The Metrewavelength Sky
ASI Conference Series, 2014, Vol. 13, pp 429 – 439
Edited by J. N. Chengalur & Y. Gupta

Radio Astronomy at TIFR, some highlights and reminiscences

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Abstract. Radio astronomy research was initiated at TIFR fifty years ago. In this historical article, I firstly trace my initiation in the field of radio astronomy during 1953-55 in the Radio Physics Laboratory of CSIRO in Australia and later during 1956-63 in USA. In September 1961, four radio astronomers working abroad wrote to a number of scientific organizations in India with their desire to start radio astronomy research in India. Soon thereafter Dr. Homi Bhabha, the founder Director of TIFR, approved the formation of a radio astronomy group therein. I joined TIFR in April 1963. During the last 50 years, TIFR has built two of the world's largest radio telescopes, namely the 530m long and 30 m wide parabolic cylinder equatorially mounted on a hill at Ooty in South India during 1960s and the Giant Metrewave Radio Telescope near Pune, consisting of 30 nos. of fully steerable parabolic dishes of 45 m diameters during 1990s. Fifty years of radio astronomy research at TIFR is briefly highlighted here.

1. Introduction

In this article, I plan to trace firstly my career during 1950-1963, that laid the foundation to my endeavors after I joined TIFR in April 1963; see more details in Swarup (2006). After my M.Sc. degree in Physics from the Allahabad University in 1950, I joined the National Physical Laboratory (NPL), New Delhi, where I set up an equipment operating at 3cm wavelength (using old WW II radar equipment) for research on paramagnetic resonance under the guidance of Dr. (Sir) K. S. Krishnan (co-discoverer of the Raman Effect). In August 1952, Dr. Krishnan attended the meeting of the International Union of Radio Science (URSI) held at Sydney in Australia. He was very impressed by the great discoveries being made at the Radio Physics Laboratory (RPL), CSIRO, Sydney, in the new field of radio astronomy. Soon after, Dr Krishnan recommended me to work at the RPL for 2 years during 1953-55 under the Colombo

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Figure 1. View looking east showing the east-west grating interferometer on the southern bank of a water supply reservoir at Potts Hill, Sygney, Australia. ATNF archive B2638-2.

Figure 2. Stanford Heliograph consisting of 32 parabolic dishes of 10Ft diameter each for daily mapping of solar radio brightness distibution at 3100 MHz (Bracewell ad Swarup 1961)

Plan fellowship. My mentor at RPL was the distinguished radio astronomer, Dr. J.L Pawsey, who fostered and guided the growth of radio astronomy research in Australia. Under his guidance, during the first year, I worked for 3 months each under four of the leading pioneers of radio astronomy at RPL, W.N. Christiansen, J.P Wild, B.Y. Mills and J.G. Bolton, and learnt the essential techniques of radio astronomy. During the 2nd year, I and R Parthasarathy converted the Chris's grating array (Fig. 1) to operate at 60 cm wavelength and published 3 papers. It was a fantastic experience.

In 1953, Christiansen was planning to build a new radio telescope at Fleurs. On my request, Pawsey offered to gift Chris's 32 antennas, each of 1.8 diameter, to India for initiating solar radio astronomy research at the NPL. Dr. Krishnan supported the proposal. I joined NPL in July 1955. As the transport of the dishes got caught in bureaucracy, I joined Harvard as a Research Associate in 1956, where a new 100-600 MHz sweeping spectrum analyzer attached to a 28 feet dish had been installed recently for solar radio astronomy observations at Fort Davis, Texas, under the leadership of Alan Maxwell. My Guru Dr. K.S. Krishnan and Dr. D.S. Kothari, Chairman of the University Grants Commission (UGC) came to the Delhi airport to wish Bon Voyage to me and my wife: Dr. Kothari touched my shoulder and said: "Govind Swarup, Vapas Ana! (Do come back)". That gesture remained in my mind for years. After a year at Harvard as a Research Associate, I joined the Stanford University in 1957 towards a Ph.D. degree, where I contributed to the construction of a Cross type antenna (Fig. 2) for making daily maps of the Sun at a wavelength of 9.1 cm (Bracewell

Figure 3. Dr. Homi Bhabha (1911-1966), founding Director of the Tata Institute of Fundamental Research, Mumbai.

