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# The Journey of a Radio Astronomer: Growth of Radio Astronomy in India

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## Abstract

In this autobiographical account, I first describe my family, then childhood and education in India. During 1953–55, I worked in the new field of radio astronomy at the Division of Radiophysics of the Commonwealth Scientific and Industrial Research Organisation in Australia. During 1956–57, I worked at the Radio Astronomy Station of Harvard University at Fort Davis, Texas, where I made observations of solar radio bursts at decimeter wavelengths. I then joined Stanford University as a graduate student in 1957. I contributed to the successful operation of the Stanford Cross Antenna and then used it for studying microwave radio emission from the Sun. I was awarded the Ph.D. degree by Stanford University in 1960 and was then appointed as an Assistant Professor for three years. With an urge to contribute to evolving scientific endeavors in India, I joined the Tata Institute of Fundamental Research (TIFR) at Mumbai, India, in April 1963. In my stay of more than three decades at TIFR, I conceived of, and guided, construction of two of the world's largest radio telescopes, namely the Ooty Radio Telescope and the Giant Metrewave Radio Telescope. These instruments have led to several outstanding contributions and discoveries in the areas of radio galaxies, quasars, pulsars, and cosmology.

## Contents



## 1. EARLY YEARS

I was born in 1929 in India in the town of Thakurdwara, District Moradabad, Uttar Pradesh. Lying in a lush green region where the plains give way to the Himalayas, Thakurdwara is about 200 km northeast of Delhi. My great grandfather, Ram Ratan, and partners built a cotton spinning mill in Moradabad in 1907. After his demise, my grandfather Brij Pal Saran became its Managing Director. The spinning mill made considerable profits during World War I, and its proceeds were used for various investments including construction of a large house in which I was born. My father was Ram Raghuhbir Saran and my mother was Gunwati Devi. My father was very enterprising. In 1931, he built a cinema theater in the Chandini Chowk area of central Delhi, showing Hindi films. Although profitable, it was sold off in 1935 owing to a joint-family dispute with his brother. My father also developed a 200-acre agriculture farm in the village of Dhouti, District Moradabad, where I spent many summer and winter vacations.

I studied from grades three to seven in the Sanathan Dharam School in Thakurdwara. Like all children, I was very curious. In the summer months, my brothers and I slept on the roof of our house. I looked at the stars in the sky and wondered what they were, why many scintillate and some not all. My teachers could not tell me about the stars. Astronomy was not taught in any school or college during the British rule of India—the syllabus was possibly prescribed to provide the required manpower for ruling the country. In 1941, my father shifted the family to the city of Moradabad, where I studied in grades eight to ten in the Hindu High School. In August 1942, all the students from the school, me included, joined a procession shouting "Quit India," in support of the call made by India's great leader, M.K. Gandhi, demanding an end to the British colonial rule. The soldiers fired on us peaceful students, though only in the air, but that episode enraged me a great deal. During my younger days, I was inspired by reading Hindi novels by Munshi Premchand and also articles by Gandhi in his weekly magazine, *Harijan*. In the ninth grade, I was awarded a copy of Gandhi's autobiography that also influenced me. In the tenth year of my schooling, I read an article by the famous poet Mahadevi Verma in my Hindi textbook. It described "Aakash Ganga," the Milky Way. I found it fascinating and read more about it in an astronomy book in the school library. That was my first lesson in astronomy! During my school years, I became keenly interested in science. I passed the tenth grade in 1944. My mother then desired that I join a civil engineering college at Roorkee, Uttar Pradesh, India, as it would very likely assure me a job right after graduation. However, aware of my interest in the field of science, my father sent me to Allahabad in India in July 1944 to study science—mathematics, physics, and chemistry—in the Ewing Christian College for two years and thereafter to join the reputed Allahabad University. The university then had several outstanding teachers. In the first year of studying for my B.Sc. in 1946, I was taught the electricity and magnetism course by K.S. Krishnan, who was coauthor in the work that won C.V. Raman the Nobel Prize in the field of Physics in 1930. Besides Krishnan, the physics faculty included several distinguished teachers and researchers, such as B.N. Srivastava, G.B. Deodhar, and Rajendra Singh, and in chemistry, N.R. Dhar. At midnight on August 15, 1947, India's first Prime Minister, Jawaharlal Nehru, declared India's independence from British rule from the Red Fort in Delhi. I heard his inspiring address at Allahabad as it was relayed at the Anand Bhawan, the house where Nehru was born. In December 1948, the Nobel laureate C.V. Raman visited the Allahabad University. We invited him to our hostel for an authentic North Indian meal, which he not only graciously accepted but also talked for two hours about the excitement of science. I also recall the visit of the renowned British mathematician and geophysicist Sydney Chapman to the Allahabad University in December 1948. I and another student took him for a boat ride at the confluence of the bluish water of the river Yamuna and the whitish water of the river Ganga. Chapman was fascinated at seeing the turbulence in the confluence of the two water streams. He told us that there would be new opportunities to work in the field of science after India's recent independence.

After completing my M.Sc. degree in physics from the Allahabad University, I joined the National Physical Laboratory (NPL) of the Council of Scientific and Industrial Research (CSIR), New Delhi, in 1950. My former teacher, K.S. Krishnan, had already become its director in 1947. On the very first day, he gave me a few papers by Bleaney and coauthors that described pioneering observations of the paramagnetic resonance in solids at microwave frequencies. Krishnan asked me to set up a 3-cm apparatus for observations of the paramagnetic resonance using surplus components from the radar equipment of World War II, which was lying in the basement of NPL. He also told me to study a few of the outstanding 28 volumes published in the MIT (Massachusetts Institute of Technology) Radiation Laboratory series, which described microwave and radar techniques developed during World War II. In the following 18 months, I was able to set up the 3-cm apparatus for paramagnetic resonance; it was an early introduction to radio techniques.

In August 1952, Krishnan attended the General Assembly of the International Union of Radio Science (URSI) held in Sydney, Australia. He was struck by the remarkable discoveries that were made in the new field of radio astronomy by young physicists and engineers from the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Division of Radiophysics (RP). Several ingenious radio telescopes were built by them under the dynamic leadership of J.L. Pawsey. After his return to India, Krishnan described these discoveries in a colloquium at NPL. Krishnan further told us that these contributions had been published in about 30 papers in the *Australian Journal of Scientific Research* and *Nature*. These were nearly half of the papers published worldwide in the field of radio astronomy at that time. After reading some of these papers in the library of NPL, I got very interested in working in that field. Krishnan recommended me for a Colombo Plan Fellowship to work for two years at RP in Australia, and that was successful.

