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Emergence of radio astronomy—The Indian scenario

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Professor S K Mitra, the initiator of post graduate studies in radio-electronics and the pioneer of radio research in India realized the far-reaching importance of the then emerging science of radio astronomy, as early as mid-forties. The exposition of the subject has been dedicated to the memory of esteemed Professor S K Mitra. The article is divided into three broad heads, namely (i) the emergence of radio astronomy—achievements made so far, (ii) some major contributions made by the Indian scientists working abroad in the fifties, and (iii) the emergence of radio astronomy in India and its present status.

1 Introduction

1.1 Emergence of radio astronomy—Highlights of achievements

Even before the fifties of the present century we knew astronomy to be one and the only one—the oldest of all sciences. It is the science which tells us all about the Universe. The devotees of this science are astronomers and astrophysicists and the tools used for investigations are big telescopes, spectroscopes and interferometers backed by complicated mathematical analyses. The aim of investigations had always been to collect as much of light energy as possible emitted from the heavenly bodies and to analyse and interpret these on the basis of standard physical laws. Size, structure, distance, movement and other like parameters of stars and galaxies were gradually determined. A pattern of the Universe with its manifold mysteries was thus known to man.

Radio astronomy is a comparatively new science, founded in the first half of the present century by the radio and electronic engineers. Basically, it is concerned with the study of the Universe by means of radio waves of wavelengths ranging from about 1 cm to about 15 m. Investigations are of two categories: (1) studies on nearby objects like meteors, moon and planets by sending suitable pulses of radio energy and detecting the reflected or scattered signals from these objects and (2) studies on the different types of heavenly bodies like planets, stars and galaxies by detecting the radio radiations at different wavelengths emitted by them. However, the scope of the first category is rather limited and as such radio astronomy to-day, is mainly concerned with the investigations of the second category. Like optical astronomy (wavelength range 0.4-0.8 micron) radio astronomy has been possible only because of the fact that the radio wavelengths 1cm-15 m and some narrow bands of mm waves can only pass through the atmosphere. Radiations at shorter wavelengths are absorbed by the atmospheric gases and the longer wavelengths are reflected back by the earth's ionosphere. It is popularly said that the atmosphere possesses two windows; optical and radio and consequently two astronomies. Optical and radio astronomies could be developed in the ground based* observatories. The origin of this new science has been based on a rather accidental discovery in the early thirties.

In 1930, Karl Jansky of Bell Telephone Laboratories, USA, while studying atmospheric static at a wavelength of about 15 m discovered electromagnetic waves of extraterrestrial origin. From repeated observations, he concluded that the principal source showed a periodicity of 23 hr 56 min, characteristic of sidereal objects like the stars and its direction coincided with that of galactic centre in the constellation of sagittarius. jansky's discovery was subsequently corroborated by Grote Reber, another radio engineer from Illinois, USA. For the purpose, he constructed a radio telescope, first of its kind, of about 31 feet in diameter and tuned at a wavelength, 1.87 m. He also observed that the radio sources were

*Since the advent of satellites and deep space probes, other astronomies like infrared, ultraviolet, X-ray & γ-ray, have also been developed subsequently.

distributed predominantly along the milky way. The production of the first radio maps of the milky way was thus another important achievement of Reber. World War II intervened and further researches in this new field were stopped. However, during the closing years of the war a remarkable discovery was made by another radio engineer, J S Hey, in England. Almost every afternoon coastal radar receivers all around the British Isles detected strong interfering signals. This was first thought to be a special type of jamming of radio signals, perhaps introduced by the Germans. But Hey, by his remarkable intuition, traced the origin of this queer signals in the setting sun which was carrying a large sunspot group at that time. He was thus credited with the discvoery of radio emission from the disturbed sun. However, the quiet sun radio emission ($\lambda = 3.2$ cm) was first detected by G C Southworth in 1942. He devised a low noise microwave receiver for this purpose.

The observations referred to above are of continuum radiation. However, the scientists soon realized that any monochromatic radiation in the radio spectrum would have immense significance. In mid-forties, H C Van de Hulst of Leiden Observatory, Holland, predicted from theoretical considerations that a line radiation at a wavelength of 21 cm** might be observable from neutral atomic hydrogen in interstellar space. In the early fifties, three groups of scientists from Holland, USA and Australia detected this predicted line almost simultaneously. This opened one of the exciting chapters in radio astronomy and helped radio astronomers to determine for the first time the spiral structure of our local galaxy.

