FROM POTTS HILL (AUSTRALIA) TO PUNE (INDIA): THE JOURNEY OF A RADIO ASTRONOMER

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Abstract: In this paper I recapitulate my initiation into the field of radio astronomy during 1953-1955 at CSIRO, Australia; the transfer of thirty-two parabolic dishes of six-feet (1.8-m) diameter from Potts Hill, Sydney, to India in 1958; and their erection at Kalyan, near Bombay (Mumbai), in 1963-1965. The Kalyan Radio Telescope was the first modern radio telescope built in India. This led to the establishment of a very active radio astronomy group at the Tata Institute of Fundamental Research, which subsequently built two world-class radio telescopes during the last forty years and also contributed to the development of an indigenous microwave antenna industry in India. The Ooty Radio Telescope, built during 1965-1970, has an ingenious design which takes advantage of India's location near the Earth's Equator. The long axis of this 530 m × 30 m parabolic cylinder was made parallel to the Equator, by placing it on a hill with the same slope as the geographic latitude (11°), thus allowing it to track celestial sources continuously for 9.5 hours every day. By utilizing lunar occultations, the telescope was able to measure the angular sizes of a large number of faint radio galaxies and quasars with arc-second resolution for the first time. Subsequently, during the 1990s, the group set up the Giant Metrewave Radio Telescope (GMRT) near Pune in western India, in order to investigate certain astrophysical phenomena which are best studied at decimetre and metre wavelengths. The GMRT is an array of thirty fully-steerable parabolic dishes of 45 m diameter, which operates at several frequencies below 1.43 GHz. These efforts have also contributed to the recent international proposal to construct the Square Kilometre Array (SKA).

Keywords: History of radio astronomy, history of science in India, Sun, solar radio bursts, cosmology, radio telescopes, GMRT

1 INTRODUCTION

There are many instances in the field of astronomy whence initial pioneering work at field stations has led to the development of major instruments for the investigation of the mysteries of the Universe. Although Karl Jansky serendipitously discovered radio emission from our Galaxy in 1931 while working at the Bell Labs in USA, active research in the field of radio astronomy only started after 1945, following developments in electronics and radar engineering during World War II (see Sullivan, 1984). The discoveries made between 1945 and 1955 at Sydney, Cambridge, Harvard, Jodrell Bank and Leiden laid a firm foundation for the new field of radio astronomy. In this paper, I describe my initiation into the field of radio astronomy in Australia during 1953-1955; my contributions during 1956-1963 in the USA; early attempts by Sir K.S. Krishnan to form a radio astronomy group at the National Physical Laboratory in New Delhi (for Indian localities mentioned in the text see Figure 1); and the subsequent development of radio astronomy at the Tata Institute of Fundamental Research (TIFR) in Mumbai, as a result of initial support given by Dr Homi J. Bhabha (who was one of the main architects of the growth of modern science in India).

Radio astronomical research is also being carried out at other institutions in India, mainly at the Raman Research Institute (Bangalore), the Indian Institute of Astrophysics (Bangalore) and the Physical Research Institute (Ahmedabad). The facilities developed by these institutes are described on their websites. There has been a close collaboration between the TIFR and the Raman Research Institute, where Professor V. Radhakrishnan established a radio astronomy group in 1971, after spending nearly twenty years abroad (mostly at Caltech in the USA, and at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia).

Figure 1: Indian localities mentioned in the text.

2 THE INITIAL YEARS

After obtaining an M.Sc. degree in Physics from Allahabad University (India) in 1950, I joined the National Physical Laboratory (NPL) of the Council of Scientific and Industrial Research (CSIR) in New Delhi, and worked in the field of paramagnetic resonance under the guidance of K.S. Krishnan (Figure 2), who was the Director of the Laboratory. During 1946-1947 he had taught me Electricity and Magnetism in the first year of the B.Sc. degree at Allahabad University before moving to the NPL. Krishnan was the co-discoverer of the Raman Effect which won C.V.

Raman the Noble Prize in Physics. Later Krishnan shifted his research interests to the field of magnetism, and he asked me to develop equipment that could be used to investigate the phenomena of electronic paramagnetic resonance at a wavelength of 3 cm. Over the next eighteen months, I was able to set up equipment by cannibalizing surplus radar sets procured by the NPL, and by studying parts of the remarkable set of twenty eight volumes of the Radiation Laboratory Series that described almost all the radar techniques that were developed during World War II.

Figure 2: Dr K.S. Krishnan, Director of the National Physical Laboratory, New Delhi (courtesy National Physical Laboratory).

In August 1952 Krishnan attended the General Assembly of the International Radio Scientific Union (URSI) in Sydney, and he was struck by the dramatic and remarkable discoveries being made in the field of radio astronomy by staff from the CSIRO's Division of Radiophysics (RP). Under the inspired leadership of J.L. Pawsey (Figure 3), several ingenious radio telescopes had been developed by the Australian scientists to investigate radio emission from the Sun and distant cosmic sources in our Galaxy (see Davies, 2005; Orchiston and Slee, 2005; Sullivan, 2005). On his return to India, Krishnan described these developments in a colloquium at the NPL, and these caught my imagination. I then visited the NPL library, where I studied some of the thirty papers that had been published by the RP scientists in the *Australian Journal of Scientific Research* and in *Nature* describing these discoveries. I was told that these were almost half of the papers on radio astronomy that had been published worldwide up to that time. I, too, was fascinated by this new field. Krishnan was also interested in initiating radio astronomical research at the NPL, and he put my name forward for a two year Fellowship under the Colombo Plan to work at RP in Sydney.