## 2. AUSTRALIA: 1953–1955

In late February 1953, I traveled by ship from Bombay (now known as Mumbai) to Sydney, my first trip overseas, and I arrived there in mid-March 1953. After a few days, I went to RP to meet its director, Joe Pawsey. After ascertaining that my interest was in learning experimental techniques rather than working in theoretical areas, he advised me to work for three months each in the groups led by W.N. Christiansen, B.Y. Mills, J.P. Wild, and J.G. Bolton. Each of them had made pioneering discoveries in the new field of radio astronomy during the preceding few years. In the second year of my stay at the RP, I was advised to propose an independent project. Pawsey requested S.F. Smerd to coordinate my activities and also guide me in the literature of radio astronomy.

I first familiarized myself with the early developments in the new field of radio astronomy. Karl Jansky, who was working at the Bell Labs in the United States, discovered in 1931 that radio waves are emanating from the direction of the Milky Way (Jansky 1933). That was indeed the birth of the new field of radio astronomy. In 1937, Grote Reber, a young engineer and amateur astronomer, built a 10-m parabolic antenna in his backyard in Chicago and made the first radio map of the Milky Way. He also discovered radio emission toward the constellation of Cygnus (Reber 1944). Several years later, its accurate position was determined by Smith (1951) in the United Kingdom. It was then identified by Baade & Minkowski (1954), with a galaxy of redshift 0.06, which was considered very distant at that time. Radio bursts were accidentally observed toward the Sun during the radar observations in 1942; these were later identified by Hey and colleagues as arising from the Sun. Using a radar antenna, Pawsey et al. (1946) determined that the Sun has an equivalent temperature of $\sim$2 MK at long wavelengths, which was a surprising result at that time. It continues to be a vexing mystery to this day as astronomers try to unlock the secret of how to heat and maintain the corona at such high temperatures atop a photosphere that is at a mere 5,800 K.

I worked with Christiansen for the first three months. During 1952, Christiansen & Warburton (1953a,b) had constructed two grating-type radio interferometers at the Potts Hill reservoir in Sydney for operation at 1,420 MHz. One was a 213-m long east–west (E-W) array with 32 parabolic dishes of 1.7-m diameter, separated from each other by 6.65 m. The north–south (N-S) array was 160 m in length and consisted of 16 dishes. Over a year, these two interferometers provided one-dimensional distributions (strip scans) of the radio emission across the solar disk at different position angles. Christiansen asked me to derive a two-dimensional map of the radio emission across the solar disk using these strip scans. Using an electrical calculator, I first determined the Fourier transform (FT) of each of the strip scans manually, which was a laborious process. I then plotted the outputs on a large piece of graph paper at their respective position angles, made contour plots manually, then took strip scans of the above contour plot at various position angles manually, calculated the FT of each of the new strip scans and combined them to derive the two-dimensional distribution of radio emission across the solar disk at 1,420 MHz. That map showed limb brightening of the radio emission across the solar disk as predicted by Smerd (1950; see also Christiansen & Warburton 1955). For a long time that was the only known method for making two-dimensional maps in various fields. A decade later when I was working at Stanford, this painstaking experience gave me the idea of deriving a two-dimensional map across the solar disk simply by superimposing the observed one-dimensional scans at different position angles after applying suitable weights without taking FTs. I could not follow this up, as I was soon returning to India. With suitable modifications, Bracewell & Riddle (1967) derived a two-dimensional map of radio emission from the Moon using the one-dimensional scans obtained with the Stanford Cross antenna. This technique is widely used today in X-ray imaging [i.e., CT (computerized tomography) scans] and has revolutionized medical tomography.

During my next three months at CSIRO, under the guidance of Paul Wild, I and J.A. Roberts developed a receiver at 45 MHz that was placed about 40 km away from the Dapto field station of the RP for daily observations of Cygnus A. Wild had constructed three rhombic antennas at Dapto for daily observations of the three types of solar radio bursts that he had discovered a few years earlier. Observations of Cygnus A were also made at Dapto every night. A longer series of

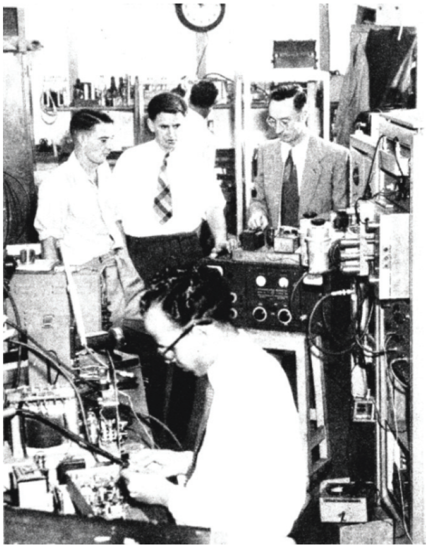

**Figure 1**

John Bolton, Gordon Stanley, Joe Pawsey, and Govind Swarup (*left* to *right clockwise*) at the Radiophysics Laboratory of CSIRO. Photo from *People* magazine, Australia, February 10, 1954, and is now in the public domain.

observations provided the drift speed of ionospheric turbulence for the first time (Wild & Roberts 1956).

My work during the subsequent three months was guided by Bernie Mills. In 1952, he had made an ingenious invention of a cross type antenna consisting of an E-W and a N-S array. Multiplying their voltage outputs resulted in a pencil beam response toward the sky. A small "cross" of 36-m size was built by him at the Potts Hill reservoir of the CSIRO, which detected continuum radiation from the Large Magellanic Cloud for the first time (Mills & Little 1953). Mills then decided to construct a much larger cross antenna at the Fleurs field station (Mills et al. 2005). He asked me to design a phase shifter that was required for the N-S antennas for pointing to different declinations. I was able to develop a suitable phase shifter during the next three months.

During the next three months, I was guided by John Bolton. He had made several pioneering discoveries in radio astronomy during 1947–1953. Using a sea interferometer, Bolton had identified several discrete radio sources in the sky for the first time. In early 1954, Bolton and Gordon Stanley were digging a parabolic-shaped hole in the ground near the Dover Heights for observing the central regions of our Galaxy passing overhead. Bolton asked me to help in the digging but I was unable to do it due to my lack of physical strength. Bolton then asked me to work with Stanley (**Figure 1**) to design and construct a highly stable D.C. power supply of 2,000 volts. I completed this over the next three months.