Immediately after the war, a band of experienced radio and electronic engineers who were mainly responsible for the development of radar, directional antenna systems, sensitive receivers and other special type of electronic instruments, went back to the universities and research institutes to pursue radio astronomical investigations. Active centres were thus created mainly in England, Australia and Holland. Their war-time expertise paid large dividends in no time and the practical application of radio and electronics invaded the realms of astronomy. By early fifties, the new science of radio astronomy gained the general acceptance of astronomers, astrophysicists and cosmologists. Radio astronomical observatories, small or big were established in many other countries including India. Colossal radio telescopes, radio interferometers, dynamic spectrographs and the like were constructed and commissioned in the radio astronomical observatories with the aim of collecting as much of radio energy as possible, emitted by the heavenly objects.

In the early days of radio astronomy, observations were severely limited by (1) poor angular resolution, (2) limited sensitivity and (3) poor image forming ability. The history of radio astronomy, has been one of steadily increasing angular resolution, improved sensitivity and image formation achieved by novel techniques [like very long baseline interferometers (VLBI), very large array (VLA) sophsiticated aperture synthesis technique, large scale use of computers, different types of radiometers and image processing techniques], developed over the decades.

1.2 Highlights of achievements

Developments in radio astronomy over the last few decades have been phenomenal. One can summarize the highlights of achievements as follows:

In the fifties, growth of radio astronomical laboratories in different countries; construction of large radio telescopes both fixed and steerable; large collinear arrays and radio interferometers of special designs; aperture synthesis technique, radio analogue of diffraction grating; cataloguing and identification of sources, measurement of the apparent angular structure of radio sources; and determination of the galactic structure, were the major achievements.

In the sixties, development of very long baseline interferometers (VLBI) or the intercontinental interferometers and the role of computers; precise position determination by the occultation technique; discovery of quasars and pulsars; detection of 2.7 K-background radiation and the interstellar molecular lines were outstanding.

In the seventies, satellites and deep space probes have widened the horizon and radio astronomical observations at all other wavelengths are now possible. Other astronomies like UV, X-ray, γ-ray and infrared astronomies are emerging. The possibilities for the search of intelligence elsewhere in the Universe have also been evoked.

Thus through well-organized researches for the last several decades with novel techniques and sophisticated instruments in the different radio astronomical observatories all over the globe, much has been known about the Universe in general and about the different sources in particular. These may be classified as follows:

**Earlier, Prof. M.N. Saha also mentioned in one of his papers the possibility of such a hyperfine transition in neutral atomic hydrogen. However, he did not mention anything about its cosmological significance (*Personal Communication*).

Radio Universe

- Radio galaxy (Milky way)
  - Radio solar system (Sun, Planets, Moon)
  - Radio stars (Variable Stars)
  - Radio nebulae
  - Remnants of supernova (Crab)
  - Neutral hydrogen atom (21 cm)
  - Interstellar molecules
  - Pulsars*
- Extragalactic sources
  - Normal galaxies
  - Radio galaxies
  - Quasars
  - †Background radiation (2.7 K)

Knowledge gained by radio astronomy can be broadly classified under two heads. First, radio astronomy supplements basic information derived by optical astronomy, viz. visible surfaces of moon and planets, solar atmosphere, flare stars and the like. Secondly, radio astronomy revealed hitherto unknown and predominantly invisible phenomena, viz. Jovian radiation belts, interplanetary plasma, galactic distribution of neutral hydrogen, zones of high energy particles and fields in radio galaxies, quasars, pulsars, maser emission of molecular lines and the like. It has thus ushered in a new era of exploration of the Universe up to its so called observable limit.

2 Major-contributions made by some Indian scientists working abroad during the fifties

In the fifties, several Indian scientists had the previlege of working in the different Radio Astronomical Centres abroad. Mention may be made of M K Das Gupta, A P Mitra, M R Kundu, Govinda Swarup, R Parathasarathy, T Krishnan, T K Menon and V Radhakrishnan, all of whom made fundamental contributions in their respective fields of investigation. Some of these are briefly discussed in the following sections.

