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A TRIBUTE TO PROFESSOR GOVIND SWARUP, FRS.: THE FATHER OF INDIAN RADIO ASTRONOMY

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Abstract: In this paper we pay a tribute to the 'Father of Indian Radio Astronomy', Professor Govind Swarup, BSc, MSc, PhD, FRS, by celebrating his 90th Birthday (which occurred on 23 March 2019) and recounting his remarkable scientific achievements in three disparate regions of the globe: the Indian Subcontinent, Australia and the United States of America.

Between 1953 and 1955 Govind served what was effectively an 'apprenticeship' in radio astronomy while on a Colombo Plan Fellowship at the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics in Sydney, Australia. After a short time back in India, he moved to Harvard University's Fort Davis Radio Astronomy field station in Texas, USA, and one year later, in September 1957, began a PhD in radio astronomy under the guidance of Professor Ron Bracewell at Stanford University.

Soon after completing his doctorate and accepting a faculty position at Stanford, Govind and Bina Swarup returned to India so that Govind could launch a radio astronomy program at the Tata Institute of Fundamental Research in what was then still known as Bombay (present-day Mumbai). In 1963 this led to the construction at Kalyan, near Bombay, of India's first radio telescope, an array of 32 six-feet (1.8-m) diameter parabolic dishes that served as a 610 MHz solar grating interferometer. This innovative T-shaped radio telescope was a rebadged version of the 1420 MHz East-West solar grating array that was designed by Dr W.N. (Chris) Christiansen and erected at the Potts Hill field station in Sydney in 1952. But it had a special place in Govind's heart because back in 1955 he and fellow Colombo Plan student, R. Parthasarathy, had reconfigured this as a 500 MHz grating array and used it to search for evidence of solar limb brightening.

Govind's next radio telescope was a solely Indian affair and an ingenious concept that took full advantage of southern India's geographical location near the Equator. The Ooty Radio Telescope was built between 1965 and 1970 and comprised a N-S oriented 530-m × 30-m parabolic cylinder that was located on a hill with the same slope as the latitude of the site, i.e. 11°. This *de facto* 'equatorial mounting' meant that radio sources could be tracked continuously for 9.5 hours every day. The Ooty Radio Telescope was used mainly to measure the positions and angular sizes of faint radio galaxies and quasars.

After abortive attempts to erect a Giant Equatorial Radio Telescope (GERT) of similar design, first in Kenya and then in Indonesia, in 1984 Govind conceived the idea of constructing a low frequency synthesis radio telescope in India. During the 1990s this emerged as the Giant Metrewave Radio Telescope (GMRT) near Pune, an array of 30 45-m diameter fully-steerable parabolic dishes that has been used over the past two decades by Indian and overseas radio astronomers to investigate a variety of discrete sources at decimetre and metre wavelengths.

In March 2019 the National Centre for Radioastrophysics, held an international conference in Pune to celebrate Govind's 90th Birthday and the recent major upgrade of the GMRT. Govind, you truly are the 'Father of Indian Radio Astronomy', and with affection and profound admiration for all that you have achieved in a lifetime devoted to radio astronomy we offer you this paper as an additional—if slightly belated—birthday present.

Keywords: History of radio astronomy, India, Govind Swarup, CSIRO Division of Radiophysics, Stanford, Tata Institute of Fundamental Research, Dr Homi Bhabha, radio telescopes, Kalyan Array, Ooty Radio Telescope, Giant Equatorial Radio Telescope, Giant Metrewave Radio Telescope

1 INTRODUCTION

Radio astronomy was born in 1931 when Karl Guthe Jansky (1905–1950) serendipitously discovered radio emission from our Galaxy (see Sullivan, 1984), but only blossomed after World War II (WWII) when nations like Australia, Canada, England, France, Germany, Japan, the Netherlands, Russia and the USA for the most part took advantage of WWII radar developments and applied them to peace-time research (Sullivan, 2009). In the process a new science was born, one that initially was viewed with suspicion by many optical astronomers (e.g. see Jarrell, 2005). Indeed, it is slightly misleading to refer to the earliest developments as 'radio astronomy' because this term was only coined

Figure 1: Professor Govind Swarup (RAIA).

(by Joe Pawsey) in 1948. Before this, the focus was on cosmic or solar 'noise' and cosmic or solar 'static' (Sullivan, 2009).

Figure 2: Indian localities mentioned in this paper (map: Govind Swarup and Wayne Orchiston).

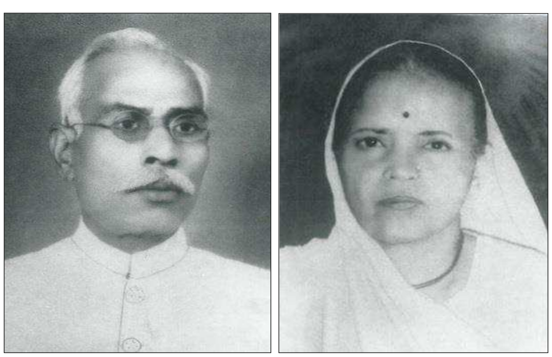

Figure 3: Govind's father, Ram Raghuvir Saran, and his mother, Gunvavati Devi (courtesy: Govind Swarup).

In 2003 the first author of this paper launched the IAU Historic Radio Astronomy Working Group, one of the aims of which was to tap into the memories, photographs, letters and other records maintained by the international pioneers of radio astronomy, while many of them were still alive. Working Group members were particularly active in the Greater Asian region where New Zealand and Australia both began radio astronomical research in 1945, followed by Japan in 1948 (see Orchiston, 2017b; Orchiston and Ishiguro, 2017; Orchiston and Slee, 2017). In the early 1960s two other Asian nations, China and India, joined the radio astronomy 'club'. This paper is about the remarkable achievements of Professor Govind Swarup (Figure 1), one of radio astronomy's pioneers, and the 'Father of Indian Radio Astronomy' (see Swarup, 2014; 2017).

2 GOVIND SWARUP'S EARY YEARS

Govind Swarup was born on 23 March 1929 in Thakurdwara, a small town in the Moradabad district of Uttar Pradesh (Figure 2) and was influenced in his early years by his grandfather and his parents. His grandfather Brijpal Saran was a landlord, owned a textile mill, and lived in a mansion. In 1895 he had graduated in philosophy from Allahabad University, and was fluent in Persian and English.

Govind's father was Ram Raghuvir Saran (Figure 3), who established the first theatre in Delhi, the capital of India. He also started a motor car garage, and purchased land for farming. Govind's mother was Gunvavati Devi (Figure 3), a housewife, who subscribed to an Indian magazine and encouraged Govind to read.

During his childhood Govind used to go to school with his brothers, but sometimes he was also taught at home by his grandfather. When Govind was 12 years of age the family moved to Moradabad, and while he was living there Govind

> … occasionally rode an elephant to school; the elephant was bought by his father to go to the farm during the wet season, but whenever there was no work for the elephant, it was available for Govind. (Phakatkar, 2015; our English translation).