Pawsey had advised me and R. Parthasarathy, another Colombo Plan Fellow from India, to propose an independent project for the second year of our stay at CSIRO. I had become aware that Stanier (1950) did not find limb brightening of the Sun at 500 MHz using an interferometer at Cambridge University, which contradicted the predictions made by Smerd (1950). For checking this result, we decided to convert the 32-element E-W interferometer, constructed by Christiansen at 1,420 MHz, to 500 MHz in order to make daily observations of the solar radio emission at 500 MHz. For phasing the antennas of the 32-element array, we compared phases of the voltages received by each pair of two adjacent antennas of the array and then made suitable changes to the connecting transmission lines, which was a laborious process that took a few weeks. From that experience, when I was making measurements at the Stanford Cross antenna, I conceived of a round-trip phase path measurement scheme that allowed phasing of the voltages received by its 32 antennas within tens of minutes, a major invention that I describe later. We made daily observations of the Sun at 500 MHz and derived a one-dimensional map of the quiet Sun. The Sun was then a very enigmatic celestial radio source, one of the few known at that time. The existence of a million-Kelvin corona was already known. A rich variety of emissions showing a huge range in intensity and their appearance in the frequency–time plane had just been discovered (Wild 1950a,b; Wild & McCready 1950). Considerable effort was being expended on the theoretical front to build a more detailed understanding of the observed emissions and phenomenon. It was truly fertile ground for us to explore. Our map showed limb brightening of the Sun, in contrast to the observations made by Stanier (Swarup & Parthasarathy 1955a,b). This provided a useful observational verification of the basic physical picture of the coronal electron density distribution. Swarup & Parthasarathy (1958) also studied radio emission associated with sunspots.

Because no further observations were planned using the 32 1.7-m diameter parabolic dishes of the E-W interferometer at Potts Hill reservoir, I asked Pawsey to donate these dishes to the NPL at New Delhi. Pawsey readily agreed and got approval from CSIRO. In January 1955, I wrote to K.S. Krishnan about the possible transfer of the 32 parabolic dishes to NPL. Krishnan replied in February 1955: "I agree with you that we should be able to do some radio astronomy work even with the meagre resources available." I joined NPL after my return to India in July 1955. The CSIRO in Australia wrote to the CSIR at New Delhi offering the transfer of the 32 dishes to NPL. However, CSIR requested CSIRO also to bear the cost of transportation, citing the severe foreign exchange crunch in India. That led to correspondence, uncertainty, and delays. Hence in December 1955, I wrote to a few organizations in the United States, expressing my interest to work there in the field of radio astronomy for a couple of years. Donald Menzel, the Director of the Harvard College Observatory, offered me a position as a research associate to work at the newly created Radio Astronomy Station of Harvard University at Fort Davis, Texas. A dynamic radio spectrograph had become operational there in 1955 for daily observation of solar radio bursts in the frequency range of 100–580 MHz, under the direction of Alan Maxwell. I accepted the offer.

## 3. FORT DAVIS, TEXAS: 1956–1957

I married Bina on June 3, 1956. That was the start of a partnership that continues to this day. Ours was an arranged marriage; her father found me through a newspaper advertisement. Bina is an educator at heart, and after we came back to India she completed her Bachelor's degree in education. Though my work made us move many times from one city to another, she sought and found opportunities to teach in schools.

Bin and I first flew to Boston in late July 1956, where Bart Bok showed us around Harvard University and also the city of Boston. We then flew to the Marfa airport in Texas. Alan Maxwell met us at the airport and drove us to Fort Davis, which is located about 40 miles away. Fort Davis was a small town with a population of about 700, yet we made a few friends including the Sprouts. I purchased my first car, in front of which Bina and I are shown in **Figure 2**. At the Radio Astronomy Station in Fort Davis, three separate receivers covering the frequency range of 100–580 MHz were connected to a paraboloid antenna of 28-ft diameter. The system was ten times more sensitive than that used anywhere else for observations of solar radio bursts at that time (Maxwell et al. 1958). I made daily observations of the Sun to investigate the association of solar radio bursts with flares and prominences (Swarup et al. 1960). In December 1956, I discovered a U-type solar radio burst (Maxwell & Swarup 1958). It had been proposed that these bursts arise


**Figure 2**

Bina Swarup and Govind Swarup at Fort Davis, Texas. Photo from the private collection of G. Swarup.

due to motion of a stream of energetic electrons outward through the corona (Wild et al. 1954). This discovery was very exciting because it implied that the direction of motion of this stream must be reversed, presumably by the coronal magnetic fields.

## 4. STANFORD: 1957–1963

In early 1957, I decided to work for my Ph.D. in the United States. I got admission letters from Caltech, Harvard, and Stanford, where research in the field of radio astronomy had been initiated recently. Pawsey wrote to me on February 8, 1957: "I also agree with you in trying to get a combination of astronomy, electronics and physics. If you are returning to India, I should recommend to you to place great emphasis on electronics. It is a key to open many doors. Stanford is famous for radio engineering, Caltech for its physics and, of course, its astronomy research, and Harvard for its training in astronomy." Hence, I joined Stanford University in September 1957 to work under R.N. Bracewell. I got a scholarship to work half time at the Stanford Cross antenna, which operated at 3,260 MHz and consisted of 32 parabolic dishes, each of 3-m diameter. Sixteen antennas were placed along the E-W directions, at 8-m spacing and the same for the N-S array. All the antennas were joined by waveguide transmission lines. I and K.S. Yang, another student, compared phases of voltages received by each pair of adjacent antennas and equalized them by placing the required dielectric components in the connecting transmission lines, which was similar to what I had done with Parthasarathy for the E-W interferometer in Australia. It took us more than three weeks to equalize phases of the voltages received by all 32 antennas of the Stanford Cross. However, the resulting map of the Sun was not real! Similar results occurred when we repeated the measurements three weeks later. We concluded that the spacing of some of the antennas of the Stanford Cross was probably incorrect. That was corrected later by Bracewell. As a graduate student attending courses, I was concerned about spending another three weeks on phase equalization of the 32 antennas. I could ill afford to spend weeks on the standard but tedious phase equalization procedure I had followed in Australia. Perhaps that is what led me to conceive of a round-trip phase path measurement scheme in 1959 (Swarup & Yang 1961). We transmitted a radio frequency (RF) signal at 3,260 MHz from a central point to all the antennas. The signal received at each of the antennas was modulated at 1 kHz and then the round-trip phase of the modulated signal was measured at the central point. Thus, we could measure phases of all 32 antennas within tens of minutes! Pawsey wrote to me in 1960: "You have made a real breakthrough in this technique. Congratulations. Chris [Christiansen] regards the idea as the key to really large Mills Crosses." Over the past 60 years, this scheme has been used for phase adjustment of all the radio interferometers in the world, and also for many other applications, such as phasing of the klystrons of the Stanford Linear Accelerator, synchronizing atomic clocks separated by tens of kilometers, and measuring the round-trip phase path of transmitters in space, etc. (Piester et al. 2011).

In December 1960, I submitted a thesis for the Ph.D. degree to Stanford University. It was titled "Studies of solar microwave emission using a highly directional antenna." Earlier, on July 12, 1960, I had received an offer from the University of Illinois to join as an assistant professor. On October 3, 1960, Dr. D.S. Heeschen, the Director of the National Radio Astronomical Observatory, USA, wrote to me, ". . .if you accept the offer, to be the leader in the development of an interferometer program based along the lines you discussed with me. . . . " Because I was planning to return to India after a few years, I did not accept the above offers. In January 1961, Professor H.H. Skilling offered me the position of assistant professor at Stanford for three years, which I accepted.