& Swarup, 1960). After getting Ph. D. degree, I joined Stanford in January 1961 as an Assistant Professor. Later, I returned to India to join TIFR on 2nd April 1963, as described below.

2. Radio Astronomy at TIFR

2.1 IAU 61, Berkeley

As Miller Goss has described in this conference (Goss 2014), four radio astronomers working abroad (T.K. Menon, M.R. Kundu and me in USA, and T. Krishnan in Australia) met during the IAU General Assembly at Berkeley in August 1961, on a suggestion made by Dr. Pawsey. After detailed discussions, a proposal was sent by us to 4 major scientific organizations in India in September 1961, expressing our desire to return to India as a group and build a world class radio astronomy facility in India. The renowned physicist, Dr. Homi Bhabha (Fig. 3), the founder Director of TIFR responded promptly and sent a telex to 3 of us who were in USA to meet him in Washington DC in November 1961 during his forthcoming trip to USA. Dr. T.K. Menon working close by met Bhabha in Washington, D.C. in November 1961. In the proposal sent by us in September 1961, we had projected a budget of Rs. 5 lakhs (US $ 100,000: at that time $1 = Rs.4.7) for the first phase. Bhabha enquired about the cost of the Jodrell Bank and Parkes radio telescopes. T. K. Menon wrote to three of us: "He talked quiet happily of funds outlay of Rs. 50 lakhs to 100 lakhs (US $ 1 to 2 million)" "Unbelievable for us at present but he seemed perfectly sincere and credible". I may add that Bhabha was a very distinguished physicist. He was a close friend of Jawaharlal Nehru, first PM of India, after its independence from Britain in 1947. Distinguished astrophysicists, Dr. Bart Bok at Mt. Stromlo (formerly at Harvard), Dr. J. L. Pawsey in Sydney and Dr. J. A. Oort in Netherlands wrote to Bhabha recommending our proposal (see Miller Goss, this volume). On 20th January 1962, Bhabha sent a telegram to all four of us: "we have decided to establish Radio Astronomy Group. Letter follows with offer". A prompt action, by any of the standards in the world. I accepted the offer vide Feb. 8, 1962. Bhabha wrote to me on February 17, 1962, to join earliest "in view of the present need to push on scientific development in India". He later wrote to me in April 1962. "if your group fulfills the expectations we have of it, this could lead to some very much bigger equipment and work in Radio Astronomy in India" (NCRA archives). M. R. Kundu joined TIFR in 1965 but returned to USA in 1968. T. K. Menon joined TIFR in 1969 and returned to USA after several years. T. Krishnan joined the Madras Institute of Technology as Director in early 1970s. After some years, he resigned and found an antenna company that later carried out software analysis of some of the primary feeds of the GMRT in mid 1990s.

2.2 Start of the Radio Astronomy Group at TIFR

After visiting Leiden, Meudon and Bologna over 3 weeks in March 1963, I joined TIFR on 2nd April 1963. In our proposal we had projected to set up at first the 32 dishes of 1.8 m diameter (that were lying in crates at NPL) for solar radio astronomy observations and soon after to build a large Mills Cross operating at metre wavelengths. In view of Bhabha's encouragement and offer of substantial funds, if justified, I started to consider other possibilities. After spending 10 years abroad, I was returning to India with a dream to set up a world class radio astronomy facility here.

2.3 Genesis of the Ooty Radio Telescope

By 1963, there was a raging controversy between the Big Bang and Steady State Model of the Universe. Martin Ryle supported the Big Bang model based on steeper counts of weaker radio sources catalogued by his group than expected in the Steady State Model (log N vs. log S). On June 4, 1963, I read 2 papers in the beautiful library of TIFR, viz. Hazard's paper on the lunar occultation of 3C273 observed with the Parkes Radio Telescope and Martin Schmidt's deduction that 3C273 has a high redshift of 0.17, becoming the most distant known object at that time. It occurred to

Figure 4. Kalyan Radio Teescope (1965-1068) consisting of 32 dishes of 5.6 ft. diameter each (24 in 2000 ft. East-West array and 8 in 800 ft. North- South array.