2.1 Contributions of M K Das Gupta (at Jodrell Bank, Manchester)

Das Gupta joined the Jodrell Bank group at Manchester in November 1950. In collaboration with R C Jennison he constructed the 'post-detector correlation interferometer', first conceived by Hanbury Brown. The theory of this new interferometer, subsequently designated as the 'intensity interferometer' was developed by Hanbury Brown and R Q Twiss[1]. This interferometer consisted of two independent receivers tuned to 125 MHz. The intermediate frequency output of each receiver was rectified in a square law detector. The detected signal was then passed through identical low frequency filters (pass-band 1-2.5 kHz). A radio link was used to bring the detected signal from the outstation to the home station and their correlation was measured in a linear multiplier. The correlation was found to be proportional to the square of the fringe visibility in a conventional interferometer[1]. With this method, using radio link, long base lines could be successfully achieved perhaps for the first time.

Measurements made at different base lines (extending up to 4 km) and orientations, proved Cassiopeia-A (CAS-A) to be nearly circular in outline with an angular size of 3.5 min of arc, while Cygnus-A (CYG-A) was elongated and measured roughly 2×0.5 min of arc (Ref. 2). Subsequent measurements at longer baselines (up to about 20 km) made by Jennison and Das Gupta[3,4] proved that CYG-A consisted of two separate sources each measuring $30'' \times 50''$ of arc and separated by $1'28''$ of arc; the central visual object being about $30''$ of arc in diameter. The studies[2,3] have been reprinted in the book, '*Classics in Radio Astronomy*' by W T Sullivan III with the remark: "The real surprise comes in Paper33[3] when Jennison and Das Gupta continue their investigation of the structure of CYG-A and find that it is not best modelled as a single elongated source, but rather as two components well separated and of approximately equal intensity ... This first double radio source then of course immediately raised the question of why the optical image and radio brightness distribution be so different. And to-day we

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Nobel Prize in Physics awarded to radio astronomers:

*Ryle—For development of radio telescopes of large resolving powers

*Hewish—For the discovery of pulsars

†Penzias & Wilson—For the discovery of the background radiation (2.7 K)

are still asking that same question." To-day, it is known that the majority of radio galaxies and quasars are double or more complicated type of sources.

2.2 Contributions of A P Mitra (at C.S.I.R.O., Australia)

Although Mitra did not work in radio astronomy, but he made pioneering contributions in the application of radio astronomical techniques for ionospheric measurements. In a comprehensive review paper[5] he examined how the radio frequency radiations from extraterrestrial sources could be utilized for such measurements like—ionospheric refraction, attentuation and absorption as also the scintillations of radio sources. Subsequently Mitra and Shain[6] developed the technique of measurement of ionospheric absorption using obsevations of 18.3 MHz cosmic radio noise. They also examined the effects of solar flares on such absorption[7]. The technique designated later as the Relative Ionospheric Opacity Meter (RIOMETER), has been widely used since then, particularly during the International Geophysical Year (IGY).

2.3 Contributions of G Swarup (at Sydney, Harvard and Stanford)

During the fifties and early sixties Swarup made some fundamental contributions in the early developments of solar radio astronomy. Swarup and Parthasarathy[8] found the brightness distribution of the quiet sun on 60 cm-λ using the 32-element interferometer developed by Christiansen. They observed that the brightness distribution does not vary with solar cycle, whereas the brightness temperature increases by a factor of two from the sunspot minimum to the maximum period. They also made detailed studies on the slowly varying component and observed that it was quite strong on 60 cm-λ. The detected short term variability having periods of ~30 min, as well as the higher brightness temperature led them to conclude that the *S*-component on longer decimetre waves may have a non-thermal origin[8].

Swarup[9] in collaboration with Maxwell made dynamic spectral observations on metre wave solar bursts (100-580 MHz range) at Fort Davis. They identified a new type of fast-drift burst appearing on the records as an inverted 'U'. It was observed that a type-III burst starting with a normal frequency drift suddenly reversed, resulting in this new type of burst.

Swarup *et al.*[10] examined the association of Type-II and Type-III solar radio bursts in the range 100-580 MHz with flares and prominences. Type-II bursts showed about 91% association with flares, but the association with prominences was rather small. Majority of the Type-III bursts were found to occur between the start and the maximum phase of the flares. Swarup in collaboration with Bracewell[11] developed the crossed multi-element interferometer at Stanford on 9.1 cm-λ. Using a digital system of recording the receiver output, daily 9.1 cm-λ maps of the sun were obtained by them.