Figure 3: Dr J.L. Pawsey, leader of the radio astronomy group within the CSIRO's Division of Radiophysics in Sydney (ATNF Historic Photographic Archive: 7454-2).

3 MY INTRODUCTION TO RADIO ASTRONOMY, AND THE SOLAR GRATING INTERFEROMETER AT POTTS HILL

The Colombo Plan application was successful, and in March 1953 R. Parthasarathy from the Kodaikanal Observatory (in South India) and I joined RP to work under Pawsey's guidance (Figure 4).

Figure 4: Govind Swarup (left) and R. Parthasarathy (right) in at Potts Hill field station in 1954. At this time, searches were being made for hydrogen clouds in the Milky Way with this 16 x 18 ft ex-radar antenna (after *Illustrated Weekly Times of India*, 14 September 1954).

Australian-born Joseph Lade Pawsey (Lovell, 1964) was a scientific leader *par excellence*. In 1931 he obtained a Cambridge Ph.D. under J.A.Ratcliffe in the field of ionospheric research, and then spent several years working on antennas and transmission lines in the television industry in UK before returning to Australia and joining the newly-formed Division of Radiophysics, which was involved in radar research.

In October 1945, as the War ended, he initiated a study of the Sun using a radar installation in suburban Sydney (Orchiston, 2005). This produced immediate results which led to further successful studies, and the small RP radio astronomy group never looked back! In a pioneering paper published in *Nature* in 1946, Pawsey announced that radio emission from the Sun arises from a hot corona at a temperature of about one million degrees. Soon, several different research groups were formed at RP (Orchiston and Slee, 2005; Sullivan, 2005), and under Pawsey's guidance they conducted detailed investigations of radio emission from the Sun, our Galaxy and distant extragalactic radio sources, with new discoveries being made every few months!

After finding that my interest was more in experimental rather than theoretical work,[1] Pawsey suggested that I work for three months each in the groups led by W.N. Christiansen, J.P. Wild, B.Y. Mills and J.G. Bolton (Figure 5). Each of these scientists had made important discoveries, and they were already acknowledged world leaders in their respective fields. I was to report back to Pawsey every two weeks. S.F. Smerd, a very pleasant man but a tough task master, was asked to coordinate my activities and to provide me with guidance on the rapidly-growing literature in radio astronomy. For his part, Parthasarathy was to develop a 10.7 cm solar radio telescope, as this was needed by the Kodaikanal Observatory (which had a long history of solar observations at optical wavelengths—see Kochhar, 1991—and now wanted to expand into radio astronomy). Then, after the first year, Parthasarathy and I would select a joint project. What a great opportunity for initiation into the new field of radio astronomy!

For the first three months, I assisted W.N. Christiansen and J.A. Warburton to make a two dimensional map of the quiet Sun at a wavelength of 21cm, using strip scans obtained with the east-west and a north-south grating interferometers at the Potts Hill field station (Figures 6 and 7). We first Fourier transformed each scan manually using an electrical calculator, plotted the outputs on large graph paper along respective angles of the scans, scanned the resulting 2-dimensional Fourier-transformed map at various angles and again reversed the process thereby obtaining a map of the quiet Sun at 21 cm. The final result, after Christiansen and Warburton (1953), is shown in Figure 8. I highlight this work here in some detail because a decade later that painstaking experience gave me an idea of a simpler scheme to make maps from one-dimensional scans without taking Fourier transforms. The new concept was described by me to R.N Bracewell in late 1962, just before I returned to India from Stanford. In this method, a 2-dimensional map can be readily obtained by multiplying amplitudes of each of the one-dimensional strip scans by appropriate weights and then plotting the resulting modified scans along corresponding scan-angles, in order to obtain a 2-dimensional map (Bracewell and Riddle, 1967). This technique is widely used today in X-ray imaging and has revolutionized medical tomography.

Figure 5: Some of the distinguished radio astronomers who attended the 1952 URSI Congress in Sydney. Chris Christiansen, Paul Wild and Bernie Mills (in the dark suit) are first, third and fifth from the left respectively, and Steve Smerd is in the front row immediate to the right of Mills. John Bolton is the man on the extreme right of the group photograph (ATNF Historic Photographic Archive: 2842-43).

Figure 6: View looking southwest across the two Potts Hill water reservoirs in 1953, showing Christiansen's solar grating arrays along the banks of the eastern reservoir. The E-W array consisted of thirty-two elements and the nearer N-S array just sixteen elements (ATNF Historic Photographic Archive: 3475-1).

Figure 7: Close-up, looking east, showing the E-W grating array (ATNF Historic Photographic Archive: B2976-1).

During the next three months, under the guidance of Paul Wild, J.A. Roberts and I developed a 45 MHz receiver that was then used at the Dapto field station to determine the velocity of ionospheric turbulence. After this, I spent three months to develop a phase shifter for the prototype Mills Cross antenna that Bernie Mills and Alec Little were building at Potts Hill field station, and for the final three months of the first year I worked in the group led by John Bolton, and made a highly stable D.C. power supply.