me that we could consider to build a large parabolic cylinder, with 4 times the area of the Jodrell Bank 76m dish, equatorially mounted on a suitable hill taking advantage of India's proximity to the earth's equator, for measuring brightness distribution of several hundred weaker radio sources with arc second resolution using the method of lunar occultation, as weaker sources would be expected to have smaller angular size in the Big Bang Model. At that time, arc second angular size data was available only for only a few dozen sources of large flux density. After a 2 hour grilling in July 1963, Bhabha told me "to first establish an experimental group in radio astronomy at TIFR and your proposal for a large equatorial radio telescope will be approved soon after"!

2.4 Kalyan Radio Telescope, near Mumbai

Professor M.G.K. Menon, Dean, TIFR advised setting up the proposed solar radio telescope at first and work on the occultation telescope in due course. On Bhabha's request to CSIR, the 32 dishes were transferred from NPL to TIFR. Kapahi and Isloor joined us in August 1963. Three technical personals joined soon after. R.P. Sinha and D.S. Bagri joined in 1964. In September 1963, we located a site 7 km south of Kalyan, about 40 km away from TIFR in Bombay. For the solar radio telescope, we used an innovative single transmission line proposed by me, rather than the branching system used by Christiansen. As a result, the Kalyan Radio Telescope (Fig. 4) was completed within 18 months by May 1965 (Swarup et al. 1966). It was designed to work at 610 MHz for studies of the Quiet Sun and slowly varying components of the active Sun.

2.5 Search for a site for the Occultation Telescope and timeline

In December 1964, N.V.G. Sarma and M.N. Joshi resigned from the NPL and joined TIFR. During January 1965, a search for a suitable site for the equatorial parabolic cylinder was made by me and Ramesh Sinha by surveying about 20 hills in South India (selected by us after examination of dozens of the Survey of India maps) using a theodolite and a tall bamboo pole with 3 flags! Normally, a heavy wooden staff is used for survey with theodolite. For making a quick survey of many potential hills we used a bamboo pole, and estimated value of distance r using the relation $h = r \times \theta$. We finalized a site in the picturesque hill of Nilgiris (Blue Mountain) near the town of Ootacamund. The hill has a slope of $\sim 11^o 23'$ in the north-south direction, same as its latitude. Bhabha approved our proposal to construct a 530 m long and 30 m wide parabolic cylindrical radio telescope at Ootacamund (Ooty) in August 1965. He also approved a budget of Rs. 50 Lakhs (Rs. 5 million = US $ 700,000). Later, Bhabha approved the site in December 1965. The site was located in a reserved forest. From Ooty, he went to Madras and got approval by the Tamilnadu Government for the required 150 acres of land with a 30 year lease for the forest land. Most unfortunately Bhabha died on January 30th 1966 at age of only 57 yrs., as a

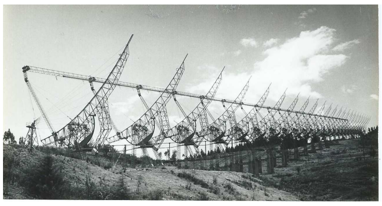

Figure 5. Ooty Radio Telescope consists of a 500m long and 30m wide parabolic cylindrical reflector. Its long axis of rotation is parallel to the axis of rotation of the Earth. There are 1054 dipoles receiving radiation at a frequency of 325 MHz (Swarup et al. 1971).

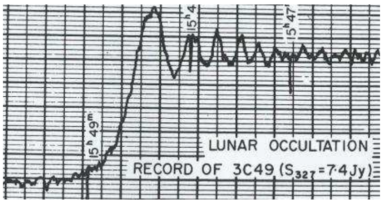

Figure 6. A lunar occultation record of the Radio Galaxy 3C49 recorded using the Ooty Radio Telescope.

result of the Air India plane crash in Alps near Geneva. (His untimely demise was tremendous loss to the national and international Science). The site was allocated to us by the District Magistrate (DM) of Ooty in April 1966 after some persuasion: [GS to DM: "Please allot the site urgently"; DM to GS: "What is life of a star"? GS to DM: "Sir millions of years"; DM to GS: "Then what is the hurry?"]. M/s Tata Consulting Engineers designed the Ooty Radio Telescope and M/s Bridge & Roof were selected as the contractor. The Ooty Radio Telescope (Swarup 1971) became operational on 18th February 1970 (Fig. 5). That night we made occultation observations of one predicted and 2 un-catalogued celestial radio sources! We had not slept for 2 nights.