Discovery of the U-type of solar radio bursts; extensive studies on the sun at cm- and dm-wavelengths; gyroradiation model to explain the slowly varying component of solar radio emission and the development of a new technique for phase adjustment of large antenna systems are some of the major contributions made by Swarup[12] in the evolution of radio astronomy in general and solar radio astronomy in particular.

2.4 Contributions of M R Kundu (Nancay, Maryland and Michigan)

Kundu in collaboration with Alon and Steinberg[13] developed a special type of interferometric device on 3 cm-λ. Besides the elaborate studies on the brightness distribution of slowly varying solar radio sources, it could successfully measure absolute flux density, angular size, brightness temperature and polarization of the cm-burst radiation. Kundu[14] made elaborate studies on persistent solar radio sources on centimetric wavelengths. He found that some of these intense and narrow sources were mostly connected with the eruptive activity of the sun. Subsequently, Kundu[15,16] made some fundamental contributions as to the structure and properties of solar activity at centimetric wavelengths from his interferometric observations. Development of one-dimensional earth-rotation synthesis technique and the determination of the core-halo structure in slowly varying component (SVC) sources by Kundu are recognized as major events in the development of solar radio astronomy at cm-wavelengths.

Besides these, Kundu in collaboration with Denisse[17] examined in details the suitability of solar decimetric radiation as an index for ionospheric studies. They found the new index to be a better one than the existing Wolf number *R* for most of the ionospheric studies.

Subsequently, Kundu and Haddock[18] made a statistical study of the nature of cm- and m-wave solar radio outbursts associated with polar cap absorption (PCA). Besides the prediction of solar proton events, they also suggested that the 'active regions' generating cm-λ outbursts and type-IV events play an important role in the storage and trapping of the protons responsible for the PCA events.

Kundu's fundamental contributions, particularly, in the different branches of solar radio astronomy in the subsequent decades have been quite phenomenal. His authoritative book, *Solar Radio Astronomy*, first of its kind, published in 1965, has always been a 'source book' for workers in this field.

2.5 Contributions of T Krishnan (Sydney)

Krishnan and Mullaly[19] used a Christiansen crossed-grating interferometer to make observations of 1420 MHz solar radio bursts. They examined the bursts recorded concurrent with solar Type-IV radiation. They found that the metre-wavelength sources were located in the high corona, but the decimetric sources remained fairly stationary in the chromosphere or lower corona. They concluded that the sources of decimetric bursts must be different from those of metre-wavelength Type-IV radiation.

Krishnan and Labrum[20] from observations of a partial eclipse combined with the narrow pencil-beam records or 21 cm-λ confirmed that the apparent solar disk temperature ($\sim$140,000 K) at sunspot maximum is about twice the value at sunspot minimum.

Krishnan and Mullaly[21] examined the position and height of bursts on 1420 MHz in relation to those of the bright regions, i.e. sources of the slowly varying component. They observed that these were never more than 1.5 arc apart. Fruther, the heights of these bursts were within 70,000 km above the photosphere.

2.6 Contributions of T K Menon (Harvard)

Menon joined the Harvard Radio Astronomy group in mid-fifties. The activities of the group were concerned with the study of galactic structure mainly from 21-cm hydrogen line emission. Menon[22] succeeded in mapping the radio distribution of the Orion nebula and the Rosette nebula at centimetric wavelengths using the NRAO 85-ft radio telescope. Using the 60-ft radio telescope of the Harvard College Observatory at Agassiz, Menon showed that the expanding Cygnus loop envelope contained a neutral-hydrogen region on the inside. Menon later became the leader of the group at Harvard and subsequently made significant contributions in the galactic structure studies based on 21-cm hydrogen line observations.

2.7 Contributions of V Radhakrishnan (Gothenberg and Cal. Tech.—Owens Valley)

In the early years of the development of radio astronomy, Radhakrishnan's major contributions were concerned with the studies on the radio emission from the planet, Jupiter, the largest in the solar system. It was believed that such a large planet having a strong magnetic field might give rise to more intense regions of magnetically trapped electrons than the earth's Van Allen belts. Radhakrishnan and Roberts[23] using the Cal. Tech. interferometer on metric wavelengths firmly established that the Jupiter's equatorial radio diameter was about three times that of the planet. They also detected a strong linearly polarized component which supported the presence of a strong non-thermal component in the Jupiter's radio emission.