The Stanford Cross antenna became operational in 1959 (Bracewell & Swarup 1961). Operating at 3,260 MHz, it produced two-dimensional images of the solar disk with a diameter of $\sim$30 arcmin with a resolution of 3.1 arcmin every day for several years. Kakinuma & Swarup (1962) developed an innovative gyroresonance model for explaining characteristics of the slowly varying component of the solar radiation. Swarup et al. (1963a) described high-resolution studies of 10 solar active regions, made at wavelengths of 3 cm in Japan, 9.1 cm at Stanford, 10.7 cm in Canada, and 21 cm in Australia. Picken & Swarup (1964) built a compound interferometer in 1962 that provided 52-arcsec resolutions at 9.1 cm. High-resolution observations of the radio source Cygnus A made with this interferometer showed that it has a central component in addition to the known pair of radio lobes (Swarup et al. 1963b). Such a component was detected for the first time. The concept of future large telescopes with area of nearly $10^6$ $m^2$ was described by Bracewell et al. (1962).

In February 1962, Dave Hogg of the Bell Labs visited Stanford University, and he also visited the Stanford Cross antenna. I then described to him our round-trip phase measurement scheme (Swarup & Yang 1961). Dave Hogg told me that measurements made with the Hogg horn at the Bell Labs showed sky temperature of $\sim$70 K at 7.5 cm. He asked me to visit the Bell Labs and measure the suspected loss of the Hogg horn antenna. My wife Bina was expecting a child in June 1962 and was not inclined to let me go away for a few weeks. Furthermore, in February 1962, I had already accepted H.J. Bhabha's offer to join the Tata Institute of Fundamental Research (TIFR) in India. Therefore, I did not go to the Bell Labs. In 1965, A.A. Penzias and R.W. Wilson reduced the loss of the Hogg horn by washing out the pigeon droppings and optimized the temperature of the receiver, culminating in the discovery of 3-K cosmic microwave background radiation for which they were awarded the Nobel Prize in Physics in 1978.

## 5. FORMATION OF THE RADIO ASTRONOMY GROUP AT THE TATA INSTITUTE OF FUNDAMENTAL RESEARCH, MUMBAI, INDIA

By 1961, T.K. Menon, M.R. Kundu, and I had worked in the field of radio astronomy in the United States for about eight years. T. Krishnan had also worked with Christiansen in Australia. On October 26, 1960, Pawsey wrote: "...you four could make an effective group...but keep off fashionable ideas...." Later he wrote on June 29, 1961: "...don't for example, buy a 60-ft dish because someone gives it to you cheap.... America is stiff with 60-ft and 80-ft dishes...by organizations which had no special ideas of what to do with one." Pawsey arranged for T. Krishnan to attend the IAU General Assembly that was held at Berkeley in August 1961. The four of us met at Berkeley in September 1961, and then Krishnan, Kundu, Menon, and I wrote a proposal for the formation of a radio astronomy group in India. Copies of the proposal were sent to five scientific organizations in India indicating our desire to return to India. Copies of the proposal were also sent to five distinguished astronomers in the world, Bart Bok, Jean-Francois Denisse, Jan Oort, Joe Pawsey, and Harlow Shapley, requesting them to send their confidential assessment of our proposal to the five organizations in India. Copies of the replies from Pawsey, Oort, and Bok are available in the archives of the TIFR, Mumbai. Pawsey wrote: "...I have a very high opinion of the scientific talent in this group...." Oort wrote: "...their plans are reasonable and balanced...." Bok wrote on October 5, 1961: "...Here is a case of four young but renowned Indian radio astronomers... hardly equaled by any group that one might assemble anywhere in the world...." The response from four of the five scientific organizations in India was not encouraging. However, Dr. Homi Bhabha, the Director of TIFR wrote to us to meet him in Washington, DC, during his forthcoming visit to the United States. We requested T.K. Menon to meet him. After meeting Bhabha, Menon wrote to us on November 7, 1961: "...he talks quite happily of final outlays of Rs. 50 to 100 lakhs ($1 to $2 million)...unbelievable for us at present.... But he seemed perfectly sincere and credible...wanting to make quick decisions...." Bhabha sent a telegram to all four of us on January 20, 1962: "We have decided to form a radio astronomy group. Letter follows with offer." On February 8, 1962, I accepted the offer. Bhabha wrote to me on April 3, 1962: "...If your group fulfills the expectation we have of it, this could lead to some very big equipment and work in radio astronomy in India than we foresee at present...."

Bina, I, our three-year-old daughter, Anju, and our 9-month-old son, Vipin, returned to India from Stanford in March 1963. We first flew to Leiden. Oort showed me a prototype of the 25-m parabolic dish that was being developed for the Westerbork Radio Telescope. He told me that they would be glad to give us all its drawings and suggested that we could fabricate it at TIFR, for making a survey of HI toward the Southern Sky from the low latitudes of India. But I was not returning to India to take up an investigation that I could have done even in the United States. After Leiden, we visited the Meudon Observatory in France and then went to Bologna, Italy, where M. Ceccarelli was planning the construction of a large cross antenna at 408 MHz. He described to me the proposed design for its cylindrical parabolic reflector.

Finally, we took a ship from Naples in Italy and arrived in Mumbai on March 30, 1963. We first went to Delhi to visit Bina's mother and one of Bina's two sisters. Bina and I were meeting them after around seven years. They were thrilled to meet us and our two young children. Bina's father had passed away in 1956 when we were in Texas. We then visited my father living at Thakurdwara. He was also very happy to meet us. My mother had died in 1957, when I was at Stanford.