2.6 Few Highlights of Scientific Contributions of ORT

During 1971 to 1977, ORT occultation observations (Fig. 6) provided 1 to 10 arcsec resolution for 1000 radio galaxies, quasars, BL Lac and a few galactic radio sources (leading to many papers by M.N. Joshi, N.V.G. Sarma, V.K. Kapahi, C.R. Subrahmanya, Gopal-Krishna, Swarup, & others) that resulted in 6 Nature papers within 6 years (and also 1 of the Kalyan Radio Telescope in 1966) ! During the last 43 years about 300 papers have been published in refereed journals based on ORT observations (Swarup 1991: 25 years of radio astronomy at TIFR). Only a few are highlighted here. The Ooty Radio Telescope operated in the band 322-328.6 MHz internationally protected for radio astronomy observations that included the important line emission by the primordial Deuterium.

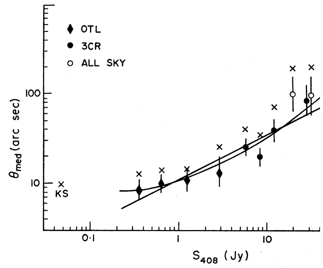

Figure 7. Angular Size Flux Density relation

Based on Ooty occultation observations, Swarup (1976) established an Angular Size - Flux Density relation (Fig.7), providing support to the Big Bang Model (Kapahi 1976). Kapahi & Kulkarni and also Gopal-Krishna discussed dependence of the spectral index of extragalactic radio sources on their flux density. Occultation observations of the Galactic Centre region, Sgr A, provided separation of its thermal and non-thermal nature (Gopal-Krishna & Swarup 1976). Pulsar observations were made and several pulsars discovered (Balasubramanin, Krishnamohan, Mohanty and Swarup). Anantharamiah and colleagues from the Raman Research Institute investigated radio recombination lines from regions of low density in the Galaxy. Interplanetary scintillation (IPS) observations of radio sources in the frequency band of 324-328 MHz provided sub arc-second resolution for 4000 radio sources (Ananthkrishnan, Rao and Bhandari). IPS observations combined with the VLA observations led to the discovery of the gravitational lens 1830-211 (Subrahmanyan, Narasimha, Rao and Swarup). Today, daily IPS observations of 1000 compact radio sources at Ooty provide daily measurement of the Solar wind velocity, providing important data about the Coronal Mass Ejections and its impact on the Earth's environment (Manoharan 2012).

2.7 Ooty Synthesis Radio Telescope at 327 MHz (1980s)

Utilizing the large collecting area of the Ooty Radio Telescope, a 4-km long Synthesis Radio Telescope at 327 MHZ was built at Ooty during 1970s and 1980s (Swarup 1986). OSRT consisted of the ORT and 7 small parabolic cylindrical radio telescopes, all equatorially mounted on hill slopes. It provided many important results (e.g. the first Giant Radio Galaxy in the southern hemisphere of 8 Mpc extent by Saripalli et al.; the first radio relic source Abell 85 by Bagchi and Joshi). Further, it gave us expertize in radio Interferometry (AP Rao, Vasant Kulkarni, Velusamy, Sukumar, Bagri) enabling us to plan bigger radio telescopes.