Besides those mentioned above, several other Indian scientists worked in the different radio astronomical centres abroad. The most notable amongst them were R V Bhonsle (Stanford), M N Joshi (France) and N V C Sarma (Netherlands).

It may thus be said that the Indian scientists working abroad in the fifties and early sixties made significant contributions in the development of different branches of radio astronomy as highlighted above. Their advanced training and research paved the way to the successful implementation of radio astronomical work in India. The following section deals with the "emergence of radio astronomy in India" and its subsequent developments.

3 Emergence of radio astronomy—The Indian scenario

The fundamental contributions made by the Indian scientists working abroad, as discussed in the previous section, aroused interest in the minds of eminent scientists like C V Raman, M N Saha, S K Mitra, H J Bhabha and others in India. Their interest was further strengthened through occasional visits they made to the advanced centres of radio astronomical research abroad. The author particularly remembers the visits of Bhabha, Saha and Sarabhai to the Jodrell Bank Experimental Station, Manchester, in the early fifties when he had been working there. They were very much impressed and perhaps were mentally prepared to see this new science emerges in India in due course.

Saha was particularly interested in the 21-cm line radiation work and visited Oort and Van de Hulst's laboratory at Leiden. He contemplated to start similar work in Calcutta which, however, could not materialize due to his sudden death. Later, in recognition of Saha's keen interest, a radio astronomy Institute was announced to be founded in his memory by his students, friends and admirers, pioneered by the renowned Chemist, Prof. P R Roy. For some reasons or other the proposed Institute was never built. On the author's return to Calcutta, Prof. Mitra showed a keen interest and inspired him to start solar radio astronomy work. A humble start was made but could not progress much due to lack of funds and appropriate facilities available at that time in a University department. Even with meagre resources similar attempts were made elsewhere and by the end of the fifties, reference was made of five radio astronomy centres in the URSI records. These are: Astrophysical Observatory, Kodaikanal (A K Das); Institute of Radio Physics and Electronics, Calcutta University (M K Das Gupta); Radio Propgation Unit of the National Physical Laboratory, Delhi (A P Mitra); Physics Laboratory, Osmania University, Hyderabad (M Krishnamurthy) and the Physical Research Laboratory, Ahmedabad (K R Ramanathan). A brief account of the activities of these centres in the fifties and early sixties are presented in the following sub-sections.

Before we discuss about the early attempts to start radio astronomical investigations at the different centres mentioned above it will be worthwhile to mention about Saha's work as early as 1947. Saha, Banerjee and Guha[24] examined in detail the condition of escape of microwaves from the sun. Applying magneto-ionic theory of propagation of radio waves through an ionized medium traversed by magnetic field they concluded that the *e*-component of the wave could escape from deeper layers of the solar atmosphere. According to them radio waves could actually be emitted by the spot region. The theory could also explain circular polarization and intensification of emission with the onset of radio flares.

3.1 Indian Institute of Astrophysics (IIA), Kodaikanal

A K Das initiated radio astronomical investigations in 1952. With an indigenously built twin-Yagi interferometer at 100 MHz continuous recording of solar radio noise flux was undertaken. Scintillation observations of two strong radio sources CYG-A and CAS-A were also made. In the early sixties, radio radiation from Jupiter at 22.2 MHz and a regular solar patrol with a 3000 MHz radiometer were also initiated[25].

3.2 Institute of Radio Physics & Electronics (INRAPHEL), Calcutta University

A simple radiometer at 100 MHz was developed to record enhanced solar radio emission. Different types of bursts were recorded for about a year in the late fifties. However, with the decline of solar activity the equipment proved to be insensitive and the observation was discontinued. Extensive statistical investigations were subsequently undertaken using the published data of solar radio emission at cm- and dm-wavelengths. From these studies, effect of the earth's orbital eccentricity on the incident solar flux at 10.7 cm (Ref.26); nature of the slowly varying component[27]; spectra of the different types of solar microwave bursts and of the slowly varying component[28,29] were delineated.

3.3 Physical Laboratories, Osmania University, Hyderabad

Led by M Krishnamurthi, the group at Hyderabad made extensive observations of 'sudden cosmic noise absorption' (SCNA) at a frequency of 30 MHz particularly during the IGY period. They reported some abnormal ionospheric behaviour[30]. They also made some valuable studies on the enhanced solar radio emission at the same frequency[31].