Govind's personality began to develop while he was at Coronation Hindu High School in Moradabad, and this is where he learnt English. In 1944 he matriculated with distinction, and then went to Ewing Christian College in Allahabad (Figure 4) for his intermediate college studies. These were unforgettable years. He learnt to swim at the confluence of the Ganges and Jamuna Rivers—a talent that would come in handy later at Potts Hill reservoir in Sydney. He saw first-hand the dreadful effects of drought as he watched people from the State of Bengal migrating to Allahabad. And he became secretary of the College's Physics Club, and was the one who invited Professor K.S. Krishnan to deliver a lecture at the College. Little did Govind realize at the time that this famous scientist and co-discoverer of Raman Scattering would later attend to his first year university training and then employ him at the National Physical Laboratory in New Delhi, thereby opening the way for him to create an illustrious career in radio astronomy.

After Govind completed his College education his mother wanted him to study engineering in Benares (Varanasi) because her brother was already studying there (Phakatkar, 2015), but Govind had other ideas: he rolled for a BSc at Allahabad University (Figure 5), graduating in physics in 1948. In his first year at the University (1946) he learnt electricity and magnetism from Professor K.S. Krishnan (1898–1962), who later that same year would be knighted and become Sir Kariamanickam Srinivasa Krishnan, and in 1947 would accept the inaugural Directorship of the Physical Research Laboratory in New Delhi.

During his undergraduate years Govind witnessed great change in Indian society. This was a transition period as India struggled to gain its independence from British rule. Govind subscribed to *Harijan* (a weekly journal published by the visionary leader Mahatma Gandhi) and he greatly admired Gandi.

In 1949, when he was enrolled for an MSc in physics at Allahabad University, the 36th Indian Science Congress was held in Allahabad. One of those who attended was the legendary Indian physicist Professor C.V Raman (1888–1970), co-discoverer of Raman Scattering, for which he received the Nobel Prize for Physics in 1930. Govind suggested to his friends that they invite Professor Raman to their hostel for an evening lecture, followed by dinner. Professor Raman agreed, but on the condition that all of the physics students attended his lecture. After the lecture and dinner Professor Raman spent three hours with the students discussing the future development of science and technology in India. As he left the hostel Professor Raman reminded the students of Thomas Edison's famous quote: "Genius is one percent inspiration and ninety nine percent perspiration".

Another famous personality who attended the Allahabad Congress was the British mathematician and geophysicist Professor Sydney Chapman (1888–1970). Govind showed him some of the historical highlights of the city and afterwards Professor Chapman told Govind and his friends:

> India is now an independent nation and from now on new opportunities and challenges will arise. Concentrate on new and innovative concepts in science and technology. (cited in Phakatkar, 2015; our English translation).

Figure 4: The main building at Ewing Christian College in Allahabad (https://www.stalkram.com/media/1866207356117834317_4631851150).

Figure 5: The main historic building at Allahabad University (https://www.indiatoday.in/education-today/government-jobs/story/allahabad-university-invites-application-to-fill-550-vacancies-check-how-to-apply-1478507-2019-03-15).

Figure 6: The National Physical Laboratory in New Delhi (after Phakatkar, 2015).

Govind recounts that

> 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 [see Figure 6], and worked in the field of paramagnetic resonance under the guidance of K.S. Krishnan … the Director of the Laboratory … 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. (Swarup, 2006: 21–22).

As it turned out Govind's future research direction was determined in August 1952 when Dr Krishnan was one of three Indian scientists who attended the Tenth General Assembly of the International Radio Scientific Union (URSI) in Sydney, Australia (Goss, 2014). This was the first time that an URSI General Assembly was held outside of Europe or North America, and Australia was selected because of its long and distinguished research tradition in atmospheric physics and by Australia's rapid emergence as arguably the world's leading nation involved in the new post-war field of radio astronomy (Robinson, 2002).

The 1952 URSI General Assembly ran from 8 to 22 August and was attended by 63 overseas delegates from 13 countries and a large number of Australian scientists. "This large and representative gathering ensured a very successful meeting." (Kerr, 1953: 59). About one-third of the overseas contingent were radio astronomers, and

> At last the RP staff could associate faces with names like Jean-Louis Steinberg from France, Robert Hanbury Brown from Jodrell Bank, F. Graham Smith from Cambridge, C. Alexander Muller from Holland and H.I. 'Doc' Ewen from the United States. (Sullivan, 2017: 483).

Among the Australian radio astronomers was John Bolton, leader of the galactic radio astronomy group based at Dover Heights, and he reported that

> Commission V (Radio Astronomy) was well represented at the conference, as members of all the major research organizations engaged in the field attended. Four formal sessions were held on Radio Astronomy –"The Sun", "Dynamics of Ionized Media", "Interstellar Hydrogen" and "The Discrete Sources". (Bolton, 1953: 23).

Apart from the paper sessions, during the Radio Astronomy business meetings, there were discussions about solar observations, instrumentation, nomenclature and frequency preservation, and the conference also included

> … official visits to two of the Radiophysics Laboratory's field stations—at Dapto on the South Coast where a spectrum analyser operating over a wavelength range of nearly ten to one is installed to observe solar noise bursts; and to Potts Hill where the remainder of the solar work is carried out and where new Hydrogen line equipment is being set up. Private visits were made to the other stations engaged on galactic work. (Bolton, 1953: 26).

Dr Krishnan attended some (if not most) of the Radio Astronomy sessions and went on the two field trips, 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 … 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 … (Swarup, 2006: 22).

When he returned to the National Physical Laboratory, Krishnan described these developments in a colloquium that Govind attended, and he reports that the Australian research also

> … 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. (ibid.).

Krishnan wanted to launch a radio astronomy research program at the NPL but there were no scientists in India with the necessary knowledge and experience, so he suggested that Govind spend a two year 'apprenticeship' working at the Division of Radiophysics in Sydney. Govind agreed to this attractive proposal, the application for a Colombo Plan Fellowship was successful, and soon Govind was on his way to Sydney. The rest … as they say … is history!

3 THE AUSTRALIAN 'APPRENTICESHIP'

In March 1953 Govind, and R. Parthasarathy from Kodaikanal Observatory in southern India[1] arrived in Sydney to begin their Colombo Plan Fellowships in radio astronomy.

Their host was the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics (henceforth RP), which had begun in 1939 as a secret research facility to develop radar. Understandably, this role expanded exponentially during World War II. Sullivan (2017: 453) describes how

> Australian radio astronomy has been at the forefront since its foundation during World War II, with imaginative scientists and engineers, innovative equipment, and strong sponsorship. Soon after War's end a multi-faceted program, by far the largest of its kind in the world, was well established at the Radiophysics Laboratory (RP) in Sydney and continually producing pioneering results. The Australians developed fundamental methods of interferometry, discovered the Sun's hot corona, pinpointed the location of solar bursts, and discovered numerous discrete radio sources.