2.8 Upgraded Ooty Radio Telescope

Recently, C. R. Subramanian and colleagues (these proceedings) have given a new dimension of great importance to the Ooty Radio Telescope by bringing 256 outputs,

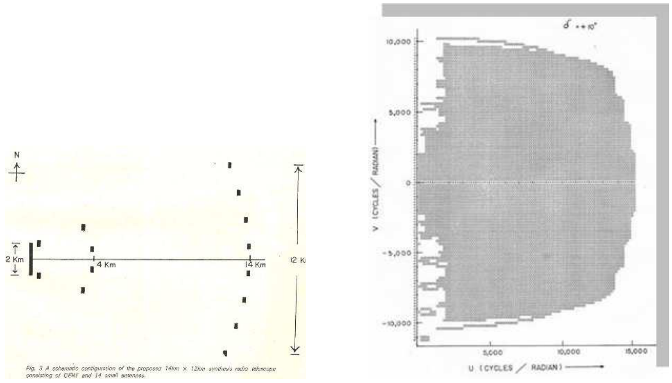

Figure 8. Arrangement of the proposed Giant Equatorial Radio Telescope (GERT) in 1979, to be constructed at the Earth's equator (left) and its UV diagram (right). GERT consisted of a 2 km long and 50m wide NS parbolic cylinderical antenna and fourteen 100m long and 50m wide paraboic cylendrical antennas placed upto 14km away.

from 4 dipoles out of 1054 located at its focal line, to a central receiver room and then cross correlating the voltage signals of the 256 outputs: this will result in 300 beams, each 6 arcmin x 20. The upgraded ORT will also allow rapid IPS observations of over 2000 radio sources daily, providing important information about the solar wind velocity and Coronal Mass Ejections. A major objective of the upgraded ORT is to search for baryon acoustic signal at z 3.2. ORT is also being used for pulsar observations and VLBI observations. Transient search can be a very active progamme, particularly if one constructs, say 36 or more log periodic antennas at 327 MHz, placed perpendicular to the ORT in eastern direction up to 600m away. Thus, one can obtain 300 simultaneous beams each 10 arc min x 6 arc min, so that one could locate positions of transients, an important objective.

2.9 Giant Equatorial Radio Telescope (GERT)

Following success of the ORT and OSRT, it was proposed to construct a Giant Equatorial Radio Telescope, consisting of a 2 km long and 50 m wide parabolic cylindrical antennas to be located at a site very close to the earth's equator, with 14 smaller antennas of 100m x 50m located up to 14 km away as shown in Fig. 8 (Swarup et al. 1979; Swarup 1981). The surface of GERT consisted of 3cm x 3cm stainless wire mesh allowing polarization observations. It was to operate at several frequencies in the range of 38 MHz to 600 MHz (total area $\sim 200,000$ m^2).The GERT was conceived as a collaboration between selected African, Arabic and Asian countries. It was supported by UNESCO and also endorsed by IAU and COSPAR. A site was located by me firstly in Kenya and later in Indonesia. Kenya got into political uncertainty after the death of President Kenyatta. Indonesian site was close to the earthquake zone.

2.10 Genesis of the Giant Metrewave Radio Telescope

During 1970s, WSRT used low loss coaxial lines to connect all the 14 parabolic dishes of 25m diametre. OSRT used radio links. VLA used an expensive circular TE01 waveguide that was required to be straight within few cm over a km. There was no other way to connect far away antennas of an array till 1983. After I got a X-mas mail from Alec Little from Australia in December 1983, I became aware of a new emerging medium: low loss optical fibres for communication. During 1978 to 1983, we had struggled for 5 years to seek support for the GERT for which detailed drawings and cost estimates had been made. On the new years eve of 1st January 1984 at 1 AM, after lots of whisky (!), in a flash, I broke the 2 km long x 50 m wide parabolic cylinder into 36 parts and placed these in a Y array with each arm 14 km long, and all antennas joined by optical fibres. All members of the TIFR radio astronomy group supported the proposal and we started to design various aspects. The proposal of the GMRT was discussed by us at the IAU GA held at New Delhi in 1985. There was strong support but the question was: Dishes (○) or Dashes (−)? Dishes won after I conceived the SMART concept (Stretched Mesh Attached to Rope Trusses) in 1986 that allowed us to design and construct 45 m dishes soon after; many astronomers abroad have called this design as the "Great Indian Rope Trick". However, the idea is quite simple.