## 6. THE KALYAN AND OOTY RADIO TELESCOPES

I joined TIFR in mid-April 1963. Inspired by its superb ambiance and the outstanding facilities in its laboratories and workshop, I started contemplating an ambitious project in radio astronomy. In June 1963, I read a recent paper by Hazard et al. (1963) in *Nature* that described the lunar occultation observations of the bright radio source 3C273 made with the 64-m Parkes radio telescope. Its arcsecond radio structure was revealed for the first time. A companion *Nature* paper by Schmidt (1963) concluded that the spectrum of the blue stellar object identified with 3C273, which had been a great puzzle for several years, could be understood as emission from a very distant object with a redshift of 0.158, which was a great discovery. Schmidt termed 3C273 as a quasi-stellar object or a quasar. While reading these two papers in the library of TIFR, it occurred to me that lunar occultation observations could reveal arcsecond structure of a large number of radio sources, much weaker than the sources in the 3C catalog, using a sufficiently large antenna. At that time there was a raging controversy between the Big Bang and the Steady State models of the Universe. By 1960, Martin Ryle had catalogued nearly 300 radio galaxies using an interferometer at Cambridge. He assumed that the more numerous weaker radio sources were likely to be located farther away than the less numerous brighter radio sources located nearby (log $N$ versus log $S$ relation). On the basis of the observed slope of this relation, he supported the Big Bang model. Earlier, Bondi & Gold (1948) and Hoyle (1948) had proposed the Steady State theory according to which matter is continuously created everywhere in the expanding Universe, rather than at the very beginning as envisaged in the Big Bang model. Hoyle argued that weaker sources may not be located farther away and therefore Ryle's acceptance of the Big Bang model could be flawed. This led to a huge controversy during the 1960s. If indeed weaker radio sources lie farther away, they should appear smaller in angular size. But, in those times angular size measurements with arcsecond resolution were available for only about 30 radio galaxies. A quick calculation by me in the TIFR library showed that lunar occultation observations providing arcsecond resolution for a large number of radio sources, say ~100 per year, would require a telescope with a collecting area of at least four times that of the 64-m Parkes or the 76-m Jodrell Bank radio telescopes, which was not at all practical at that time even in advanced countries. Therefore, taking practical advantage of India's location at low latitudes close to the equator, I conceived of the construction of a large parabolic cylindrical radio telescope nearly 500 m long and 30 m wide, to be located on a hillside of slope such that it would make its long axis parallel to the axis of rotation of the Earth. Such an equatorial radio telescope would be able to track the Moon for several hours every day and observe lunar occultations of many discrete radio sources with arcsecond resolution. I discussed this idea with Prof. M.G.K. Menon, the Dean of the Physics Faculty, who responded enthusiastically. In early August 1963, I had a long discussion with Dr. Bhabha. He grilled me for a couple of hours about the scientific objectives and also the structural and mechanical details of the proposed telescope. I asked him about the required project report. 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 design and construction."

In parallel, in August 1963, V.K. Kapahi and J.D. Isloor, fresh graduates from the Atomic Energy Establishments Training School in Mumbai, joined the newly formed radio astronomy group of TIFR. By then the 32 parabolic dishes of 1.7-m diameter, which formed a part of the Potts Hill array and were donated by the CSIRO in Australia to NPL, had finally arrived at TIFR. The following year, two more graduate students, D.S. Bagri and R.P. Sinha, joined the group. N.V.G. Sarma and M.N. Joshi, who were both already experienced with radio astronomy, moved from the NPL, New Delhi, to join us in the same year. With this group, I decided to build India's first radio telescope, a grating-type radio interferometer operating at 610 MHz, similar in design to the Potts Hill interferometer, for studying the Sun. We located a site 7 km south of Kalyan town and 40 km away from the TIFR. There we installed 24 parabolic dishes along a 630-m long E-W baseline and 8 dishes along a 256-m long N-S baseline to form two radio interferometers. I conceived of a novel transmission line for bringing the radio signals received by the dishes to a central receiver (Swarup & Kapahi 1970). The transmission line for the E-W array used a pair of 630-m long copper wires separated by 3 cm, which were stretched to keep them straight and then connected to the dipoles of the parabolic dishes using direction couplers, instead of using the rather cumbersome and costly branching transmission lines used by Christiansen in Australia. The transmission line for the N-S array used a similar scheme. The Kalyan Radio Telescope became operational for daily observations of the Sun at 610 MHz in 1965, and our work on the limb brightening of the Sun appeared in *Nature* (Swarup et al. 1966).

In January 1965, Ramesh Sinha and I searched for a suitable site for locating the proposed equatorial hillside radio telescope. Using a theodolite, we surveyed about 30 hills in South India. Most of these could be rejected on a cursory look. Finally, a suitable site was identified near the Muthorai village in the picturesque hill range of the Nilgiris (Blue Mountains), about 5 km away from the town of Udhagamandalam (known as Ooty) in the state of Tamil Nadu. As was required for the proposed equatorial radio telescope, the hill at the Muthorai site has a slope of ~11 deg, 23 arcmin in the N-S direction, which is the same as its latitude. Bhabha approved the site after visiting it in May 1965 and again in December 1965. Because the selected site was inside a reserved forest, it was difficult to acquire. However, after a request by Bhabha to the government of Tamil Nadu, it was allocated for construction of the proposed equatorial radio telescope that we named the Ooty Radio Telescope (ORT). In August 1965, Bhabha proposed the construction of ORT as part of an Inter-University Centre (IUC) for which a 400-acre site was also allocated by the government of Tamil Nadu. He requested that I participate in the development of the IUC in addition to the ORT, telling me that in due course I would require engineers and scientists, and the IUC would be a good place to nurture and train them. After corresponding with Nehru, India's Prime Minister, Bhabha had received a grant of Rs. 2 crores (~$4 million) for the IUC. Out of that, Bhabha approved a budget of Rs. 50 Lakhs (approximately $1 million at that time) for the ORT. Most unfortunately, Bhabha met a tragic end in January 1966 in a plane crash near Mont Blanc in the Alps, and hence the IUC did not materialize. In April 1965, Tata Consulting Engineers were selected for designing the required structural and mechanical parts of the ORT. The design and construction of the ORT was fully indigenous. The electronics system required many innovations: As one of the many examples, coaxial cables and type N connectors were developed for the first time in India, using the conceptual designs that I obtained from one of the 28 volumes of the MIT Radiation Laboratory. There were difficulties in importing these and many other items from abroad due to the severe foreign exchange crunch in India in those days. In 1967, M/s Bridge and Roof of Kolkata were awarded the contract for constructing the structural and mechanical parts of the ORT. The reflecting surface of the 530-m long and 30-m wide parabolic cylindrical antenna of the ORT is made of 1,100 parallel stainless wires (**Figure 3**). The design of the ORT enables it to track a given celestial object continuously for 9.5 h per day just by mechanical rotation about the antenna's long axis. Along the focal line are installed 1,054 dipoles. Each dipole is connected to a phase shifter allowing the ORT to be pointed in declination within ±45 deg (Swarup et al. 1971). The electronics system was designed by N.V.G. Sarma, M.N. Joshi, D.S. Bagri, S. Ananthakrishnan and others. The ORT operates in the radio frequency band of 322–328 MHz, an internationally protected band for radio astronomical observations. The telescope became operational on February 18, 1970. On that night, a predicted lunar occultation of a 4C radio source was observed; later that night two uncatalogued weaker sources also were occulted—that added to our great excitement! We had not slept for two days. By 1978, the Ooty lunar occultation survey

**Figure 3**

Ooty Radio Telescope (ORT) consists of a 30-m wide and 530-m long parabolic cylindrical antenna that is placed on a hill with inclination of 11 deg 23 arcmin, same as its altitude. ORT can be rotated for 9.5 h, and a phased array allows pointing in declination by ±45 deg. The 1,100 parallel stainless steel wires that form the reflecting surface of the telescope are stretched across the frames seen to the right. Figure from NCRA-TIFR Archives.

had provided angular sizes of nearly ∼900 radio sources at 327 MHz, with resolutions varying between 0.5 and 10 arcsec for the predicted 3C and 4C radio sources and also many uncatalogued weaker radio sources. That was the best resolution achieved anywhere in the world for these radio sources at that time.