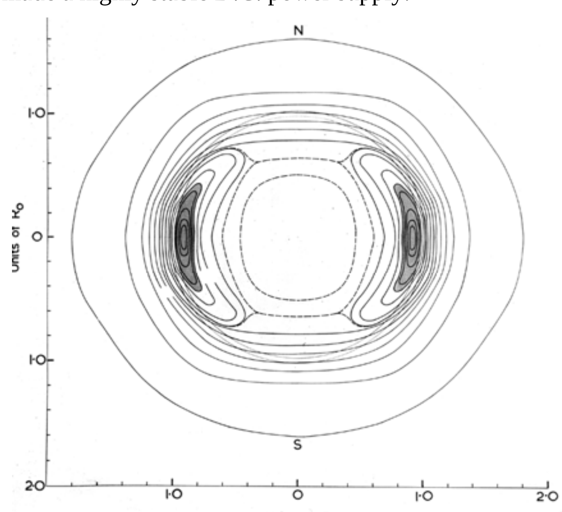

Figure 8: Isophote map of the quiet Sun at 21 cm, showing equatorial limb-brightening (ATNF Historic Photographic Archive: B3400-3).

In 1954, Christiansen went to work at Meudon Observatory in France for a year. After discussions with Pawsey, Parthasarathy and I decided to convert the Potts Hill EW grating array (Figure 7) from 21cm to 60 cm (500 MHz), in order to investigate whether the quiet Sun exhibited limb brightening at that frequency. This was predicted by Smerd (1950), but was in conflict with measurements made at Cambridge by Stanier (1950). Our results (Swarup and Parthasarathy, 1955; 1958) agreed with Smerd's prediction. For us, this was a great experience: building dipoles, a transmission line network and a receiver system; making the observations; and finally, carrying out data reductions—not to mention saving my dear friend Parthasarathy from drowning in the Potts Hill reservoir! At the time he was using a bucket to draw some water from the Reservoir so that we could make a cup of tea and wash our faces (after a day of hard work), and he accidentally fell into the water.

Upon his return from France in early 1955, Christiansen decided to build a new cross-type antenna array at RP's Fleurs field station near Sydney. Known as the Chris Cross, this consisted of two orthogonal grating interferometers, which were used to make daily solar maps at 21cm (see Orchiston, 2004). As a result, all thirty-two of the 6 feet diameter dishes making up the E-W grating array at Potts Hill, along with associated equipment, became surplus to requirements and were to be scrapped. Pawsey liked to visit all the RP field stations unannounced to see what his staff were doing (Sullivan, 2005), and during one of his surprise visits to Potts Hill I asked whether these dishes could be gifted to India. He readily agreed to this suggestion, as did E.G. (Taffy) Bowen, Chief of the Division of Radiophysics.[2] On 23 January 1955, I wrote to K.S. Krishnan about the possibility of transferring the thirty-two dishes from Sydney to the NPL in New Delhi (Swarup, 1955). I proposed simultaneous dual frequency observations with a 2,100-feet long grating interferometer using the thirty-two dishes at 60 cm and 1.8m. On 22 February Krishnan (1955) replied: "I agree with you that we should be able to do some radio astronomy work even with the meager resources available." Pawsey obtained approval from the CSIRO authorities for the donation of the dishes to India under the Colombo Plan scheme, but with the proviso that India must bear the cost of their transportations (which amounted to about 700 Australian Pounds, as I recall).

4 RADIO ASTRONOMY AT THE NATIONAL PHYSICAL LABORATORY

Upon my return to New Delhi in August 1956, Krishnan gave approval to start a radio astronomy program at the NPL. I then began building a sensitive receiver system for operation at 500 MHz. However, Krishnan could not get approval from the CSIR authorities in New Delhi for transfer of the dishes from Sydney. Instead, the CSIR had suggested that the Australian authorities should bear the cost of transportation, considering the shortage of foreign exchange in India at the time, but this request was turned down. As there seemed to be no early resolution to the tangle, later in 1956 I decided to go to the USA for a year or two. Meanwhile, Parthasarathy had also joined the NPL in 1956, and he went on to build a 10.7 cm receiver, but left the NPL in the following year and joined C.G. Little's group in Alaska. T. Krishnan also joined the NPL in 1956, after completing the physics tripos at Cambridge and spending a year working with Martin Ryle. In late 1958 he joined RP to work with Pawsey and Christiansen (Figure 9). Dr M.R. Kundu joined the NPL in 1958 after completing his Ph.D. in solar radio astronomy in France, but also went to the USA soon afterwards. M.N. Joshi and N.V.G. Sarma joined the NPL soon after finishing their M. Sc. degrees in India in 1956, and they built a 500 MHz receiver for the proposed grating array. Later, Joshi went to France for a Ph.D. degree, which he obtained in 1962. For his part, Sarma spent two years at Leiden Observatory, where he built radio astronomy receivers. Both he and Joshi subsequently returned to India and joined the NPL. In the meantime, CSIRO eventually paid for the transport of the thirty-two Potts Hill dishes to New Delhi. Thus, it may be said that the NPL acted as a foster mother for the subsequent development of radio astronomy in India by the above persons, who were trained across the world.[3]

