REMINISCENSES REGARDING PROFESSOR W.N. CHRISTIANSEN

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Abstract: In this short paper I describe my initiation into the field of radio astronomy fifty years ago, under the guidance of Professor W.N. ('Chris') Christiansen, soon after I joined the C.S.I.R.O.'s Division of Radiophysics (RP) in Sydney, Australia, in 1953 under a 2-year Colombo Plan Fellowship. During the early 1950s Christiansen had developed a remarkable 21cm interferometric grating array of 32 east-west aligned parabolic dishes and another array of 16 dishes in a north-south direction at Potts Hill. Christiansen and Warburton used these two arrays to scan the Sun strip-wise yielding radio brightness distribution at various position angles. During a three month period I assisted them in making a 2-dimensional map of the Sun by a complex Fourier transform process. In the second year of my Fellowship, Parthasarathy and I converted the 32-antenna east-west grating array to study solar radio emission at 60cm. During this work, I noticed that the procedure adopted by Christiansen for phase adjustment of the grating array was time consuming. Based on this experience, I later developed an innovative technique at Stanford in 1959 for phase adjustment of long transmission lines and paths in space. In a bid to improve on the method used by Christiansen to make a 2-dimensional map of the Sun from strip scans, I suggested to R.N. Bracewell in 1962 a revolutionary method for direct 2-dimensional imaging without Fourier transforms. Bracewell and Riddle developed the method for making a 2-dimensional map of the Moon using strip scans obtained with the 32 element interferometer at Stanford. The method has since revolutionized medical tomography. I describe these developments here to highlight my initial work with Christiansen and to show how new ideas often are developed by necessity and have their origin in prior experience! The 32 Potts Hill solar grating array dishes were eventually donated by the C.S.I.R.O. to India and were set up by me at Kalyan near Mumbai, forming the core of the first radio astronomy group in India. This group went on to construct two of the world's largest radio telescopes, the Ooty Radio Telescope and the Giant Metrewave Radio Telescope. Chris Christiansen was not only my *guru* but also a mentor and a friend for more than fifty years. I fondly remember his very warm personality.

Keywords: W.N. Christiansen, history of radio astronomy, history of science in India, solar radio emission, the Ooty Radio Telescope, the Giant Metrewave Radio Telescope

1 INTRODUCTION

Radio emission from the Sun was discovered during the Second World War in 1942 independently by Hey (1946) and Southworth (1945), in 1943 by Reber (1944; 1946), and in 1945 by Alexander (Orchiston, 2005). Appleton (1945) also described reports of radio noise received by ham radio operators at wavelengths between 7.5 m and 30 m during the previous sunspot maximum. In mid-1945, three separate reports describing the discovery of the solar radio emission by Hey, Reber and Alexander were received at nearly the same time by the C.S.I.R.O.'s Division of Radiophysics (RP) in Sydney (Ruby Payne-Scott, 1945), and these inspired Pawsey and collaborators to initiate systematic research activities in the new field of radio astronomy, starting in October 1945 (Pawsey et al., 1946). They discovered solar radio emission arising from the corona, a slowly varying component related to sunspots, and strong radio bursts associated with flare activity (see Christiansen, 1984b; Orchiston, Slee and Burman, 2006; Pawsey, 1950).

Two major instruments were built in Australia for detailed investigation of the solar radio emission. In 1948 Paul Wild erected a solar spectrograph at RP's Penrith field station[1] in order to study solar radio bursts (see Stewart et al., 2009), and in 1952 W.N. (Chris) Christiansen (1953) set up an innovative multi-element 21cm grating interferometer at the Potts Hill field station[1] in order to investigate radio brightness distribution across the Sun. This interferometer consisted of 32 parabolic dishes each 6ft in diameter aligned along a 700ft east-west baseline. One year later a 350ft north-south array comprising 16 dishes was installed at Potts Hill (see Wendt et al., 2008).