For deconvolving the lunar occultation profiles, Subrahmanya (1975, 1980) developed an optimum deconvolution method that considered constraints such as positivity and smoothness for the first time, resulting in higher resolution by roughly a factor of about two compared to the earlier method described by Scheuer (1962). Based on the Ooty lunar occultation observations and observations of the much brighter 3C sources made at Cambridge, I derived an angular size–flux density relation for extragalactic radio sources that indicated that the sources of smaller flux density have smaller angular diameter and are likely to be located statistically at larger distances (Swarup 1975). Combining this relation with the angular size counts for the previously known stronger sources, Kapahi (1975) showed that not only the comoving number density of radio sources was higher but also their linear sizes were smaller at earlier cosmic epochs, as expected in the Big Bang model.

I describe here only a few results out of many hundred obtained with the ORT. From the lunar occultation observations of the Galactic Center source Sagittarius A at 327 MHz, Gopal-Krishna et al. (1972) discovered an ∼20-pc diameter nonthermal radio halo around the Galactic Center. Using the additional information available at higher frequencies, Gopal-Krishna & Swarup (1976) determined the two-dimensional structure of the thermal and nonthermal emissions from Sagittarius A for the first time. The combination of the Ooty occultation scans with the aperture synthesis observations made at 5 GHz at Cambridge showed increasing prominence of the bridge emission from centimeter to meter wavelengths (Gopal-Krishna & Swarup 1977), which allows estimating the ages of radio galaxies. Another major program with the ORT was observations of the interplanetary scintillation (IPS) of radio sources. These showed that a significant amount of emission occurred in compact components of <0.5 arcsec (Ananthakrishnan et al. 1972, Bhandari et al. 1974). The gravitational lensing of the very bright radio source 1830-211 was discovered serendipitously from the IPS and the Very Large Array (VLA) observations by Pramesh Rao & Subrahmanyan (1988) and by Subrahmanyan et al. (1990). This source is an "Einstein ring lens" (Jauncey et al. 1991). Subrahmanyan & Swarup (1990) placed an upper limit on the HI mass of superclusters on the basis of observations made with the ORT at 327 MHz.

In order to make two-dimensional images of celestial radio sources, the Ooty Synthesis Radio Telescope (OSRT) was built for operation at 327 MHz during the early 1980s (Sukumar et al. 1988). It consisted of eight antennas: the ORT, six parabolic cylinders of 22 m × 9 m size, and one of 90 m × 9 m size. These were placed at distances of up to 4 km away from the ORT. Considering that the effective area of a pair of antennas is given by the geometric mean, $\sqrt{A1 \times A2}$, the OSRT yielded good sensitivity because the ORT has a large effective area of about 8,000 $m^2$. OSRT was used by many graduate students and research scientists at TIFR to observe the two-dimensional structure of radio galaxies, clusters of galaxies, and supernova remnants. A giant radio galaxy, 0503–286, was discovered in the Southern Hemisphere (Saripalli et al. 1986). From 1964 to 1989, 285 papers were published in refereed journals by the Radio Astronomy Group of TIFR. Of these, 20 were published in *Nature*, using data taken with the Kalyan Radio Telescope, the ORT, and the OSRT.

After two decades abroad, in Caltech and Sydney, V. Radhakrishnan joined as the director of the Raman Research Institute (RRI) at Bangalore (now known as Bengaluru) in 1972. He also formed a radio astronomy group at RRI. Using the ORT, Anantharamaiah (1985) observed radio recombination lines at 327 MHz from sources in our Galaxy. Using the ORT, Anantharamaiah & Radhakrishnan (1979) placed an upper limit on the deuterium-to-hydrogen ratio toward the center of our Galaxy. During the past ∼45 years, scientists at RRI have made many important contributions in the field of radio astronomy, particularly concerning pulsars and observations of spectral lines, and they have built up a strong electronics laboratory.

The design and construction of the ORT led to a major microwave antenna industry in India. In early 1968, on the basis of work being done for the ORT, Dr. Vikram Sarabhai, the Chairman of the Atomic Energy Commission, got an approval from Indira Gandhi, who was then Prime Minister of India, for manufacturing a 28.6-m (i.e., 97-ft) diameter antenna for satellite communication in India instead of it being imported as was being planned by the Overseas Communications Service. The 28.6-m antenna was fabricated by a firm in Mumbai and installed at the Arvi village, ∼80 km north of Pune, and was then made operational for satellite communication. India was the sixth country in the world to develop satellite communications at that time.

## 7. THE GIANT EQUATORIAL RADIO TELESCOPE

In August 1975, I attended the General Assembly meeting of the URSI at Lima, Peru. On my return, the airplane in which I was traveling made an unscheduled halt at Belem in Brazil. I noticed that Belem is located very close to the Earth's equator, just south of the mouth of the river Amazon. I then conceived of constructing a Giant Equatorial Radio Telescope (GERT), consisting of a 2-km long and 50-m wide parabolic cylindrical antenna (which would be a telescope six times larger than the ORT), at a location close to the Earth's equator in Brazil. On my return to India, I wrote to Fernando de Mendoza, then the Director of the National Institute of Space