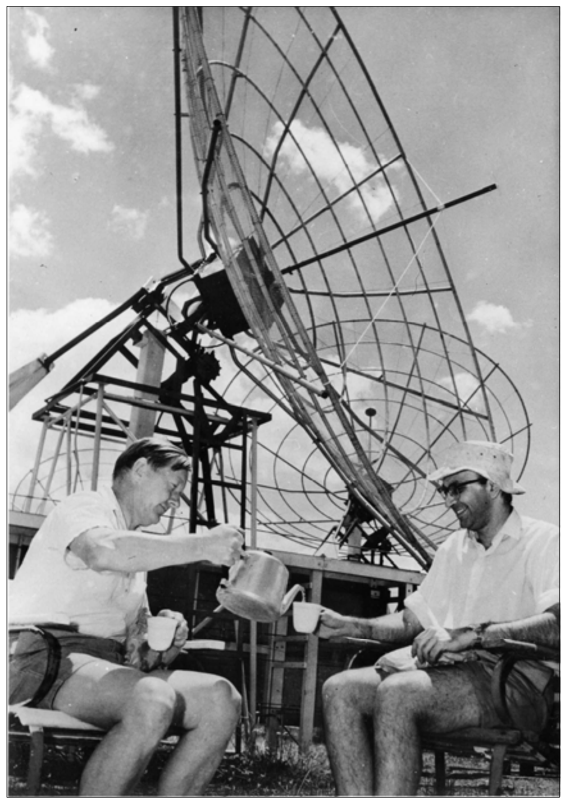

Figure 9: W.N. Christiansen (left) and T Krishnan (right) at Fleurs field station in front of one of the Chris Cross antennas (Krishnan Collection).

5 INDIAN RADIO ASTRONOMERS IN THE USA IN THE EARLY YEARS

I joined the Fort Davis Radio Astronomy Station of the Harvard Observatory in August 1956. This Texas field station was set up by Dr Alan Maxwell, a New Zealander with a Ph.D. from Manchester, in order to record the dynamic spectra of solar radio bursts over the frequency range 100-600 MHz using a swept-frequency receiver connected to a 28-ft dish (Figure 10). In December 1956 I discovered the Type U burst while Maxwell was on a holiday in New Zealand (Maxwell and Swarup, 1957). In early 1957, I decided to work for a Ph.D. degree in the USA and received favourable responses from Harvard, Caltech and Stanford, all of which were already active in radio astronomy (e.g. see Bracewell, 2005; Cohen 1994; Kellermann et al. 2005). Pawsey (1957) wrote: "Stanford is famous for radio engineering, Caltech for its physics and, of course, its astronomy research, and Harvard for its training in astronomy… If you are returning to India, I should recommend to you to place great emphasis in electronics. It is a key to open many doors."

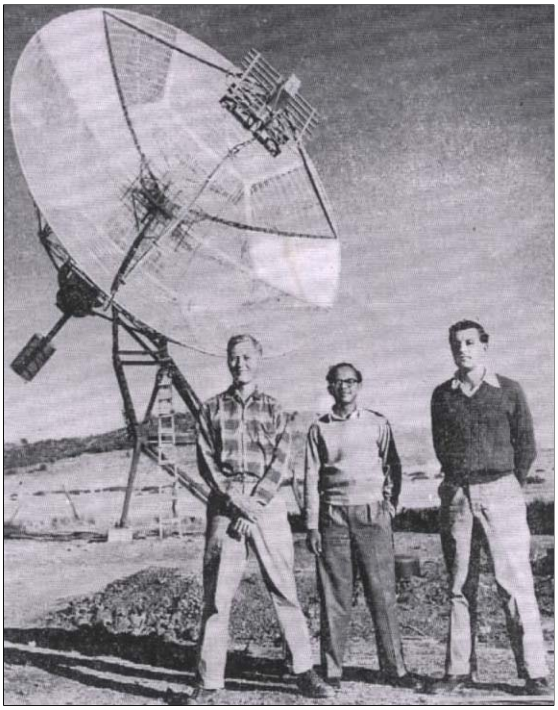

Figure 10: Alan Maxwell, Govind Swarup and Sam Goldstein (left to right) posing in front of the 28-ft dish at Harvard Observatory's Fort Davis field station in Texas.

I decided to join Stanford University, and in September 1957 began Ph.D. research under the guidance of R.N. Bracewell, who was in the process of building a cross-antenna interferometer (Figure 11) that would be used to generate daily solar maps at 9.2 cm (Bracewell and Swarup 1961). On 1 January 1961, soon after obtaining my Ph.D. degree, I joined the University as an Assistant Professor.

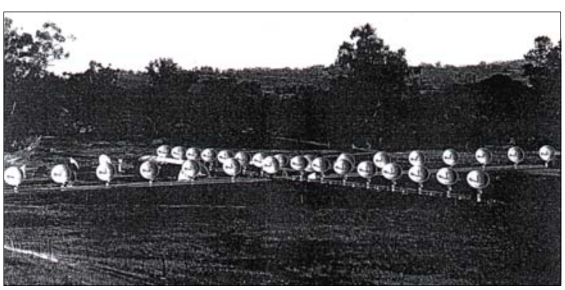

Figure 11: The completed Stanford 9.2 cm cross-antenna interferometer (after Bracewell, 2005: 75).