This pioneering development in radio interferometry by Chris led subsequently to the construction of many major solar radio telescopes around the world, including the 21cm Chris Cross antenna at Fleurs, near Sydney (Christiansen et al., 1957; Orchiston 2004), the 9.1cm Stanford Cross antenna in the U.S.A. (Bracewell, 2005; Bracewell and Swarup, 1961), radio interferometers at 7.5cm and 3.2cm in Japan (Tanaka, 1984), the 50cm Kalyan Radio Telescope in India (Swarup, 2006), the 120cm Miyun Radio Telescope in China, the 10.7cm solar radio interferometer in Canada (Covington, 1984), 3.2cm and 1.7m solar arrays in France (Denisse, 1984), and a 107cm solar grating array near Lake Baikal in Russia (Salomonovich, 1984). Based on their work in Australia and at Cambridge, Chris and Jan Hogbom were the main proponents for the construction of the Westerbork Synthesis Radio Telescope (WSRT). Success of the WSRT fostered the development of ever more powerful synthesis radio telescopes: the VLA in the USA, the AT in Australia, the GMRT in India and now the LOFAR in the Netherlands and the SKA in Australia or South Africa! Chris must have been very proud to see these developments.

I learned the powerful technique of radio interferometery from Chris in 1953 and have not looked back (Swarup 2006). To recapitulate, I first describe my early years. After receiving an M.Sc. in Physics from Allahabad University in north India in 1950 I joined the National Physics Laboratory (NPL) in New Delhi to work on paramagnetic resonance under the guidance of its Director, Sir K.S. Krishnan. In August 1952 Krishnan attended the Congress of the International Union of Radio Science (URSI) held in Australia. He was very impressed by outstanding discoveries being made in the new field of radio astronomy by scientists of RP, under the leadership of Joe Pawsey. Krishnan decided to initiate radio astronomical research at the NPL. With a recommendation from Krishnan, I obtained a two-year Fellowship under the Colombo Plan Scheme, and joined RP in March 1953. Pawsey suggested that I work with Christiansen for the first three months and then with Bernie Mills, Paul Wild and John Bolton for three months each. During the second year of the Fellowship, I was asked to work independently on a major project along with my Indian colleague, R. Parthasarathy, who had also joined RP in early 1953. We decided to convert the above-mentioned east-west grating array to operate at 60cm (instead of at 21cm) in order to study solar radio emission at this longer wavelength.

During my stay in Australia, I had close contact with Chris not only academically but also culturally and socially. He was not only my *guru* but became a close mentor and remained a friend for the next fifty years.

2 THE SOLAR GRATING INTERFEROMETER AT POTTS HILL

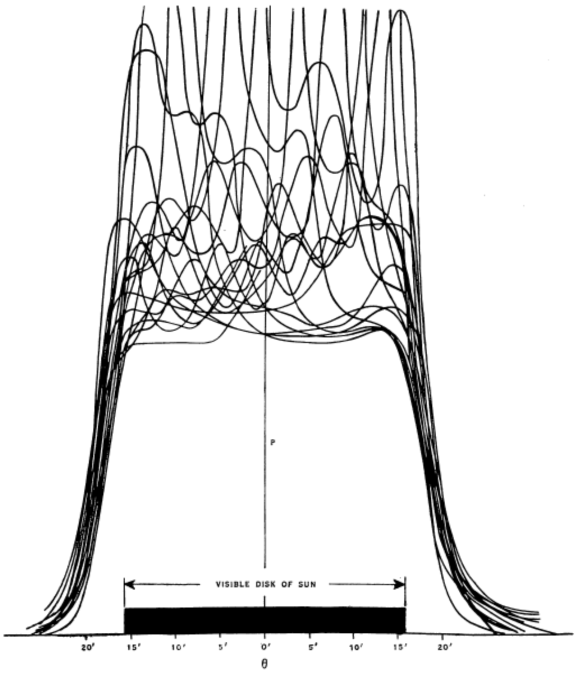
As mentioned above, in 1952 and 1953 Chris set up innovative multi-element east-west and north-south grating interferometers along the banks of a Sydney water supply reservoir at Potts Hill (Christiansen 1953; Christiansen and Warburton 1953a). A close-up of the east-west array is shown in Figure 1, while Figure 2 provides an aerial view of both arrays. Chris' objective was to study the daily radio brightness distribution across the Sun, and by March 1953 he and Joe Warburton had obtained a large number of daily strip scans across the Sun at a wavelength of 21cm (1,420 MHz), where the resolution was 4 minutes of arc. By superimposing the daily records, they determined the contribution of the quiet Sun from the strip scans at various position angles with respect to the polar axis of the Sun (see Figure 3).