Research in Brazil, whom I had taught at Stanford, but got no response. Later, I described the proposal of the GERT to Sam Okoye of Nigeria at a meeting of the IAU General Assembly that was held at Grenoble in France in August 1976. Okoye had obtained his Ph.D. from the University of Cambridge working under Anthony Hewish, the Nobel laureate. He got very interested in the proposal and invited me to attend the IAU summer school in Nigeria in 1977. During my visit to Nigeria, I from India, T.R. Odhiambo from Kenya, and Okoye from Nigeria proposed setting up an International Institute of Space Sciences and Electronics (INISSE), with GERT to be built under its aegis in Kenya. Kenyan scientists were very interested in the proposal of the GERT, but Kenya went into turmoil after the death of President Jomo Kenyatta on August 21, 1978. Earlier in June 1977, A.M. Bow, the Director General of UNESCO (United Nations Educational, Scientific and Cultural Organization), visited TIFR. He also got interested in the proposal of GERT. In September 1978, UNESCO gave a grant of US $14,000 to TIFR for writing a feasibility report. Under the sponsorship of UNESCO, a workshop was organized at Ooty in early 1979 that was attended by W.N. Christiansen, A. Hewish, and several scientists from Asian and African countries. They strongly supported the INISSE and GERT proposal (GERT: NCRA-TIFR archives). Under a grant from TIFR, Tata Consulting Engineers Ltd. (TCE) had developed detailed drawings of the GERT that consisted of a 2-km long and 50-m wide parabolic cylinder, as well as 10 antennas of 100 m in length and 50 m in width to be placed at distances of a few kilometers to 14 km away to form a synthesis radio telescope, with a total collecting area of $\sim$150,000 $m^2$, which is much larger than any other radio telescope existing even today. It was to operate at frequencies of 38, 327, and 610 MHz (Swarup 1981, Swarup et al. 1984). The total collecting area of GERT was nearly ten times that of the ORT. It was estimated that INISSE and GERT would cost about US $20 million. In 1979, the government of India wrote to the Kenyan authorities agreeing to meet half the cost, but their response was not positive. In 1981, I visited Indonesia to attend an international conference held there. Bambang Hidayat, a senior astrophysicist at the Bandung Institute of Technology, arranged my visit to West Sumatra. Under a UNESCO grant, I, an engineer from TCE, and three Indonesian engineers located two suitable sites close to the Earth's equator in West Sumatra, preferring the one at Bukittinggi. Although the response of the Indonesian government was positive, the frequent occurrence of earthquakes in West Sumatra was our major concern. Though GERT did not come to fruition, it seeded the idea for an even more ambitious telescope, which I describe next.

## 8. THE GIANT METREWAVE RADIO TELESCOPE

In May 1983, B.V. Sreekantan, the Director of TIFR, suggested that I think of a truly innovative project. This led me to consider various possibilities. At that time it was not easy to conceive of a very large synthesis radio telescope operating at meter wavelengths due to the difficulty of bringing radio signals from far away antennas to a central laboratory. In 1980, for the VLA in the United States, which has an extent of $\sim$35 km, waveguides were installed using the TE01 mode for bringing the RF signals from distant antennas to its central laboratory. These waveguides are required to be straight to within a few centimeters up to distances of $\sim$1 km. This was possible at the VLA, being located on a relatively flat plane with low population density. The high cost of this technology and the lack of availability of large stretches of relatively flat and sparsely populated land made this impractical for India! In December 1983, Alec Little from Australia wrote to me in his Christmas mail that they were investigating the possibility of using optical fibers for one of their radio telescopes. After receiving his letter, I went from Ooty to the Indian Institute of Science at Bengaluru and read about optical fibers. Thereafter, on the midnight of January 1, 1984, in a flash (after a few pegs of whiskey!), I envisioned dividing the 2-km long and 50-m wide parabolic cylindrical antenna of the proposed GERT into 34 parts, to be located in a Y-shaped configuration extending over ~25 km in India, using lasers and optical fibers for communication to all the antennas. I named the proposed instrument the Giant Metrewave Radio Telescope (GMRT). It could investigate certain outstanding astrophysical problems that are exclusively or best studied at decimeter and meter wavelengths, such as observations of redshifted neutral hydrogen, pulsars, and the diffuse radio emission from celestial radio sources (Swarup 1990). The proposal was supported by all concerned at TIFR as well as the Planning Commission of the government of India. After a considerable search, a suitable site was selected near the town of Narayangaon that is located about 80 km north of Pune in Maharashtra, India, for locating the central array of the GMRT in an area of ~1 $km^2$ and the Y-shaped array in a region of ~25-km diameter. Considering that parabolic cylinders have limited frequency coverage and steerability, TCE was requested in early 1985 to design a parabolic dish antenna of 40–45-m diameter at an affordable cost, using wire mesh for the reflecting surface of the dish in order to minimize the wind loading. However, the cost of the dishes designed by TCE was quite high because of the required support of the wire-mesh to maintain a parabolic shape. In early 1986, I conceived of a novel design for supporting the wire-mesh panels of a parabolic reflector using Stretched Mesh Attached to Rope Trusses (SMART). The cost of 45-m diameter dishes using the SMART concept was affordable. Thereafter, the GMRT project was approved by Rajiv Gandhi, then Prime Minister of India, in February 1987. Detailed design of the structural and mechanical parts of the dishes was carried out by TCE over the next two years. Contracts were awarded in December 1989 to two companies for fabrication and erection of the 45-m dishes, with each company to build fifteen dishes. All thirty 45-m dishes were erected by March 1996, under supervision of Suresh Tapde, who was the Project Engineer, and me. I had retired from TIFR in March 1994. The servo system was designed by an engineering group at the Bhabha Atomic Research Centre, Mumbai. The entire electronics antenna feeds operating in the frequency ranges of 130–150, 230–235, 320–350, and 590–620 MHz and the complex correlator system were designed by the Radio Astronomy Group of TIFR. The RRI at Bengaluru designed the antenna feeds for the 1,000–1,450 MHz band; RRI also contributed to the GMRT array combiner, which was used for pulsar work as well. GMRT became operational in 1999. In 2001, it was opened to all astronomers and astrophysicists not only from India but also from any country in the world, with proposals reviewed and time allotted by an independent committee.

The GMRT consists of 30 fully steerable parabolic dishes, each one 45 m in diameter (**Figure 4*a***) (Swarup 1990, Swarup et al. 1991); 14 dishes are located in a central area ~1 km × 1 km in extent in order to observe extended features of celestial sources. The remaining 16 antennas are located along a ~25-km Y-shaped array, with each arm being ~15 km in length, in order to observe celestial radio sources with resolutions varying from ~2 arcsec at 1,400 MHz to ~20 arcsec at 150 MHz (**Figure 4*b***). Antenna feeds mounted on a rotating turret are placed near the focal point of the 45-m dishes so as to allow observations at one of the five frequency bands: 130 MHz, 235 MHz, 325 MHz, 619 MHz, and 1,430 MHz, each with 32 MHz of bandwidth. Recently, Yashwant Gupta and colleagues have installed new antenna feeds and receivers at the GMRT, which provide nearly continuous coverage from ~130 MHz to ~1,430 MHz and also have wider bandwidths up to 400 MHz in some of the frequency bands. This upgrade has resulted in the change of name from the GMRT to the uGMRT (Gupta et al. 2017). This has increased the sensitivity of the GMRT by a factor of about three. The RF signals received by the antenna feeds and amplifiers located at the focus of the dishes are brought to a central laboratory using optical fibers, where the signals are cross-correlated. The correlations give a raw map that is deconvolved using the CLEAN procedure (Högbom 1974), and the closure phase and self-calibration techniques (Jennison 1958), that were developed for use in synthesis radio telescopes. Thompson et al. (1986)