After graduating from the Indian Institute of Science in Bangalore in 1950, T.K. Menon (Figure 12) went to Harvard University in 1952, where he completed M.S. and Ph.D. degrees. He was on the faculty of the Astronomy Department from 1956 to 1958, before joining the (U.S.) National Radio Astronomy Observatory in 1959 as one of the senior scientists. He went on to make pioneering contributions to the studies of HII regions and HI clouds in our Galaxy.

In 1958, M.R. Kundu (Figure 12) joined the radio astronomy group led by Fred Haddock at the University of Michigan, and he soon became an internationally-recognized leader in the field of solar radio astronomy.

During meetings of the American Astronomical Society and of the URSI chapter in the USA, on several occasions the three of us working in USA discussed the possibility of returning to India and forming a major radio astronomy group. In 1960 and 1961, I also corresponded with Christiansen, Frank Kerr and Pawsey in this regard. They recommended to us T. Krishnan (Figure 13), who was then at the University of Sydney. On 22 September 1960, Christiansen wrote "… you two and Menon and Kundu should get together for a united attack on the monolith of Indian bureaucracy….", and on 26 October Pawsey (1960) wrote: "But keep off the fashionable ideas. Be original."

Figure 12: T.K. Menon (left) and M.R. Kundu (right) at the Berkeley IAU General Assembly in 1961 (Menon Collection).

In August 1961, Krishnan, Kundu, Menon and I met at Berkeley during the General Assembly of the International Astronomical Union (Figure 12), and we discussed our interest in returning to India to form a radio astronomy group. We wrote a detailed proposal indicating our initial plans to start solar radio astronomical observations using the thirty-two dishes already donated to the NPL (which had still not been used), and thereafter to set up "… a very high resolution radio telescope of a novel design would be the next step in our programme ... certain types of radio telescopes would be cheaper to build in India due to lower labour cost … such as a Mills Cross operating at low frequencies ..." (Krishnan et al., 1961). In September 1961, the proposal was sent to five major scientific organizations and agencies in India, indicating our desire and willingness to return to India and form a radio astronomy group and also to attract others in due course. Copies of our proposal were also sent to five distinguished astronomers, Bart Bok, D.J. Denisse, Jan Oort, Joe Pawsey and Harlow Shapley, and they were asked to send their confidential assessments to the authorities in India. Copies of the letters of recommendation from Bok, Oort and Pawsey to Bhabha are available in the TIFR archives. Bok's (1961) recommendation was very generous: "… it seems to me that their offer to return to India as a group is a unique one, and that should by all means be accepted and acted upon promptly. An offer like the present one comes only rarely in the history of a nation, which scientifically, is obviously coming of age". We got replies from all the concerned authorities from India, but the most encouraging and highly supportive was from the great visionary scientist and a dynamic organizer, Dr Homi J. Bhabha (Figure 14), Director of the Tata Institute of Fundamental Research (TIFR) in Mumbai. He sent a cable to all four of us on 20 January 1962: "We have decided to form a radio astronomy group stop letter follows with offer…." (Bhabha, 1962a). He wrote to me on 3 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 than we see foresee at present." (Bhabha, 1962b). The above-mentioned correspondence and several other related letters from the period 1955-1963 in my files have been scanned, and are now available at the NCRA Library in Pune.

6 RADIO ASTRONOMY AT THE TIFR; BEGINNING WITH THE KALYAN RADIO TELESCOPE

I resigned from Stanford, and returned to India on 31 March 1963. On a request made by Homi Bhabha to the NPL and CSIR authorities, the thirty-two Potts Hill dishes were transferred to the TIFR by the middle of 1963. In the meantime, I developed a design involving 20-ft dishes to complement the thirty-two smaller dishes for operation at a longer wavelength. Soon after, in June 1963, I came across a paper by Cyril Hazard in a recent issue of *Nature* describing observations of a lunar occultation of the radio source 3C273 made with the 64 m Parkes Radio Telescope, as well as a companion paper by Marteen Schmidt, concluding that the enigmatic spectrum of the blue stellar object identified with 3C273—which had been a great puzzle for several years—was easily explained for an object with a redshift of 0.17. This marked the discovery of quasars, and has revolutionized our understanding of the Universe. While reading the two papers, a thought flashed through my mind: that the lunar occultation method could provide accurate positions and angular size measurements of a large number of radio sources, much weaker than those in the 3C catalogue, and thus distinguish between competing cosmological models. At that time there was a raging controversy between the Steady State and Big Bang cosmologies. A quick calculation showed that in order to obtain occultation observations of a sizable sample of distant weak radio sources, say ~200 per year, one would need a telescope with a collecting area of more than four times that of the 64 m Parkes or the 76 m Jodrell Bank Radio Telescopes, which was not practical to build, even in advanced countries. It occurred to me that the solution would be to construct a large cylindrical radio telescope on a suitably-inclined hill in southern India so as to make its axis parallel to the Earth's axis, and thus taking advantage of India's close proximity to the Equator. I discussed this idea with Professor M.G.K. Menon, Dean of the Physics Faculty, who responded enthusiastically. In August 1963 I had a long discussion with Bhabha, who grilled me for over two hours. I asked him whether I should write a detailed Project Document and he replied: "Young man, do not waste your time writing a project report; your main problem would be to collect a team; when you have managed that, you can submit a project report and proceed with its design and construction."