As suggested by Pawsey, I joined Chris to work under his guidance for three months. Chris asked me to assist in preparing a two-dimensional radio brightness distribution map based on observations that he and Joe Warburton obtained. Using an electrical calculator, I first determined the Fourier Transform (FT) of each of the strip scans obtained at various position angles, plotted the values on a large piece of graph paper, made contour plots manually, determined manually strip scans of the two-dimensional plot at various position angles, calculated the FT of each of these and finally determined the two-dimensional distribution of 21 cm radio emission across the solar disk. Ron Bracewell described short cuts to me for faster calculation of the FTs. Nevertheless, it was a very laborious process, but thanks to Chris' gentle guidance it ultimately led to success! The map that was published by Christiansen and Warburton (1955) is shown in Figure 4. Years later it occurred to me that a much simpler procedure can be used to determine a two-dimensional distribution directly from strip scans without doing any FTs, as described in Section 4 below.

The above-mentioned two-dimensional map showed limb brightening at 21cm, as predicted earlier by Steve Smerd (1950), who assumed a higher electron density in the solar corona near the equatorial regions. However, measurements made by Stanier (1950) at Cambridge conflicted with Smerd's prediction and showed no evidence of limb brightening at 60cm.

Figure 1: View looking east showing the east-west grating interferometer on the southern bank of one of the two Sydney water supply reservoirs at Potts Hill (courtesy: ATNF Historic Photographic Archive, B2638-2).

Figure 2: Aerial view looking southwest across the two water supply reservoirs at Potts Hill. The 32 antennas comprising the east-west solar grating array can be seen on the southern edge of the foreground reservoir, and the 16-element north-south grating array is clearly visible along the eastern edge of this same reservoir (courtesy: ATNF Historic Photographic Archive, 3475-1).



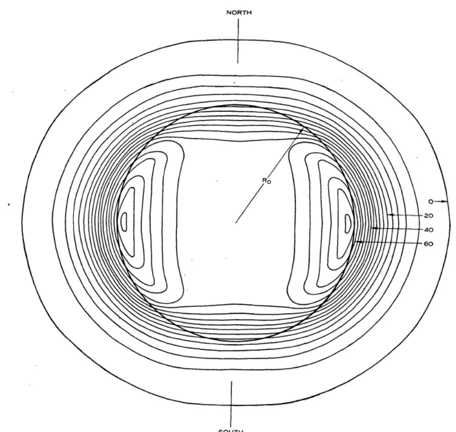


Figure 3 (left): Twenty individual daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the black bar on the x-axis (after Christiansen and Warburton, 1953b: 200).

Figure 4 (above): The two-dimensional distribution of radio brightness across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K (after Christiansen and Warburton, 1955a: 482).

In 1954, Christiansen went on a one-year sabbatical to work at the Meudon Observatory in France, and the Potts Hill grating array observations were discontinued. Parthasarathy and I were interested in Stanier's earlier finding, and so we suggested that the east-west grating array should be converted from 21cm to 60cm (500 MHz), so that we could investigate this anomaly. Both Chris and Joe Pawsey enthusiastically supported our proposal. Chris explained the intricacies involved in matching the transmission lines of the 21cm grating array, particularly to ensure that the lengths of the lines from the central point of the array to each of the 32 dipoles was within a few mm. This involved a cumbersome procedure whereby a 21cm signal was transmitted from the junction of each adjacent pair of dishes, the signals were received at the dipole feeds of the adjacent dishes using a movable probe, their phase was then measured using a slotted line, and finally appropriate corrections were made to ensure equality of the lengths of the transmission lines to within a few mm. In 1954, while we were involved in this exercise I asked Pawsey whether I could short the outputs at each dipole successively and measure the positions of the short at the central point of the transmission line network of the entire array. Pawsey replied that my suggestion would not work as any mismatch in the long transmission lines would add to the resulting phase from the dipoles. Six years later I took care of Pawsey's objections by conceiving a round trip phase measurement scheme and modulating the signals at the outputs of the Stanford array parabolic dishes (see Swarup and Yang 1960, and Section 4 below). At the time, Pawsey (1960) wrote me:

> I had already heard of your phase measurement technique and think that you have made a real break-through in this technique. Congratulations! Chris regards the idea as the key to really large Mills Crosses. Without a good checking technique, they could not operate.

Once the Potts Hill east-west array was operational at 60cm we were able to dispute Stanier's finding (see Swarup and Parthasarathy, 1955) and show the presence of limb brightening at this wavelength (see Figure 5). We also studied localized radio bright regions associated with the slowly varying component and determined their emission polar diagrams by measuring the intensity with the rotation of the Sun (Swarup and Parthasarathy, 1958). For us this was a great experience as we were initiated into the wonderful world of radio astronomy: constructing dipoles, matching transmission lines, building a 500 MHz receiver, making observations, reducing data and finally, deriving meaningful astronomical conclusions.

