop an Indian VLBI network by installing modest size radio telescopes, say of 6 m diameter, at some of the Indian Institutes of Technologies (IITs), Indian Institutes of Science Education and Research (IISERs) and selected universities; this is practical today with the availability of low cost storage disks of 1,000 GB and also economical Rubidium clocks. The pressing need is to undertake novel educational training programmes which would attract more students in the field of experimental astronomy in India and its potential spin offs. There are many unsolved problems and key questions concerning the Nature that would continue to inspire mankind for decades to come.

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