The inspirational radio astronomy program was led by Dr Joe Pawsey (Figure 7). Joseph Lade Pawsey was born in 1908 in Ararat, Victoria (see Figure 8 for Australian localities mentioned in the text), and after excelling at secondary school he entered the University of Melbourne where he obtained BSc and MSc degrees. He then was awarded an Exhibition Research Scholarship and went to Cambridge where he carried out ionospheric research under J.A. Ratcliffe, graduating with a PhD in 1931. Then he stayed in England and worked on technical side of television before returning to

Figure 7: Dr J.L. Pawsey, leader of the radio astronomy group within the CSIRO's Division of Radiophysics (CSIRO Radio Astronomy Image Archive (henceforth RAIA) 7454-2).

Australia in 1940 and joining PR. There his back-ground in antennas and transmission lines proved useful for radar research, and later when radio astronomy was selected as one of the major post-war research fields of the Division. Joe Pawsey would go on to build an international reputation in radio astronomy (Lovell, 1964), but he died from a brain tumor in 1962—he was only 53 years of age.

Whereas WWII radar research facilities in most other nations were disbanded after the war, Australia was able to retain RP because

> At this time, RP was CSIR's glamour Division, arguably containing within its walls the densest concentration of technical talent on the continent, and CSIR[2] was eager to keep this 'winner' intact. (Sullivan, 2017: 456).

Moreover,

> RP's assets included not only its scientists and engineers, but also its significant support staff of technicians, a camaraderie molded during the War, ample laboratory space and workshops, and bulging stores with the latest radio electronics. This last was considerably augmented shortly after the War's end by an extraordinary bonanza. A large amount of American and British equipment (including whole aircraft!) was being discarded by loading it on the decks of aircraft carriers, taking it a few miles off-shore, and bulldozing it into the sea. Bowen got wind of this, however, and for two or three weeks was allowed to take RP trucks down to the Sydney docks and load them up with radar and communications equipment, often in unopened original crates. For several years thereafter RP researchers drew on this surfeit. (ibid.).[3]

Figure 8: Australian localities mentioned in this paper (map: Wayne Orchiston).

RPs immediate post-war accomplishments in radio astronomy grew from the strong foundation laid by radar research during the war, but almost all of the scientific staff had radio engineering qualifications and employment backgrounds, and it would take time for them to come to terms with the astronomical nature of their new preoccupations.[4] Indeed, the term 'radio astronomy' was only adopted in 1948 after being introduced by Joe Pawsey.

The RP headquarters were located in the grounds of the University of Sydney, but much of the research took place at field stations scattered around Sydney, and in the case of the afore-mentioned Dapto, near the southern city of Wollongong. By February 1953 (when Govind arrived in Sydney) there were five functioning field stations, and their locations are shown in Figure 9, and the main research programs and their team leaders are listed in Table 1. While Dover Heights (number 3 in Figure 9) was a former WWII radar station, all the other field stations were purpose-built for radio astronomy at suitable radio-quiet locations (for a summary of each field see Orchiston and Slee, 2017; Robertson, 1992).

Each field station was home to one or occasionally more small close-knit research teams —generally of 2–4 individuals—who planned, built and maintained their own radio telescopes that were designed to address specific research problems. The field stations brought back fond memories for those who were lucky enough to experience them. Thus, the first author of this paper used to work at Fleurs field station in the early 1960s, before it was handed over to the University of Sydney, and he reminisces:

> … those of us lucky enough to have lived through this era remember the field stations with genuine affection. There was a freedom not experienced by those back at the 'Lab' (as the Radiophysics Laboratory was known): the pervading sunshine, the clean fresh air, those incident-packed return trips from home to field station by Commonwealth car, and the sense that we were somehow making history. There were also snakes to contend with, wet days when antennas still had to be aligned and observations made, floods that had to be negotiated, and those times—fortunately they were few and far between—when vehicles became bogged and had to be rescued by a co-operative local farmer …

> Slide rules were the norm and computers but a future dream. Signal generators, not sources, provided calibrations, and results were displayed in real time on Esterline Angus and other all-too-familiar chart recorders. These were pioneering days. (Orchiston and Slee, 2017: 498–499).

This was the scientific and cultural milieu within which Govind would be immersed for the next two years.

From the start, Pawsey decided that Govind

> … would work for three months each in the groups led by W.N. Christiansen, J.P. Wild, B.Y. Mills and J.G. Bolton … [who] had made important discoveries, and … 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… Then, after the first year, Parthasarathy and I would select a joint project. (Swarup, 2006: 23).

All of these RP radio astronomers are included in Figure 10, which was taken during the 1952 URSI meeting

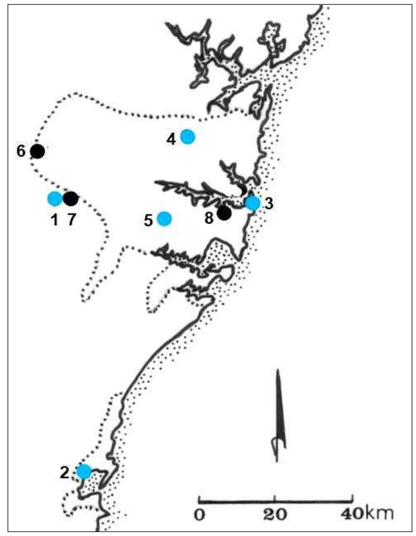

Figure 9: The location of the Radiophysics Laboratory (8) and the RP field stations that existed in 1953 (shown in blue), with the approximate boundaries of present-day greater Sydney and greater Wollongong shown by the dotted lines. Key: 1 = Badgerys Creek, 2 = Dapto, 3 = Dover Heights, 4 = Hornsby Valley, 5 = Potts Hill. An earlier field station, Penrith (6), and a later field station, Fleurs (7), are also mentioned in the text and therefore are included here (map: Wayne Orchiston).

Table 1: RP field stations, research programs and team leaders in February 1953.

Field Station	Founding Year	Research Program	Team Leader	Reference(s)
Badgerys Creek	1949	Discrete sources	Mills	Frater et al. (2013; 2017); Orchiston and Slee (2017)
Dapto	1952	Solar	Wild	Stewart (2011a)
Dover Heights	1945	Discrete sources	Bolton	Orchiston and Robertson (2017); Orchiston and Slee (2002; 2017); Robertson (2017)
Hornsby Valley	1947	Discrete sources	Shain	Orchiston et al. (2015)
Potts Hill	1948	Discrete sources	Piddington	Frater et al. (2013; 2017); Orchiston and Wendt (2017); Wendt (2011b)
		Hydrogen line	Kerr	
		Solar	Christiansen	
		Prototype Mills Cross	Mills	

Figure 10: Some of the radio astronomers who attended the 1952 URSI Congress. 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. The only person absent is Joe Pawsey (RAIA 2842-43).

Meanwhile, Govind's reference to Steve Smerd being 'a tough task master' is interesting because one of the authors of this paper (WO) worked closely with him during the 1960s and never encountered this. But perhaps Steve had mellowed by this time! Stefan Friedrich Smerd (1916–1978; Figure 11), or simply Steve Smerd to all who worked with him, was born in Vienna, but when the political situation in Austria worsened in 1939 he moved to England. There he obtained BSc and DSc degrees from the University of Liverpool. For part of WWII he worked on radar at the Admiralty Signals Establishment and in 1946 he accepted a post at RP and emigrated to Australia. Working closely with Pawsey, Steve Smerd soon became the Solar Group's resident theoretician. Later Smerd would lead RP's Solar Group, before dying prematurely in 1978 during a heart operation. He was only 62 years of age (Orchiston, 2014b; Wild, 1980).