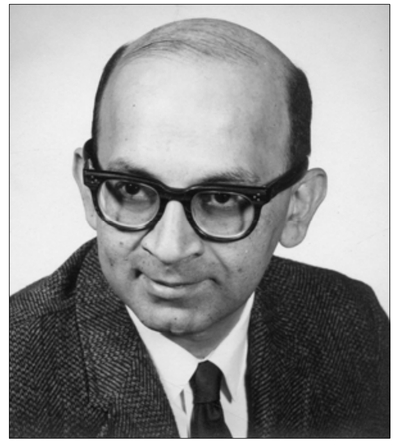

Figure 13: T Krishnan in India in 1970 (Krishnan Collection).

In August 1963, V.K. Kapahi and J.D. Isloor, fresh graduates from the Atomic Energy Establishment Training School (AEET) and two scientific assistants, joined the young radio astronomy group of the TIFR. R.P. Sinha, who was also from the AEET, joined in August 1964. As a first step, a grating type of radio interferometer was set up at Kalyan near Bombay to observe the Sun at 610 MHz (Figure 15). The array consisted of thirty-two ex-Potts Hill parabolas; twenty-four of them were placed along a 630 m East-West baseline and the remaining eight along a 256 m North-South baseline. As we used a simple and novel transmission line system to connect the antennas, we were able to complete the Kalyan Radio Telescope by April 1965 (*Nature*, 1966). This radio telescope was used to investigate properties of the quiet and active radio Sun at 610 MHz during 1965-1968. It was found that the Sun showed considerable limb brightening, and that the solar corona had a temperature of around one million degrees.

Figure 14: Dr Homi Bhabha (1911–1966), founding Director of the Tata Institute of Fundamental Research, Mumbai (courtesy: TIFR Archives).

Figure 15: View of the east-west grating array consisting of twenty-four 6-ft diameter dishes built at Kalyan, near Mumbai, in 1965.

Figure 16: The Ooty Radio Telescope, consisting of the 530 m long and 30 m wide cylindrical parabolic antenna placed along a north-south sloping hillside at an angle of 11.3° so that its axis of rotation is parallel to that of the Earth.

Figure 17: Another view of the Ooty Radio Telescope; reflections of sunlight by 1,100 stainless steel wires are seen on the right.

N.V.G Sarma and M.N. Joshi resigned from the NPL and joined the TIFR in 1964. D.S. Bagri, with a fresh M.Tech degree, joined the group in August 1964. Mukul Kundu returned from USA in early 1965 and contributed a great deal to the growth of the group during its critical formative years. Later, in 1968, he returned to the USA and joined Cornell University.

7 THE OOTY RADIO TELESCOPE

In early 1965, after an extensive search Sinha and I located a suitable hill at Ooty for the proposed equatorial radio telescope. This site is situated in the picturesque Nilgiri Hills in southern India, at an altitude of about 2,100 m. In late 1965, Bhabha approved the setting up of the Ooty Radio Telescope at that site, as part of an Inter University Centre (IUC). After corresponding with Jawahar Lal Nehru, India's Prime Minister, funding designed to give a boost to science education in India was obtained by Bhabha. A 600 acre plot of land was earmarked by the Tamil Nadu State Government for the IUC (Bhabha 1966). Soon after, in January 1966, Bhabha met a tragic end in a plane crash in The Alps at a relatively young age of 55 years, and the IUC did not materialize. However, the radio astronomy group continued to receive support from the TIFR, due the close interest and guidance of Professor Menon, an eminent cosmic-ray physicist who succeeded Bhabha as Director of the TIFR.

The Ooty Radio Telescope (ORT) was completed in early 1970, and it is still in operation. It consists of a 530m long and 30 m wide parabolic cylindrical antenna (Figures 16-17), located along a North-South hill slope equal to the latitude of the station (+11.35°). It is, therefore, possible to track celestial radio sources continuously every day up to 9.5 hours by a simple mechanical rotation of the telescope along its long axis. Along its 500-m long focal length is placed a phased array consisting of 1,024 dipoles operating in the RF band of 322-328.6 MHz, an internationally-protected band for radio astronomical observations. The structural and mechanical design was done by M/s Tata Ebasco, later named as Tata Consulting Engineers (TCE). The ORT was completed in December 1969, and the first occultation observations were made on 18 February 1970 (see Swarup et al., 1971). By early 1971, the radio astronomy group consisted of sixteen research workers: S. Ananthakrishnan, D.S. Bagri, V. Balasubramanian, Gopal Krishna, J.D. Isloor, M.N. Joshi, V.K. Kapahi, S. Krishna Mohan, V.K Kulkarni, D.K. Mohanty, T.K. Menon, A. Pramesh Rao, N.V.G. Sarma, C.R. Subrahmanya, T. Velusamy and myself. Dr. V.R. Venugopal joined in 1971. In addition, the group included several engineers and technical staff members. S.V. Damle, who had built the novel trombone-type phase shifters for ORT in collaboration with Kapahi, shifted to the microwave group at the TIFR. S.M. Bhandari from the Physical Research Laboratory also worked at Ooty for a Ph.D. degree. The design and construction of the ORT was a great challenge to the above team, as the development of technology in India was still in its infancy in those years, and foreign exchange for importing components was very limited (particularly after the India-China conflict in 1962, and later during the war between India and Pakistan). We were fortunate to receive a grant of US$70,000 from the National Science Foundation of the USA, which was used mainly to import a Varian Computer and test equipment. For the required electronic components, we ended up arranging for coaxial cables, type N and UHF connectors, and many other critical components to be developed by various firms for the first time in India. It must be noted that our success was solely due to a close teamwork of all the staff, whose median age in 1971 was about 27 years. The above scientists made many pioneering contributions and gained world-wide recognition for themselves and for Indian radio astronomy, thus paving the way for the future growth of radio astronomy in India.