3 TRANSFER OF THE THIRTY-TWO DISHES TO INDIA

Upon his return from France in early 1955 Christiansen decided to build a new cross-type array at RP's Fleurs field station near Sydney. Affectionately known as the 'Chris Cross', this consisted of two orthogonal grating interferometers, which were used to make daily solar maps at 21cm (see Christiansen and Mathewson, 1958; Christiansen et al., 1957; Orchiston, 2004). As a result, both of the grating arrays at Potts Hill, and associated equipment, became surplus and were to be scrapped. I therefore asked Pawsey and Chris whether the 32-element east-west grating array could be gifted to India. They readily agreed to this suggestion, as did E.G. (Taffy) Bowen, Chief of the Division of Radiophysics. On 23 January 1955, I wrote to K.S. Krishnan about the possible transfer of the 32 dishes to the NPL in New Delhi (Swarup, 1955). On 22 February he replied: "I agree with you that we should be able to do some radio astronomy work even with the meager resources available." (Krishnan, 1955). C.S.I.R.O. then approved the donation under the Colombo Plan scheme, but with the proviso that India must bear the cost of their transportation (which amounted to about 700 Australian Pounds, as I recall). I returned to join the NPL in July 1955, but the transfer of the dishes was delayed by bureaucratic correspondence. So in August 1956 I decided to join the Harvard College Observatory as a Research Associate in order to study dynamic spectra of solar bursts using the 100-600 MHz swept-frequency radio spectrograph that had just been installed at Fort Davis, Texas. One year later, I moved to Stanford University as a Research Assistant, and began research for a Ph.D. degree (Swarup, 2006).

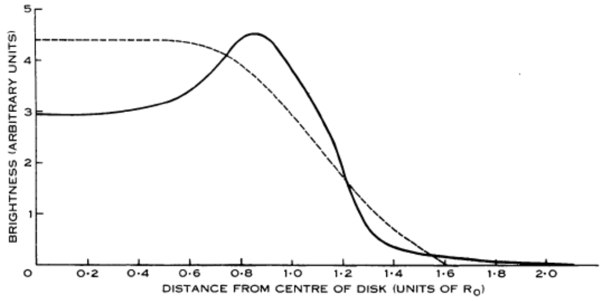


Figure 5: Brightness distributions at 500 MHz showing Stanier's result (dashed line) and Swarup and Parthasarathy's observations (after Swarup and Parthasarthy, 1955b: 493).

4 THE STANFORD MICROWAVE SPECTRO-HELIOGRAPH ANTENNA

In late 1955 Ron Bracewell resigned from RP and joined Stanford University in order to teach in the Department of Electrical Engineering and build a solar radio telescope. The outcome of the latter venture was the Stanford Microwave Spectro-heliograph Antenna, which operated at 9.1cm and consisted of east-west and north-south grating arrays arranged in the form of a cross (see Figure 6). Each array consisted of 16 parabolic dishes 10 feet diameter, spaced at 25 feet intervals (Bracewell and Swarup, 1960). The voltage outputs of the two arrays were multiplied giving a pencil beam of 3.1 arc minutes. In September 1957, soon after joining Stanford, I made a detailed study of a Cross antenna versus a T-shaped antenna and showed that both provided the same resolution but that the latter, although more economical, was much more sensitive to phase errors, which resulted in spurious sidelobes. Bracewell (2004) subsequently wrote to me: "I had a letter from Christiansen sometime later that he believed that the T-idea came from Stanford."