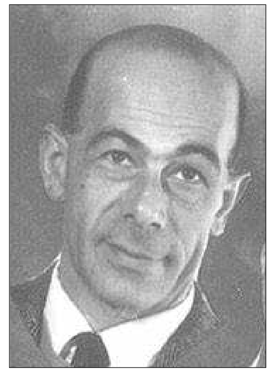

Figure 11: Steve Smerd in 1968 (adapted from an RAIA image).

After a crash course reading up on radio astronomy, Govind spent three month at Potts Hill field station working with Chris Christiansen and Joe Warburton. This field station was set up in 1948 beside a metropolitan water reservoir in what at that time was an outer southern suburb of Sydney (see Figure 12) and it quickly evolved into one of RP's leading field stations (see Davies, 2005; Wendt et al., 2011b). By early 1953, major radio telescopes at Potts Hill were:

Figure 12: 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 (RAIA 3475-1).

(1) An ex-WWII experimental radar antenna, used to observe discrete sources and galactic hydrogen line emission (see Orchiston and Wendt 2017).
(2) A 10-ft diameter ex-US WWII AN/TPS-3 parabolic antenna used to observe discrete sources (see Wendt and Orchiston, 2018).
(3) An E-W solar grating array that was completed in 1951 (Christiansen; 1953; Wendt et al., 2008b).
(4) A N-S solar grating array then under construction, which was completed during 1953 (ibid.).
(5) An 11-m parabolic transit dish, then under construction, which was completed in 1953 and dedicated to hydrogen line studies (ibid.).
(6) The prototype Mills Cross, completed in 1952 and used to test Mills' innovative concept of the cross-type radio telescope (see Mills and Little, 1953).

Govind was involved with the two solar grating arrays, which were the brain-child of Chris Christiansen. Wilber N. (Chris) Christiansen (Figure 13) was born in Melbourne in 1913 and was

Figure 13: W.N. (Chris) Christiansen (adapted from RAIA B2842-66).

awarded BSc, MSc and DSc degrees by the University of Melbourne. He joined RP during WWII and was involved in radar research. After the War, Christiansen played a key role in the multi-site observations of partial solar eclipses in 1948 and 1949 to pinpoint the locations of the radio-emitting regions (see Orchiston et al., 2006; Wendt et al., 2008a). He then continued with this solar focus through the construction of the E-W grating array, but these activities were interrupted when he was diverted to design and construct a hydrogen line receiver, and then use this and the ex-WWII experimental radar antenna to confirm the existence of the line (see Orchiston and Wendt, 2017). Christiansen then returned to solar work and the construction of the second (N-S) grating array at Potts Hill. Later he combined the concepts of the grating array and the Mills Cross to erect the 'Chris Cross' (Orchiston and Mathewson, 2009) at the Fleurs field station that was set up near Sydney in 1954. Christiansen was one of several leading radio astronomers who left RP in the late 1950s and early 1960s following the decision to focus all research on the Parkes Radio Telescope and Culgoora Radioheliograph and close down the field stations. This was the start of 'Big Science' at RP (see Sullivan, 2017 for details). After RP abandoned Fleurs, Chris inherited his 'Chris Cross' and converted this into the Fleurs Synthesis Telescope, which was used mainly to research discrete sources (Frater et al., 2017). Chris had an international perspective and passion and assisted many nations with their radio astronomical programs (e.g. see Wang, 2017). His book *Radio Telescopes* (Christiansen and Hogbom, 1969) followed the book by Pawsey and Bracewell, and also became a standard reference work throughout the world. Chris was Vice-President of the International Astronomical Union (1964–1970) and President of URSI (1978–1981). He was one of Australia's most famous radio astronomers, and died in 2007. For further biographical details see Frater and Goss (2011), Frater et al. (2017), Swarup (2008) and Wendt et al. (2011a).

Following RP's ambitious 1948 and 1949 solar eclipse programs, Christiansen (1984) wanted to pinpoint the location of radio-active regions in the corona without having to rely on eclipses, and in 1950 he came up with the idea of the solar grating array. The following year saw the construction of the world's first solar grating array along the southern margin of the reservoir at Potts Hill (Davies 2009; Wendt et al. 2008b):

> Designed to track the Sun at 1420 MHz, this novel radio telescope comprised 32 solid metal parabolic dishes each 1.83 m (72 in.) in diameter and spaced at 7 m intervals … (Orchiston and Slee, 2017: 523–524).

This array (see Christiansen and Warburton, 1953a) is shown in Figures 14 and 15, and it

> … provided a series of 3′ fan beams each separated by 1.7°, which meant that the Sun could only be in one beam at any one time. The array was operational from February 1952, and was used daily for ~2 h, centred on midday, to produce E-W scans of the Sun. These showed up the positions of localized active regions situated low in the solar corona and the motion of these as the Sun rotated … (Orchiston and Slee, 2017: 524–525).

For example, Figure 16 shows strip scans obtained between 26 and 30 June 1952, where one major radio plage is visible. Then, by deducting all radio plages and superimposing a succession of strip scans, Christiansen and Warburton (1953b) could determine the level of 'quiet Sun' emission at 1420 MHz (see Figure 17).

When Govind first visited Potts Hill field sta-

Figure 14: View looking west along the E-W grating array soon after it was completed (courtesy: Rod Davies).

Figure 15: Close-up, looking east, showing the E-W grating array and Chris Christiansen (RAIA B2976-1).

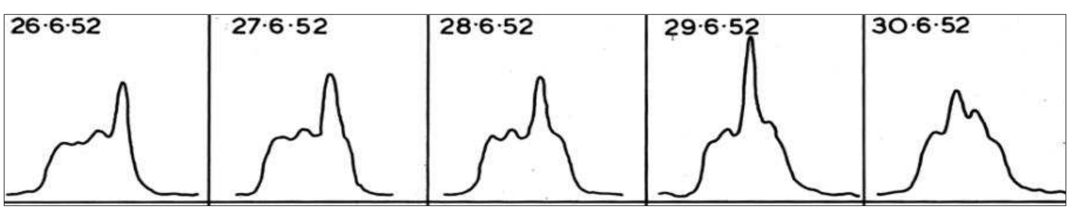

Figure 16: A series of 1420 MHz strip scans of the Sun over a 5-day period in June 1952, showing the existence and motion of a prominent radio plage (adapted from RAIA B2849-1).