2.11 GMRT progress

A detailed survey was made in 1985 at several locations, including RFI measurements, for a suitable site for the GMRT. Two sites were shortlisted: a site near Indore with considerable lower degree of RFI than the present site near Pune. For various logistic reasons, the group favoured Pune. The Prime Minister of India, Rajiv Gandhi, approved the proposal of GMRT in early 1987 for about Rs. 38 crores; final cost by 1986 was Rs. 45 crores (US $ 20 million at then prevalent foreign exchange rate). Detailed drawings of the 30 antennas of the 45m diameter of the GMRT were made by the Tata Consulting Engineers during 1988-89 and contact awarded to two firms in Nov. 1989. All the 30 antennas were erected by mid 1996 (I retired in 1994 with 2 year extension). The servo system, antenna feeds and electronics and the correlator were designed and fabricated by a close team of scientists, engineers and technicians of the NCRA radio astronomy group, with important contributions by the Raman Research Institute and the Bhabha Atomic Research Centre.

The GMRT (Fig. 9) became fully functional by 2001 and was then opened to the Indian and international community on the basis of best proposals to be selected by the GMRT Time Allocation Committee (GTAC). During the last 12 years, the GMRT has been used by astronomers from nearly 30 countries and about 300 papers have been published in refereed journals. GMRT observations have been made of a wide varieties of objects viz. planets in the Solar system, Sun, extra-solar planets, HII regions, supernova remnants, Galactic Centre, recombination lines, star burst galaxies, radio emission from normal galaxies, radio galaxies, quasars, HI survey of Dwarf Galaxies

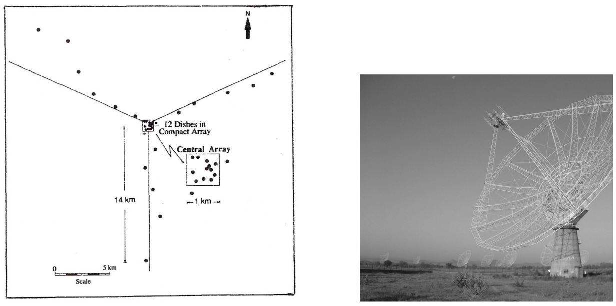

Figure 9. GMRT consists of 30 parabolic dishes of 45 m diameter each and are located in a Y-shaped array of 25 km in extant.

and normal galaxies, Damped Ly-alpha systems, epoch of reionization, etc. Highlights of the GMRT have been covered during the MWSKY conference (elsewhere in this volume).

2.12 uGMRT

The GMRT is currently being upgraded, briefly as follows: (a) new primary antenna feeds to provide nearly continuous frequency coverage from 130 MHz to 1430 MHz; (b) improved electronics system, including new LNAs with lower noise figure and large dynamic range; (c) broadband analogue optical fibre links with large dynamic range; (d) a wideband (400 MHz) hybrid correlator with a large number of frequency channels and (e) a new Servo system for tracking antennas, etc. The uGMRT would lead to increase in its sensitivity due to its wider bandwidth and also allow searching for spectral lines in emission or absorption over a wider frequency range.

SKA was conceived in 1990 soon after my talk at the conference at Socorro on the 10th year of VLA. Peter Wilkinson from UK proposed the HI array. I published it as an International Telescope for Radio Astronomy (ITRA; essence in Persian) (Swarup 1991). Around the same time, the Dutch radio astronomers proposed SKAI that got shortened to SKA. Now 11 countries are partners of SKA (including India) and over 30 institutes across the world are contributing to its design. SKA is being located at radio-quiet zone in South Africa and Australia. Many innovation in the design of antennas, RF electronics, digital and computational technology, etc. would give SKA unique capability for an unprecedented exploration of the Universe. SKA will become the largest scientific instrument on the Earth.

3. Conclusion

Radio Astronomy expertise in India has been built from scratch. An article in a book (Swarup (2010) has described in detail the "Growth and Development of Radio Astronomy in India" including that at the Indian Institute of Astrophysics, Raman Research Institute and the Physical Research Laboratory. The success of ORT, OSRT and GMRT has been entirely due to a close team work by all (astronomers, engineers, technical and administrative staff). Most important: team work and team work! There will be continued challenges at GMRT to remain competitive internationally.

Acknowledgements

I am deeply grateful to all the members of the TIFR radio astronomy group as well other supporting members of TIFR who have worked with full dedication for setting up outstanding experimental facilities in the field. I also thank Nimisha Kantharia and Jayaram Chengalur for their valuable comments on this paper

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