In September 1957 Chris visited Stanford and I got valuable tips from him concerning the Stanford Cross Antenna project. Bracewell asked me and K.S. Yang (another graduate student) to design and adjust the waveguide transmission line system. We equalized the lengths of the transmission lines and the resulting phases of the signal outputs of the 32 antennas using the technique developed by Christiansen for the Potts Hill array (Section 2). After more than six months of hard work we were able to make maps of the Sun but we found huge spurious sidelobes. Bracewell asked us to make fresh phase measurements. Again we found large sidelobes and we concluded that the spacing and physical location of the antennas could be in error. Bracewell decided to survey their positions himself and to make corrections as required but asked us to make the phase measurements again. How strenuous and boring, getting up early in the morning in order to make phase measurements before the length of the probes was affected by temperature changes caused by sunlight, not to mention having to attend classes at 9a.m.! Hence, I conceived the idea of transmitting a signal at 9.1 cm from a central point of the transmission line network to all the antennas, modulating and reflecting the voltage signal from the output of each antenna and measuring the round trip phase of the modulated signal, thus avoiding Pawsey's objections (Swarup and Yang 1960). The idea was conceived while I was a graduate student, when time was of the essence, so prior experience (at Potts Hill) and necessity became the mother of invention! The concept of round trip phase measurements has been widely used for phase adjustments to all of the synthesis radio telescopes built in the world over the last fifty years, klystrons of the Stanford linear accelerator, clocks and local oscillators in Space, and many other applications.

Figure 6: Panoramic view of the 9.1 cm Stanford Microwave Spectro-heliograph Antenna (courtesy: Stanford University Photographic Department, Negative No. 9448).

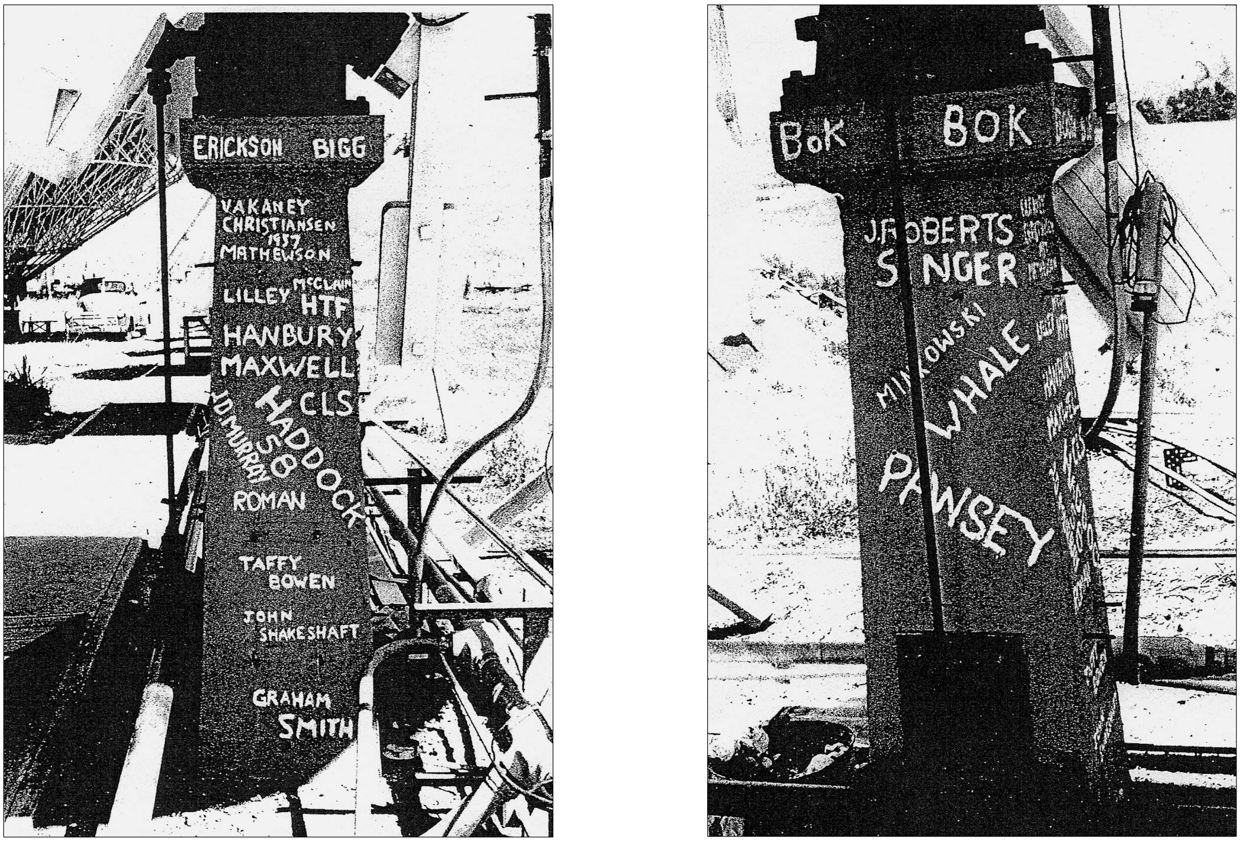


Figure 7: Two of the Stanford pillars with carved names of notable optical and radio astronomers.