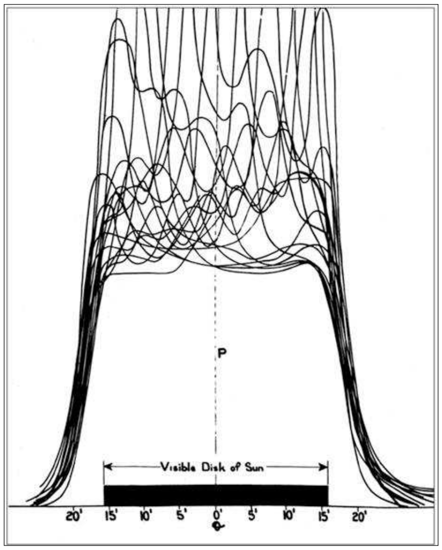

Figure 17: Twenty individual daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the black bar on the x-axis (after Christiansen and Warburton,1953a: 200).

tion a second solar grating array was under construction along the eastern margin of the reservoir. This also operated at 1420 MHz, but instead of 32 solid metal dishes there were 16 equatorially mounted 3.4-m (11-ft.) diameter mesh dishes (see Figure 18). This new array was used to obtain N-S scans of the Sun.

Govind's task at Potts Hill was to help Christiansen and Warburton

> … make a two dimensional map of the quiet Sun at a wavelength of 21cm, using strip scans obtained with the east-west and north-south grating interferometers … (Swarup, 2006: 23).

To do this,

> 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! (Swarup, 2008: 195).

As Figure 19 illustrates, the 1420 MHz quiet Sun was non-circular, with conspicuous limb-brightening in the near-equatorial regions (Christiansen and Warburton, 1955b), as had been predicted earlier by Steve Smerd (1950), "… who assumed a higher electron density in the solar corona near the equatorial regions". (Swarup, 2008: 195). Christiansen (1976) later told Woody Sullivan that he regard this project as particularly

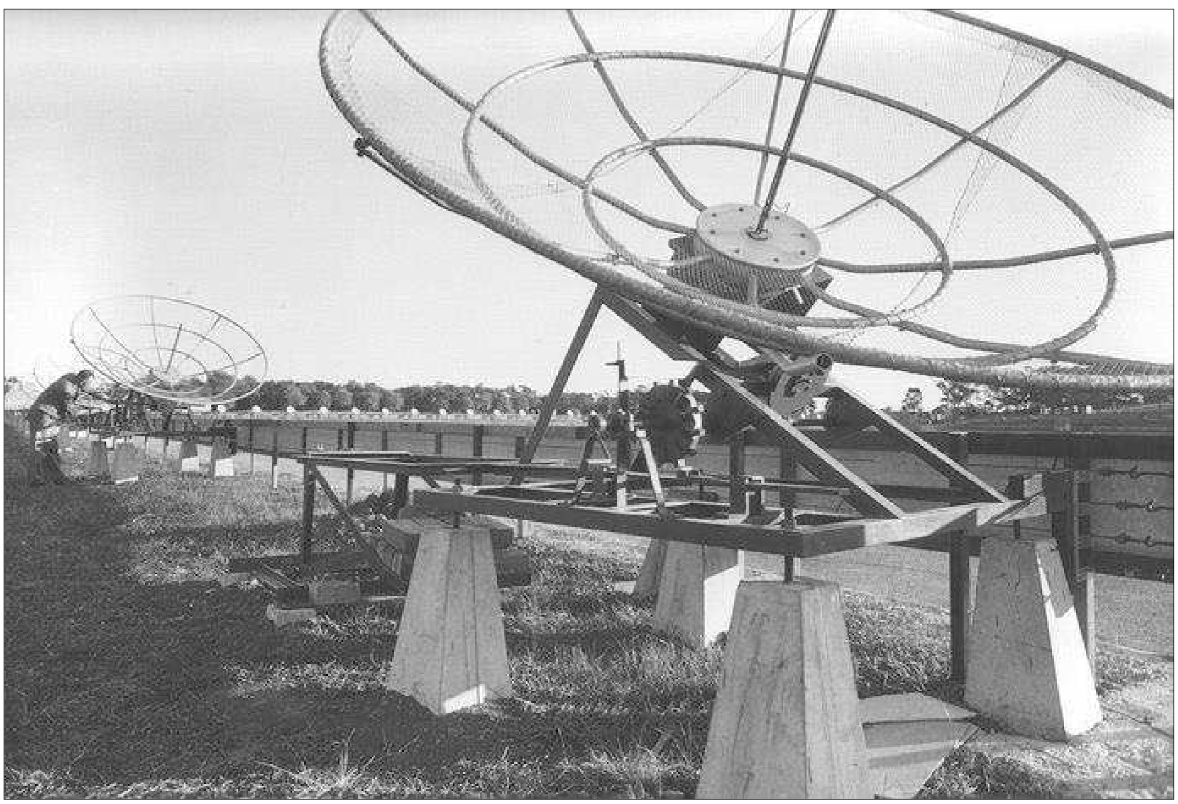

Figure 18: The second 1420 MHz solar grating array, looking south; the antennas of the first solar array are only just visible in the background as a series of small white 'dots' (RAIA 3116-1).

important, since it was the first time that the concept of Earth-rotational synthesis had been used in radio astronomy.

There is an extensive RP historic photographic archive (see Orchiston, 2001; Orchiston et al., 2004), but unfortunately this does not include any images of Govind at Potts Hill. But instead we can enjoy Figure 20, which was published in an Indian newspaper and shows Govind and Parthasarathy posing beside the ex-WWII experimental radar antenna at Potts Hill.

Govind's next 3-monthly assignment was with RP's other leading international solar authority, Paul Wild. British-born John Paul Wild (1923–2008; Figure 21) completed an abridged BA at Cambridge before joining the Royal Navy as a radar officer during WWII. This piqued an interest in radio astronomy, and in 1947 he applied successfully for a position at RP. Soon he

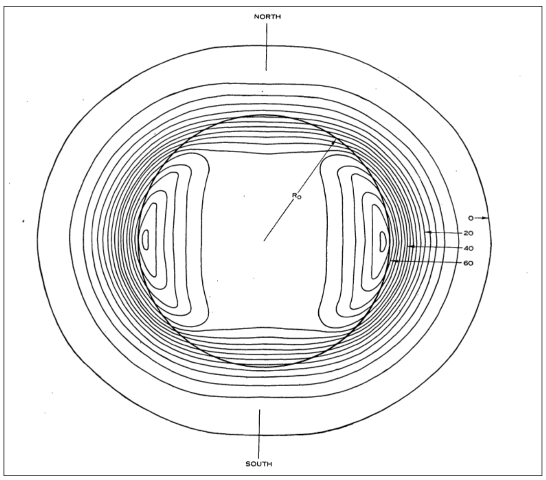

Figure 19: The two-dimensional distribution of radio brightness across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K (after Christiansen and Warburton, 1955a: 482).

was involved in Pawsey's solar program, and went on to head the Solar Group and built this into the finest team of solar radio astronomers in the world. He developed radio spectrographs at RP's Penrith and Dapto field stations, and a unique instrument, the Culgoora Radioheliograph, which gave real-time images of the movement of solar emission in the corona (McLean and Labrum, 1985). In 1971 Wild took over as Chief of the Division. Then for a time he was Chairman of the CSIRO in the nation's capital, Canberra, before dying in 2008. Back in 2011 Stewart, Orchiston and Slee—who all knew and worked with Paul Wild at RP—wrote:

> His legacy includes amongst other things a list of impressive publications and inventions which established Australia at the forefront of solar radio astronomy from 1949 to 1984, a period that spanned four cycles of solar activity …

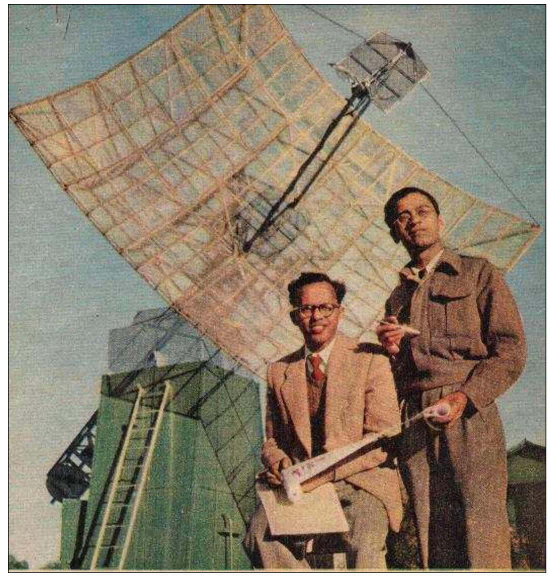

Figure 20: Govind Swarup (left) and R. Parthasarathy (right) at Potts Hill field station in 1954. At the time, this 16 × 18 ft ex-radar antenna was being used to map the distribution of neutral hydrogen in our Galaxy (after *Illustrated Weekly Times of India*, 1954).

> We will always remember how he could light up a room with his wit, intelligence and charm. He loved a party and a few beers, and would amuse the audience with his impressions of Churchill and Hitler at parties … (Stewart et al., 2011b: 539).

For further details of Wild's career and research see Frater and Ekers (2012), Frater et al. (2017); and Stewart et al. (2011a; 2011b).

When Paul Wild joined RP, the analysis of solar bursts was constrained by single-frequency observations. What Wild and his RP colleague Lindsay McCready (1910–1976) did was build the world's first dynamic spectrograph that recorded solar emission over the frequency range of 70–130 MHz, and in 1949 install this at a new PR field station at Penrith, 50 km west of Sydney (see Figure 22). The results were stunning: after just five months observing they were able to identify three very different types of solar bursts. Wild and McCready (1950) named these Types

Figure 21: Paul Wild in 1952 (adapted from a RAIS image).

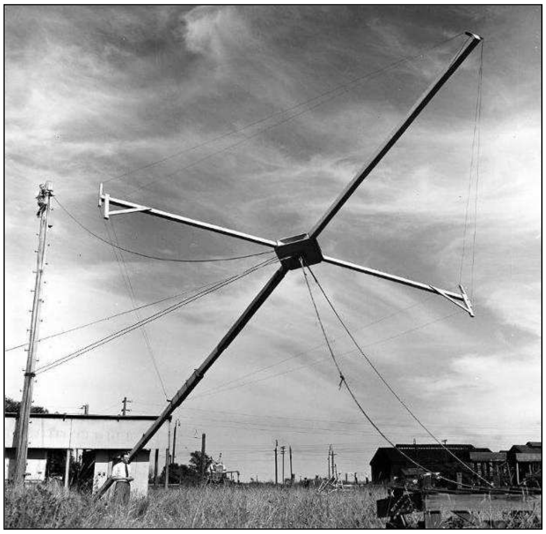

Figure 22: The rhombic aerial of the world's first radio spectrograph, at RP's Penrith field station (RAIA).

I, II and III, and this simple nomenclature was quickly adopted world-wide (Stewart et al., 2010) and became the foundation that then led to the discovery of other types of solar bursts (as Govind knows only too well—but more of this anon).

The challenge then for Wild and his group was to find a new larger radio-quiet site where they could set up further radio spectrographs (and eventually a swept-frequency polarimeter and a swept-frequency position interferometer). After an intensive search they located a suitable site down near Wollongong, to the south of Sydney (see Figure 5), and by the time Govind joined RP three radio spectrographs had been installed. These covered the frequency ranges 40–75, 75–140 and 140–240 MHz, and used crossed rhombic antennas (Figure 23) so that the polarisation of the bursts could be investigated (Stewart et al., 2011a).

But apart from solar bursts, Wild (1953) also was interested in scintillations, and he explains why:

> Although the main long-term programme of work at Dapto is concerned with the sun, it has seemed desirable to find a supplementary line of research to enable the equipment to be put to maximum use during the sunspot minimum. With this in view, exploratory observations of the spectrum of Cygnus fluctuations in the frequency range 40–70 Mc/s have been carried out since September 1952.

The fact that the Cygnus A discrete source showed conspicuous intensity fluctuations that were caused by ionospheric or interplanetary scintillations was well known (e.g. see Stanley and Slee, 1950). At Dapto, three spaced aerials were used to investigate these, and Govind's Dapto project was to work with J.A. (Jim) Roberts (b. 1929) and develop a 45 MHz receiver once it was established that this would be preferable to observing over the full 40–70 MHz fre-