3.4 Physical Research Laboratory (PRL), Ahmedabad

Radio astronomical investigations at the PRL were initiated in mid-fifties with the development of a simple radio telescope. The group was first led by K R Ramanathan and subsequently by R V Bhonsle. Regular monitoring of cosmic radio noise at 25 MHz (Ref.32) began in 1956. Subsequently a RIOMETER was used for measurement of ionospheric attenuation at 21.3 MHz. Bhonsle and Alurkar[33] constructed a solar radio spectroscope in the frequency range 40-240 MHz. A solar microwave radiometer at 2.8 GHz; a solar radiopolarimeter at 35 MHz and phase-switched interferometers at 60, 74 and 120 MHz for studying scintillations of radio sources CAS-A and CYG-A were also subsequently developed[34]. The centre gradually developed to be one of the major centres in India.

3.5 National Physical Laboratory (NPL), Delhi

As the leader of the Radio Propagation Unit (later designated as the Radio Science Division), NPL, A P Mitra introduced different radio astronomical techniques for upper atmospheric investigations and also for radio patrol of solar flares[35,36]. Large scale use, particularly of the RIOMETER technique at different centres during the IGY and IQSY period was due to his initiative as the secretary and co-ordinator of the Indian IGY programmes. Regular solar flux measurements at 2000 MHz for several years were also made. Solar geophysical data books had been published for use by the Indian workers. Besides these, solar microwave radiations at a couple of frequencies had been subsequently monitored for studying the attenuation characteristics under different meteorological conditions, for the first time in India.

From the above discussions it will be quite evident that starting from the early fifties to mid-sixties (particularly during the IGY and IQSY periods) main emphasis in India was on the large scale use of radio astronomical techniques for ionospheric measurements and on the measurements of enhanced solar radio emission at several frequency ranges. It must be admitted that nothing spectacular in radio astronomy was achieved out of these initial efforts. However, it helped in growing an awareness about the importance of the emerging science in the minds of the Indian scientists and science policy makers in the Government organizations. In the following section a brief account of the emergence of radio astronomy and subsequent developments in India is presented.

4 Mid-sixties and the subsequent developments of major facilities in India

In the early sixties a unique venture was made by four Indian radio astronomers working abroad (G Swarup, M R Kundu, T K Menon and T Krishnan). They sent a letter of appeal, particularly, to Dr Homi J Bhabha emphasizing the importance of the emerging science and their keen interest in developing the same in India. Dr Bhabha immediately responded to the proposal and granted necessary funds initially from the Tata Institute of Fundamental Research (TIFR), Bombay. Led by G Swarup a group was formed in the early sixties. A high resolution grating-type radio interferometer operating at 600 MHz was set up at Kalyan. In the fifties Swarup and Parthasarathy* worked with this interferometer, developed by Christiansen at Potts Hill near Sydney. The dishes were subsequently sent to the National Physical Laboratory, under the Colombo plan. In the set-up, 24 parabolic dishes each of 1.8 m diameter were placed along an east-west baseline of 630 m and 8 along north-south baseline of length 256 m. The resolution achieved was 2.3 × 5.2 arc min. For about a period of three years the telescope was in use for studying the solar radio emission. It was observed that the quiet sun shows limb-brightening at 50 cm-λ, the corona has a temperature of about 1.5×10^6 K and the scattering effects in the inner corona are not as large as suggested by earlier workers. Subsequently, one of the finest radio astronomy centres came into operation since 1970 under the dynamic leadership of G Swarup at a specially selected site at Ootacamund in the Nilgiri Hills.

4.1 Ooty Radio Telescope (ORT)

Operating in the frequency band 322-328.5 MHz, ORT[37,38] is one of the largest of its kind in the world. A cylindrical paraboloid having closely spaced conducting wires as the reflecting surface, it is 530 m long in the N-S and 30 m wide in the E-W directions. It has an effective collecting area of about 8000 m^2. Erected on a convenient slope ($\sim 11°$) of the Nilgiri Hills its N-S axis is parallel to the earth's rotational axis. This means that once set properly, it can track a radio source for about 9.5 hours by mechanical rotation of the telescope in E-W direction. It can be conveniently pointed in declination by about $\pm 40°$, steering the beam by electronic phasing of the 1056 dipoles at the focal line of the cylinder. The ORT has been designed and fabricated fully indigenously.