T.K. Menon joined the TIFR in 1970 and guided several of the young research workers in the radio astronomy group. He returned to USA in 1974.

During the 1970s, lunar occultation observations of more than 1,000 radio sources were made at a frequency of 327 MHz using the ORT. The median flux density of these sources is about 0.6 Jy at 327 MHz, being about ten times lower than that of the 3C catalogue. The occultation survey was able to provide accurate positions of the source, and to reveal their angular structure with arc-second resolution. The data provided independent support to the Big Bang model (Kapahi, 1976; Swarup, 1976). Detailed physical properties of many Galactic and extragalactic were also derived. In addition, interplanetary scintillation (IPS) observations of selected samples of radio galaxies and quasars provided information on their compact structure with a resolution of 0.05 to 0.5 arc-second at 327 MHz. Valuable contributions were also made in the new field of pulsar astronomy. By 1984, the Ooty Synthesis Radio Telescope (OSRT) of 4 km extent was set up. It consisted of seven small parabolic cylindrical antennas measuring 23 m × 7.5 m and the large ORT itself, all combined with rather cumbersome radio links. The OSRT provided a resolution of ~45 × 50 arc second at 327 MHz. Scientific contributions made by the above group during the first twenty-five years are described elsewhere (Swarup, 1991).

8 THE GIANT EQUATORIAL RADIO TELESCOPE (GERT)

Following the success of the equatorially-mounted ORT, a proposal was mooted, first in 1976 and later more formally in 1978, to construct a Giant Equatorial Radio Telescope (GERT) consisting of a 2 km long and 50 m wide cylindrical radio telescope. This would be placed at a suitable site at the Earth's Equator in either Kenya or Indonesia. It was envisaged as the focal point of an associated International Centre for Space Sciences and Electronics (INISSE), a collaborative effort between several developing countries (Swarup et al., 1979). There was much talk at that time by world leaders stressing the need for South-South cooperation and India was very supportive of this concept. UNESCO provided a grant of US$14,000 for a feasibility study of the GERT and also arranged visits by Professor A.R. Hewish, Nobel Laureate, and myself to Kenya, Nigeria and Senegal, and later by an Indian team to Indonesia. The TIFR provided funds for the design and cost estimates of the proposed telescope, and also of a proposed 10 km synthesis radio telescope consisting of ten 100 m × 50 m parabolic cylinders in conjunction with the 2 km × 50 m main telescope. India indicated support for half of the all-up cost of the project, which was estimated as US$20 million. With the help of the local authorities, a suitable site was located close to the Equator in Kenya. However, Kenyan scientists were not able to follow up on the project after the demise of President Kenyatta. Later, two suitable sites were identified in West Sumatra (Indonesia) very close to the Equator, but progress was slow because of a lack of astronomical interest in most of the developing countries. In 1983 President Suharto of Indonesia pledged support for half the cost of the GERT. However, concerns were expressed about the high levels of seismic activity in West Sumatra, even though our engineers indicated that a suitable antenna could be built there without much cost penalty. Meanwhile, other major developments were taking place in international radio astronomy instrumentation and image processing techniques, as summarized below.

9 THE GIANT METREWAVE RADIO TELESCOPE: THE OFFSHOOT

By early 1982, revolutionary methods of phase and amplitude closures and self-calibration allowed radio astronomers to obtain radio maps of celestial sources of high quality even in the presence of phase and amplitude variations caused by electronics, the ionosphere or the atmosphere. It also seemed feasible to connect the antennas of a radio interferometer of a relatively large separation by using lasers and optical fibres. Further, after Ravi Subrahmanyan joined our radio astronomy group in 1983, we started calculating whether the ORT or the Very large Array (VLA) in the USA or the GERT would be suitable for studies of proto-clusters, the postulated condensates of neutral hydrogen existing at very high redshifts prior to the formation of galaxies in the Universe. To pursue this interesting problem, which is still a major challenge for radio astronomy, it became clear to us that a major new instrument was needed in order to fill the existing gap in radio-astronomical facilities at metre wavelengths. This goal, experience gained in designing and building the ORT, and the dynamism of the younger members of our group propelled me to propose the Giant Metrewave Radio Telescope on 1 January 1984.

Initially, in a flash, I divided the 2 km long and 50 m wide GERT into 34 smaller parabolic cylindrical antennas, joined by optical fibres, to form a synthesis radio telescope of about 25 km in extent. Since the operation over a wide frequency range seemed problematic using parabolic cylinders, we finally invented the concept of SMART (Stretched Mesh Attached to Rope Trusses) in order to build parabolic dishes of 45 m diameter economically and affordably: in this case necessity was the mother of invention![4] The GMRT project was approved by the Government of India in March 1987.