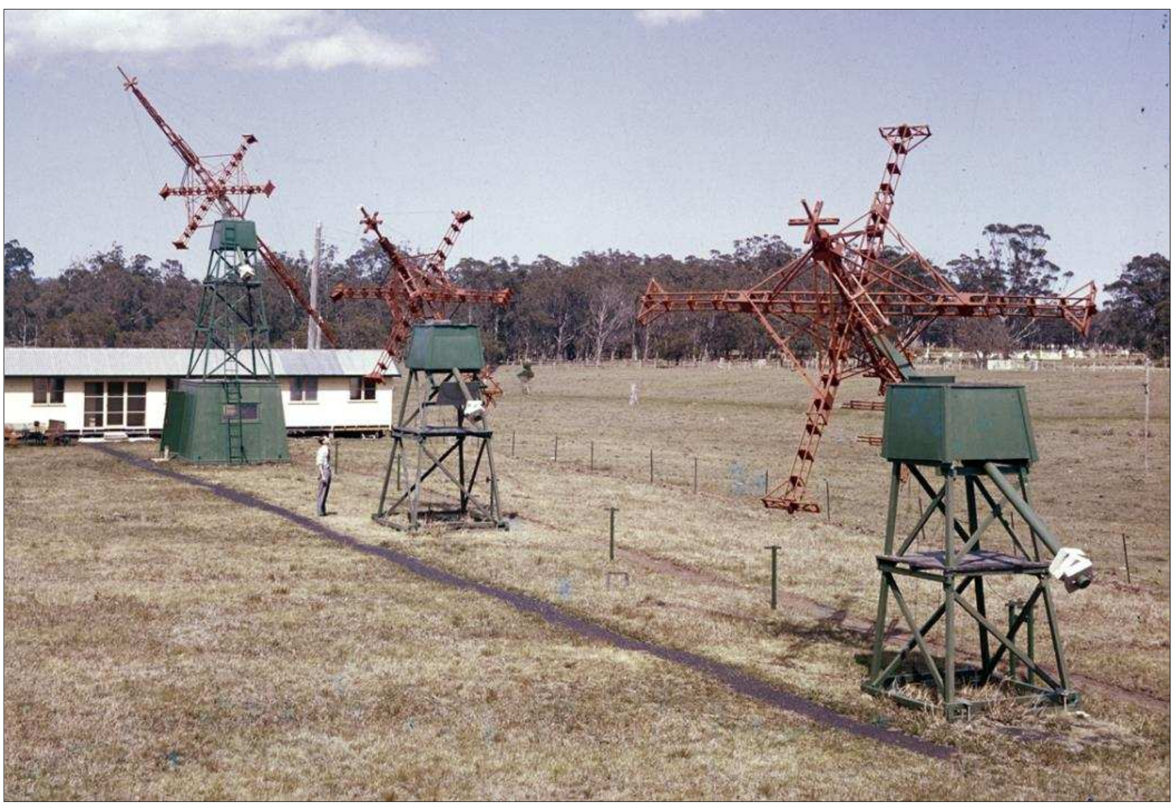

Figure 23: The Dapto field station, showing the three crossed-rhombic antennas and associated buildings (RAIA 12429-1).

quency range (Stewart et al., 2011a). Subsequently, Wild and Roberts (1956a; 1956b) published two papers based on observations made with the 45 MHz receiver.

So Govind's second RP project was about ionospheric research and had nothing to do with solar bursts, but it did give him experience that would prove useful later: designing and constructing a receiver.

After this, Govind returned to the all-too-familiar Potts Hill field station and spent three months working with Bernie Mills and Alec Little who were busy constructing a new radio telescope of novel design.

Bernard Yarnton (Bernie) Mills (Figure 24) is another great Australian name in international radio astronomy (Frater et al., 2013; 2017). Born in Sydney in 1920 and dux of Kings School, he completed a Bachelor of Engineering degree in December 1942 and began working at RP on radar. After the war he was involved in RP's new digital computer before joining Pawsey's radio astronomy group in 1948. His first project was to participate in the 1 November 1948 solar eclipse program, resulting in his first radio astronomy publication, but "… it also was to be his sole foray into solar radio astronomy." (Orchiston, 2014a: 1482). Mills' greatest achievement was to provide one solution to the resolution problem

Figure 24: Bernard Yarnton (Bernie) Mills (adapted from an RAIA image).

plaguing early radio astronomy by inventing the cross type radio telescope (see Mills, 1963), an

> … antenna in the form of a symmetrical cross, where the outputs from the two orthogonal arms were combined electrically so that only the signal received in the overlapping region of the two fan beams was recorded. (Orchiston, 2014a: 1483).

This novel design provided the same resolution as an equivalent circular parabola with a diameter equal to the length of the arms of the cross. To test out the concept Mills and Little constructed a prototype at Potts Hill (see Figure 25) consisting of

Figure 25: In the foreground is part of the prototype Mills Cross, and in the background are the ex-Georges Heights radar antenna, the 11-m hydrogen-line dish and various instrument huts (RAIA 3171-4).

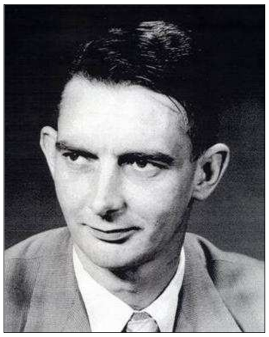

Figure 26: John Bolton at Caltech (courtesy: Edward Waluska).

> … N-S and E-W arms, each 36.6 m (120 ft) in length and containing 24 half-wavelength E-W aligned dipoles backed by a wire mesh reflecting screen (Mills and Little 1953). This novel instrument operated at 97 MHz, and had an 8° pencil beam which could be swung in declination by changing the phases of the dipoles in the N-S arm. (Orchiston and Slee, 2017: 534).

The success of the 'Potts Hill mini-cross' led to construction of a full-scale Mills Cross at RP's new Fleurs field station in 1954 (Mills et al., 1958) and later the Molonglo Cross near Canberra—after Mills joined the exodus from RP following the decision to close down the field stations and he moved to a Readership at the University of Sydney. Over the years Mills received many honours, including a DSc and election as a FRS. He died in 2011, and for further details of his remarkable career see his autobiography (Mills, 2006) and Frater and Goss (2011); and Frater et al. (2017).

Govind's task on this occasion was to help Mills and Little develop a phase shifter for the prototype Mills Cross (Swarup, 2006), experience that would prove to be extremely useful later back in India.

The final project Govind faced during his first year at RP was to work with John Bolton's group at Dover Heights field station and made a highly stable D.C. power supply. John Gatenby Bolton (Figure 26) was born in England in 1922 and by a strange coincidence his early life mirrored closely that of fellow-Briton, Paul Wild: a Cambridge degree, service as a radar officer on a Royal Navy vessel, joining RP following WWII, and marriage to an Australian girl whom he met in Sydney during the war. In 1946 Bolton began working at Dover Heights field station located on the coast just south of the entrance to Sydney Harbour and atop 79-m high cliffs (see Figure 27). In 1953, not long after Govind's arrival, Bolton abandoned radio astronomy and worked on rain-making—RP's other major research field—until 1955 when he moved to Caltech in the USA, set up radio astronomy, and founded the Owens Valley Radio Observatory. In 1961 he returned to Australia as inaugural Director of the Parkes

Figure 27: An aerial view of Dover Heights at the end of WWII, showing the 200 MHz radar antenna (right) used for the earliest radio astronomy observations, with the entrance of Sydney Harbour in the background (RAIA B81-1).

Radio Telescope. After retiring, Bolton and his wife moved north to coastal Buderim in warm sunny Queensland, where he died in 1993. For a summary of Bolton's career see Orchiston and Kellerrnann (2008) and for details of his important contributions to international radio astronomy see Robertson (2017).

So during his first year at RP Govind became familiar with international radio astronomy by reading widely; he gained experience in reducing observations; and he constructed equipment that was used for making observations. All this would prove handy in the second year of his 'apprenticeship' when he and Parthasarathy would carry out a major collaborative project.

As it happened, settling on such a project was not difficult. Christiansen and Warburton had finished their initial research with the two Potts Hill grating arrays and had already published, or were in the process of publishing, their initial results (see Christiansen and Warburton, 1953a; 1953b; 1955a; 1955b). Christiansen was now off to Europe to spend a year working with the French radio astronomers at Paris Observatory, so after discussions with Pawsey

> … Parthasarathy and I decided to convert the Potts Hill EW grating array … 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). (Swarup, 2006: 25).

Figure 28 shows Smerd's (1950) predicted radial brightness distributions at different frequencies.

Converting the E-W array was an interesting exercise:

> 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. (Swarup, 2008: 197).