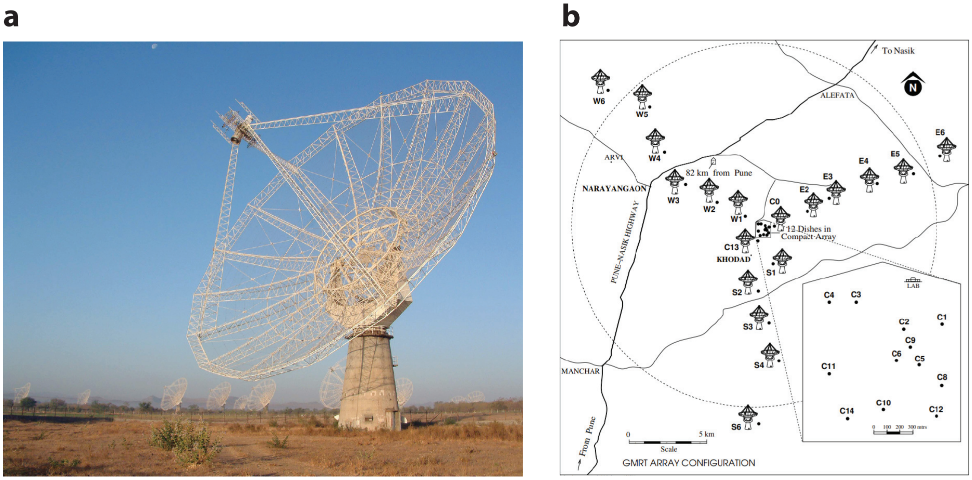


**Figure 4**

(*a*) One of the 30 Giant Metrewave Radio Telescope (GMRT) antennas of 45-m diameter: 10 other antennas can be seen in the distance. (*b*) 14 antennas of the GMRT are located randomly in a central square of ~1 km × 1 km and another 16 antennas are placed in a Y-shaped array of ~25 km in size. Figure from NCRA-TIFR Archives.

have described interferometry and synthesis in radio astronomy. In a typical 10-h observation of a celestial radio source made with the GMRT, images are obtained as if made with a parabolic dish of 25 km in size, which is similar to that by the VLA in the United States. When I described that to S. Chandrasekhar (Nobel laureate) during his visit to the GMRT in 1992, he wrote in the visitors book, "…shouldn't have thought that such things can be done."

The effective area of the 30 GMRT antennas is ~30,000 m$^2$ for the lower-frequency bands and ~18,000 m$^2$ at the 1,430-MHz band. GMRT is the most powerful radio telescope in the world in the lower-frequency range. GMRT provides complementary information for the celestial radio sources in the frequency band of 130 MHz to 1,430 MHz in comparison with that provided by the VLA in the frequency band from ~1,000 MHz to 30,000 MHz.

GMRT has been used for observations of planets; exoplanets; the Sun; and a wide variety of radio sources in our own Galaxy including pulsars, clusters of galaxies, radio galaxies, quasars, and other celestial objects. Recently, Intema et al. (2017) have published a catalog of ~0.6 million radio sources in the declination range from −53 deg to +90 deg, based on ~2,000 h of observations made with the GMRT at 150 MHz by the radio astronomers at NCRA-TIFR [the survey is called the TIFR-GMRT Sky Survey (TGSS)].

Here, I describe my own somewhat personal selection of results obtained with the GMRT. Saikia et al. (2006) discovered a double-double radio galaxy (J1453+3304). Brunetti et al. (2008) made extensive surveys of those clusters of galaxies that emit at very low frequencies. Machalski et al. (2010) described observations of a giant radio galaxy (J1420+0540) with a projected linear size of 4.69 Mpc. Roy & Pal (2013) discovered possibly the youngest supernova remnant at 330 MHz in our Galaxy. De et al. (2016) detected polarized quasi-periodic microstructure emission in millisecond pulsars. Recently, Saxena et al. (2018) have discovered the most distant radio galaxy identified to date at a redshift of $z = 5.72$. Mohan et al. (2019) described polarizations and brightness temperature observations of Venus, placing constraints on its emission mechanism. Using the uGMRT, neutral hydrogen, HI, has been detected at a redshift of 0.37 by stacking 445 galaxies (Bera et al. 2019). Chowdhury et al. (2020) have recently detected HI at the redshift ~1 by stacking 6,400 galaxies. I may note that observation of HI at high redshift was one of the most important objectives of the GMRT (Swarup 1990, Swarup et al. 1991). During the past 18 years, the GMRT has been used by astronomers from 35 countries in the world; about half of those were from India.

## 9. INDIAN INSTITUTES OF SCIENCE EDUCATION AND RESEARCH (IISERs)

I retired from TIFR in 1994 at the age of 65 years. At that time, I was very concerned about the lack of quality education in physics, mathematics, chemistry, and biology in India. During the 1950s, only ~20 universities existed in India, with each providing education to ~40 students in a four-year course at the B.Sc. and M.Sc. levels, by reputed teachers. As an example, I was taught by distinguished teachers at the Allahabad University during 1946–1950. During the past 60 years, there has been an explosive growth of higher educational institutions in India. There are more than 760 universities in India today! Education at the B.Sc. levels is done mostly in the affiliated colleges, and M.Sc. classes are conducted in the universities. Therefore, students are not taught at the B.Sc. levels by quality teachers in their formative years. The brightest students join engineering colleges after their twelfth-year examination because of the lack of suitable science education at the B.Sc. level and also because of better career opportunities in the corporate sector. Two years after my retirement from TIFR in 1994, I wrote to Prof. Vasant Gowrikar, then Vice Chancellor of the Pune University, proposing a five-year integrated course providing science education during the first four years and in the fifth year advanced teaching and research by reputed teachers in well-equipped laboratories. A detailed proposal was prepared by V.G. Bhide, former Vice Chancellor of the Pune University, and me. In spite of a lot of correspondence and many personal meetings by us with the concerned authorities and the Ministers of the government of India, the proposals were not approved for eight years! Finally, the approval of our proposal materialized in 2004, after a change of the government in Delhi. In 2005, at the initiative of C.N.R. Rao, it was decided by the government of India to establish Indian Institutes of Science Education and Research (IISERs) for a five-year science education course, after completing the 12th year of education. To begin with, two IISERs were established at Pune and Kolkata (Swarup 2015). There are now seven IISERs across India. Because of their well-equipped laboratories and good infrastructure, IISERs have been attracting both talented faculty and students.

## 10. CONCLUSION

The ORT became operational in February 1970 and was the first major astronomical instrument in India. In recent years, astronomical observations have been made in the radio, optical, and X-ray wavelengths at many institutions in India. Theoretical astrophysicists have also made important contributions, particularly by those working at the Indian University Centre for Astrophysics (IUCAA) at Pune. In this prefatory, I have given a brief account of my own journey in the field of radio astronomy including its emergence and growth in India (Swarup 2006, 2010).


## DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that may be perceived as affecting the presentation of this account.

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