By 1962 we had made large numbers of daily two-dimensional maps of the Sun at 9.1cm using the Stanford Cross. I found that the radio emission from the quiet Sun seemed to show a north-south asymmetry, and I wondered whether this arose from phase errors in the transmission line network of the Cross, including the rotating phase shifters in the north-south lines. Since the total power outputs of the two grating arrays of the Cross antenna were expected to be much less sensitive to phase errors, I wondered whether a much simpler procedure could be used to determine a two-dimensional distribution directly from the strip scans rather than the method recommended to me by Chris (and outlined previously in Section 2). I quote from one of the two letters that Bracewell later wrote to me about this: "I do remember being in someone's car while our group was driving to have lunch when you proposed superimposing the scans in real space without any Fourier Transform at all." (Bracewell, 2004; cf. 1992).

Since I was to return to India from the U.S.A. after nearly seven years, I did not pursue the idea, but the method subsequently was used by Bracewell and Riddle (1967) to make two-dimensional maps of the Moon using strip scans obtained with the Stanford arrays. It is interesting to note that this technique is widely used today in X-ray imaging and has revolutionized medical tomography (see Bracewell, 2005). I describe this here to highlight the initial work done by me under guidance from Chris. New ideas often have their origin in prior experience!

Before leaving the Stanford story there is one further recollection that I wish to share. There were a number of concrete pillars at the Stanford radio astronomy site that supported the different antennas, and Ron Bracewell would encourage visiting radio astronomers from around the world to carve their names on these. Many of my former RP colleagues' names are to be found on these pillars, including Chris, Taffy Bowen, Don Mathewson, Joe Pawsey, Jim Roberts and John Murray (e.g. see Figure 7). The survival of these historic pillars was at stake when Stanford University decided to abandon the radio astronomy site in 2006 and remove all evidence of its former scientific past, and it is heartening to know that these pillars have all survived and will not be destroyed (pers. comm., Miller Goss, 2008).

5 FORMATION OF THE RADIO ASTRONOMY GROUP AT THE TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Chris, Joe Pawsey and Frank Kerr were very supportive when it came to forming a radio astronomy group in India (Swarup, 2006). By the 1960s, T.K. Menon, M.R. Kundu and I all had more than eight years experience working at leading radio astronomy observatories and institutions abroad, and at the time T. Krishnan was working with Chris at RP in Sydney. On 22 September 1960, Chris wrote to me about Krishnan and said "…you two and Menon and Kundu should get together for a united attack on the monolith of Indian bureaucracy…" About a month later, on 26 October 1960, Pawsey wrote: "… you four could make an effective group … but keep off fashionable ideas …" Later, on 29 June 1961, he wrote: "… 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 who had no special ideas of what to do with one." (Pawsey, 1961). Pawsey arranged for Krishnan to attend the Berkeley IAU General Assembly in August 1961, and during the meeting Krishnan, Kundu, Menon and I wrote a proposal to start a radio astronomy group in India and we submitted this to five major scientific organizations and agencies in India, including Dr Homi Bhabha, founding Director of the Tata Institute of Fundamental Research (TIFR) in Mumbai (Swarup, 2006). Our proposal was approved by Dr Bhabha, and I returned to India on 31 March 1963 in order to join the TIFR.

At that time there was a raging controversy between the Steady State and Big Bang Cosmologies. In June 1963 I suggested measuring the angular sizes of hundreds of extragalactic radio sources to arc second accuracy by lunar occultation observations in order to test the predictions of the two theories. For this purpose, I proposed the construction of a large parabolic cylindrical antenna placed on a suitably inclined hill in South India, so as to make its axis of rotation parallel to that of the Earth (Swarup, 1963). This concept was enthusiastically supported by Kundu and Menon, and Dr Bhabha approved the proposal but asked us to first form a core group. In August 1963, V.K. Kapahi and J.D. Isloor joined the group as Research Associates after their graduation.

As a first step, a solar radio interferometer was constructed by the group at Kalyan (near Mumbai) during 1963-1965, using the 32 dishes from Chris' Potts Hill grating array. The resulting Kalyan Radio Telescope (Figure 8) was used to determine the two-dimensional distribution of radio emission from the quiet Sun at 49cm (Swarup et al., 1966). Considerable limb brightening was found at this wavelength.