The GMRT consists of thirty parabolic dishes of 45 m diameter each, located across a region of about 25 km (Figure 18). Fourteen antennas are placed somewhat randomly in a central array of about 1 km × 1 km in extent, while the other sixteen dishes are situated along three 14 km long arms, making a Y-shaped array (Swarup et al., 1991). The GMRT operates at five radio frequency bands between ~ 110 and 1,430 MHz. Because of recent developments in electronics, it seems feasible to be able to operate the GMRT in any band free of radio frequency interference between ~ 40 MHz to 1,700 MHz. The GMRT became fully operational in 2000. Since January 2001 Indian and international astronomers are invited to apply for observing time, which is subsequently assigned to those who submit the best proposals. The GMRT has become the world's largest radio telescope operating in the above frequency range, and it complements existing large telescopes elsewhere. It has been used by more than three hundred astronomers from over twenty countries, and many interesting results have been obtained.[5]

I may note here that the untimely demise of M.N. Joshi in 1988 and of V.K. Kapahi, who were amongst the main architects of the group, was a great loss to the India and international radio astronomical communities.

10 THE SQUARE KILOMETRE ARRAY PROJECT (SKA): TO THE FUTURE

In 1960 Jan Oort highlighted the importance of building a radio telescope with a collecting area of about one million square metres in order to investigate the distribution of neutral hydrogen gas and its evolution in our Galaxy and across the Universe. As a result, Belgian and Dutch astronomers proposed a large Cross-type antenna with an area of ~1 million square metres, which they called the Benelux Cross, but this did not materialize. After noting the success of the one mile telescope in UK and developments in interferometry in Australia and elsewhere, the Dutch astronomers decided to build the Earth's Synthetic Radio Telescope at Westerbork, consisting of twelve dishes each 25 metres in diameter (two more were added later).

Oort's vision of a radio telescope with a large collecting area also led to a proposal for an array of 'Venetian blind' type configuration with a large number of parabolic cylindrical antennas (see Bracewell, Swarup and Seeger, 1963). In 1980, Barney Oliver proposed construction of 1,000 microwave antennas each of 100 m diameter in order to search for evidence of extra-terrestrial intelligence (SETI). In 1988, a proposal was put forward by Swarup at the International Astronautical Congress at Bangalore, for the construction of 1,000 dishes of 45 m diameter (similar to the GMRT antennas) for SETI, as well as for radio astronomical studies. In a symposium held at Socorro on the occasion of 10th anniversary of the operation of the VLA, Peter Wilkinson (1981) proposed construction of 100 antennas of 100m diameter, called 'The Hydrogen Array'. Swarup (1991) examined the cost of a large number of 45 m dishes for such a telescope, and called it the International Telescope for Radio Astronomy (ITRA). Earlier, Jan Nordaam in Netherlands had informally discussed a large telescope with similar objectives, called the SKAI. All of these ideas led to the setting up of a 'Large Telescope Working Group' at the Kyoto URSI meeting in 1993, and the IAU endorsed this group in 1994.

These historical developments paved the way for a more definite proposal for a billion dollar radio telescope project, called the Square Kilometre Array (SKA), which will be built between 2010 and 2020 by an international consortium consisting of institutions in Argentina, Australia, Brazil, Canada, China, seventeen countries in Europe, India, South Africa and the USA. The SKA will be mankind's most ambitious step in the exploration of the Universe through the radio window of the electromagnetic spectrum.

Figure 18: A close view of one of the thirty 45 m diameter fully steerable parabolic dishes of the Giant Metre Wavelength Telescope located at Khodad, near Pune, in western India. A few dishes of the central array of the GMRT are also visible in this picture.

11 EPILOGUE

Ever since its independence, India has made steady progress in scientific endeavours, thanks largely to the substantial support of the great visionary Prime Minister, Jawahar Lal Nehru, who viewed the newly-established scientific laboratories as the temples of modern India. Although pioneering work in international radio astronomy started at metre wavelengths, the emphasis in advanced countries soon shifted to much shorter wavelengths, in order to obtain high angular resolution (even though it required more expensive equipment). However, there are many exciting and challenging astrophysical problems that can be studied better, or exclusively, at metre wavelengths. At such long wavelengths the required tolerances of antennas are much lower, and wire mesh suffices as the reflecting surface of parabolic antennas, and minimizes the wind loading. Further, such antennas are labour-intensive, and because of low labour costs they can be built economically in India. The above factors have contributed to the success of radio astronomy endeavours in India.

Currently, several countries are building order-of-magnitude larger facilities at decimeter and metre wavelengths, such as LOFAR in Netherlands, Milleura in Australia (a joint venture of US and Australian scientists), and the seeding of the very ambitious SKA project. India can make substantial contributions to these efforts by using expertise developed in the field of radio astronomy and its proven expertise in the area of computer software development.

12 NOTES

1. Pawsey remarked that I was unlike most Indians, who preferred theoretical work.
2. Dr Bowen had played an important role in the development of radar in the UK and the USA during the War years. After joining RP, rain-making and upper atmospheric physics became his personal fields of research, but throughout his directorship he continued to provide vital support for the growth of radio astronomy within the Division. His principal legacy must surely be the 64 m Parkes Radio Telescope (see Robertson, 1992).
3. In recent years, tens of radio astronomers and engineers have migrated from India to observatories around the world, thus proving that the Earth is round!
4. We understand that Chinese radio astronomers are adopting certain aspects of the above concept for their proposed 500 m diameter antennas for the SKA, and that they have recently constructed a 30 m diameter prototype antenna.
5. For examples of some of the research results see the web site: www.ncra.tifr.res.in).

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