Subsequently, a more refined equipment, Ooty Synthesis Radio Telescope (OSRT)[39] was set up. It consists of ORT and seven small parabolic reflectors of size 22 m × 9 m spread along base lines up to 4 km With a resolution of ~ 1 arc min at 92 cm, it has been used very effectively, particularly, for the mapping of some radio galaxies. Fundamental contributions from these centres have been made in the following branches of radio astronomy: (i) studies on the position and brightness distribution of galactic and extragalactic radio sources (about 1200 in number) using the lunar occultation technique, (ii) detection of several new pulsars and interplanetary scintillation observations for the structure determination of radio galaxies and quasars.

Besides these, India participated in the VLBI observations at 327 MHz made in December 1983. Radio telescopes at Ooty, Jodrell Bank (UK), Crimea (USSR), Westerbark (Netherlands) and Torun (Poland) were used. Structures of nuclei of many radio galaxies and quasars were determined from the data thus obtained. A recent publication, *25 Years of Radio Astronomy at Tata Institute of Fundamental Research* by the Radio Astronomy Centre, Ootacamund (1989) is an authoritative document on the subject. A 'giant metrewave radio telescope' (GMRT), conceived by Swarup is under construction at a site near Pune. Swarup has also taken an initiative in involving some of the universities in radio astronomical investigations.

4.2 Radio astronomy at the Raman Research Institute (RRI), Bangalore

V Radhakrishnan initiated radio astronomical investigations at the RRI in 1972 when he took over as the Director. A large decametre radio telescope operating on 34.5 MHz has been set up at Gauribidanur as a collaborative project with the Indian Institute of Astrophysics, Bangalore[40]. The telescope consists of a T-shaped array of 640 broad band dipoles in the E-W arm (extending upto ~ 1.5

* *The Early Years of Radio Astronomy*, edited by Sullivan III W T (Cambridge University Press, GB) 1984, 124.

km) and 360 in the south arm ($\sim$0.5 km). With an effective collecting area of $\sim$ 20,000 sq.m, it has a resolution of 28 arc sec × 40 arc sec and has a sensitivity of 30 Janskys. Since 1979 it has been in use to study the sun and interplanetary space by the scintillation technique and to investigate extended galactic regions such as ionized hydrogen clouds. Radio mappings of the sun, the Cygnus loop and of the galactic central region at 34.5 MHz are some of the major achievements. Besides these, high resolution pulse profiles and accurate estimates of pulse energies for eight pulsars have been determined.

Another major new facility has recently been commissioned at the Raman Research Institute. This is an indigenously built, mm-wave radio telescope, first of its kind in India, with a 10.4 m diameter reflector dish operating in the ranges 22-110 GHz. The programmes include: the determination of the continuum flux from quasars and compact nuclei of distant galaxies, investigations on the high resolution molecular lines' spectroscopy and studies on the profiles of atmospheric ozone[41].

4.3 Solar Wind Observatory at PRL, Ahmedabad

First conceived by Bhonsle and subsequently developed by Bhonsle, Alurkar and their collaborators, the three-station 'Interplanetary Scintillation' (IPS) network has been set up for interplanetary studies. The IPS telescope[42] consists of a three-station array on a frequency of 103 MHz, located at Thaltej (near Ahmedabad), Rajkot and Surat in Gujarat, forming a triangle with baselines of about 200 km each. The Thaltej radio telescope array has a collecting area of 10,000 sq.m and those at Surat and Rajkot around 5000 sq.m each. All the three telescopes have crystal controlled clocks assuring synchronization in operation. Solar wind velocity measurements are being regularly made. Using the Thaltej radio telescope, enhanced scintillations of PKS 2314 + 03 have been studied when the source was occulted by the ion tail of Halley's comet in December 1985. The IPS network can also be used as a VLBI system to study the angular size of radio galaxies and quasars at metre-wavelengths. Recently, the antenna array of the IPS telescope at Thaltej is being enlarged to $\sim$20,000 sq.m, which in conjunction with 32 double channel receivers will be able to continuously monitor scintillation flux of hundreds of radio galaxies.

Indigenous development of radio astronomical instrumentation and techniques coupled with experimental and theoretical investigations of high standards made by the workers in centres like TIFR, RRI, IIA and PRL have led India to be one of the leading centres of radio astronomy today. The dreams of the visionaries like Raman, Saha, Mitra and Bhabha have thus been fulfilled by their successors.

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