Figure 8: View of the Kalyan Radio Telescope.

In late 1963 I discussed the occultation project with Chris during a brief visit that he made to the TIFR while he was on his way to the Netherlands. He described the 21cm Westerbork Synthesis Radio Telescope (WSRT), which was under development at the time in the Netherlands. An even less ambitious synthesis radio telescope operating in India at a longer wavelength would have required access to considerably more expertise and technology than was then available in India. Many components would have to be imported, but there was a serious foreign exchange constraint in India at that time. Hence we continued to pursue the cylindrical radio telescope project for lunar occultation and other investigations. N.V.G. Sarma and M.N. Joshi from the NPL, who had respectively worked at Leiden for two years and obtained a Ph.D. in radio astronomy in France, joined the TIFR group in late 1964. Then M.R. Kundu returned from the U.S.A.

in early 1965 and provided considerable support for the project. In January 1965, Ramesh Sinha and I located a suitably-inclined hill at Ooty in southern India, and construction of the 325 MHz Ooty Radio Telescope (ORT) was completed by February 1970 (Figure 9). This comprised a 530m long parabolic cylinder which was 30m wide (Swarup et al., 1971). The angular sizes of ~1,000 discrete radio sources were then measured with a resolution of between 1 to 10 seconds of arc for the first time, and these supported the Big Bang theory. T.K. Menon joined the group in 1970, and although he and Kundu eventually returned to the U.S.A., both played a very important role in the growth of the TIFR radio astronomy group, and particularly in the training of students. Since 1970 the Ooty Radio Telescope has been used for a wide variety of investigations (see Swarup et al., 1991), and it is currently making interplanetary scintillation observations of more than 900 sources every day (Manoharan: www.ncra.tifr.res.in).

During 1975-1984, a 4 km long synthesis radio telescope was set up at Ooty by combining the ORT with six much smaller parabolic cylinders measuring 23m × 7.5m (Swarup, 1984).

In early 1984 a proposal was prepared for the Giant Metrewave Radio Telescope (GMRT) (Swarup, 1984), and this was sent to several respected overseas radio astronomers. On 30 July 1984, Chris wrote to me: "… I think that you are doing the right thing in continuing your work at the lower end of the radio frequency spectrum. This part of the spectrum has been relatively neglected. India is a good place to do such work because of its relative radio "quietness" and you have developed good techniques for such work ..." (Christiansen, 1984a). Dave Heeschen, Director of the National Radio Astronomy Observatory in the U.S.A. wrote in September 1984: "... The GMRT ... would almost certainly be a uniquely powerful telescope for many years to come ... The GMRT would be a major step forward in Radio Astronomy that would benefit the science and radio astronomers everywhere ..." A site was located about 80km north of Pune in western India by 1986. The GMRT was approved by the Government of India in early 1987, after the Prime Minister, Rajiv Gandhi—who was an active radio ham—was satisfied after asking three penetrating questions. A detailed design was finalized by 1990 (Swarup et al. 1991). The GMRT consists of 30 parabolic dishes each 45m diameter and of innovative design (Figure 10). The GMRT became operational in 1999 and has been used by hundreds of astronomers from India and more than twenty different countries.

6 CONCLUSION

Although I worked with Chris only for a part of my two years at Radiophysics during 1953-1955, it was a very fruitful and valuable interaction. Later I had valuable discussions with him and received very helpful advice from him during his visits to Stanford and India. I also met him and his wife, Elsie, at their home in Sydney in 1953 and at several international meetings, particularly those of URSI. As the President of URSI, Chris strongly supported URSI's programmes for the growth of radio science in developing countries. Pioneering contributions by Chris to many aspects of radio interferometers led to the construction of several major radio telescopes throughout the world, and the book by Christiansen and Högbom titled *Radio Telescopes* (1969) has been widely used by students, antenna designers and astronomers.

Figure 9: The Ooty Radio Telescope, a 530m × 30m cylindrical parabolic antenna in Southern India.

Figure 10: Panoramic view of some of the Giant Metrewave Radio Telescope antennas.

7 NOTES

1. Potts Hill and Penrith were two among a network of 20 field stations and remote sites maintained by RP in or near Sydney during the late 1940s through into the 1960s. For a review of these field stations and remote sites see Orchiston and Slee (2005). The history of Potts Hill—the sole RP field station at which I was based—is also discussed by Davies (2005) and by Wendt (2008).

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