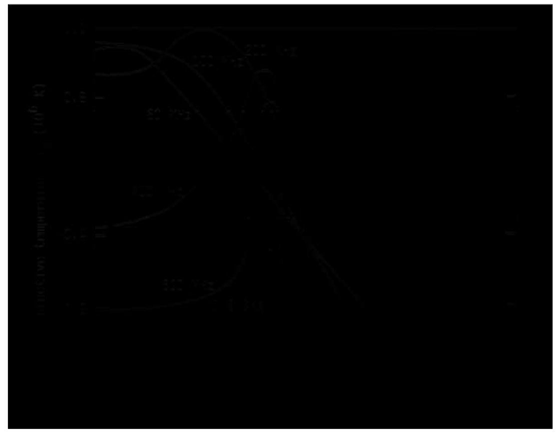

Figure 28: The theoretical distribution of temperature as a function of distance from the centre of the solar disk. Temperatures of 3×10^4 K and 10^6 K are assumed for the chromosphere and corona respectively (after Smerd, 1950: 46).

After modifying the E-W array, Swarup and Parthasarathy carried out solar observations from July 1954 to March 1955, and found strong evidence of limb-brightening (Swarup and Parthasarathy, 1955a; 1955b; 1958). Their results agreed with Smerd's prediction and mimicked the earlier finding by Christiansen and Warburton (see Figure 29). Swarup and Parthasarathy, (1955a: 9) noted that

> Stanier's observations were made near the maximum phase of the solar cycle, while the present observations have been made during the current minimum phase. The dis-

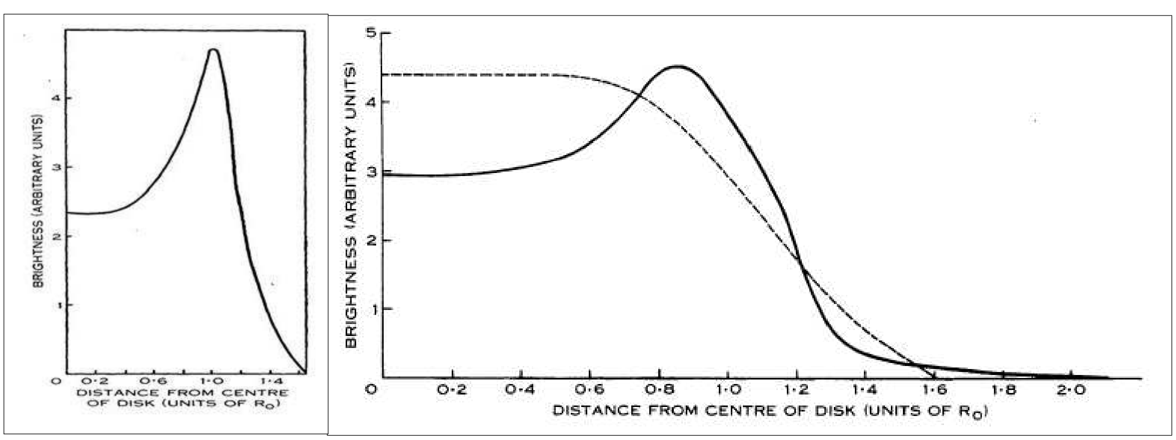

Figure 29: On the left is the radial brightness distribution across the solar disk based on one-dimensional scan observations at 1400 MHz (after Christiansen and Warburton, 1953b: 268). The plot on the right shows the radial brightness distributions at 500 MHz comparing Stanier's result (dashed) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy, 1955b: 493).

crepancy between the two results could be due either to an actual change in the "quiet" Sun or to errors in Stanier's result, caused by the presence of unrecognized bright areas. Stanier has not given details of the method he used to allow for such bright areas, and without further information it is not possible to decide which alternative is the more likely.

In addition, Govind and Parthasarathy

… 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).

Govind obviously thoroughly enjoyed this ambitious practical project, for he would later reflect:

… 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

Figure 30: Dr K.S. Krishnan, Director of the National Physical Laboratory, who began assembling a fledgling radio astronomy group in 1956 (courtesy: NPL).

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. (Swarup, 2006: 25).

When he return from France in early 1955, Christiansen decided to build a new radio telescope combining the concepts of his Potts Hill grating arrays and Mills' cross-type antenna. This would be installed at Fleurs field station, and known as the Chris Cross (Christiansen et al., 1961). Consequently, the two Potts Hill grating arrays became 'surplus to requirements' and were to be scrapped. Govind describes what happened next. During one of Pawsey's visits to Potts Hill

… I asked whether these dishes [from the E-W array] could be gifted to India. He 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 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." (Swarup, 2006: 25).

CSIRO authorities in Canberra agreed to donate the dishes to India through the Colombo Plan scheme, but they insisted that India must pay for their transportation.

4 RETURN TO THE NATIONAL PHYSICAL LABORATORY IN INDIA:

In July 1955 Govind returned to the National Physical Laboratory (NPL) in New Delhi and began building a 500 MHz receiver for the ex-Potts Hill array, as Dr K.S. Krishnan, Director of the NPL (Figure 30) was keen to start a radio astronomy program. This soon attracted others. In 1956 his namesake T. Krishnan (but no relation) joined the NPL after studying physics at Cambridge University and working with Martin Ryle for a year. Parthasarathy also left Kodaikanal Observatory in 1956 and came to the NPL. M.N. Joshi and N.V.G. Sarma also joined the NPL in 1956, soon after completing their MSc degrees in India, and in 1958 they were joined by Mukul Kundu, who had just completed a solar radio astronomy DSc in France.

However, all was not well. Notwithstanding his enthusiasm, commitment and political acumen, Krishnan could not get the CSIR authorities in New Delhi to agree to fund the transportation of the Potts Hill dishes to India. Instead, they "… suggested that the Australian authorities should bear the cost of transportation, considering the shortage of foreign exchange in India at the time." (Swarup, 2006: 25). The Australians refused, and over the next few years this led to a mass exodus of NPL radio astronomers: Parthasarthy went to Alaska; T. Krishnan to RP in Sydney; Joshi to France (for a PhD); Sarma to Leiden Observatory (to build receivers); Kundu to the USA, not long after joining the NPL; and in August 1956 Govind also decided to go to the USA. In just two short years Krishnan's promising young radio astronomy group had all but disappeared, just as quickly as it had emerged!

Finally, the Australians agreed to pay for the transfer of the 32 dishes to New Delhi, but by then it was too little too late. The Indians may have won the diplomatic battle, but in the interim they lost their fledgling radio astronomy group!

Govind (2006: 25) is somewhat more charitable (and diplomatic): "Thus, it may be said that the NPL acted as a foster mother for the subsequent development of radio astronomy in India …"

5 FORT DAVIS, THEN STANFORD UNIVERSITY AND DOCTORAL RESEARCH

When Govind decided to leave the NPL in late 1956 and travel overseas with his new wife, Bina, he had a challenging decision to make. Where should he go for the next couple of years that would be in the best interest of his future career in radio astronomy and provide a suitable family environment?

All his experience had been in solar radio astronomy, and this is what India would offer when it eventually received the Potts hill dishes and mounted them, but there were various options, since

> The success of the Division of Radiophysics' solar research program in the late 1940s and throughout the 1950s inspired other groups in America, Japan, France, Holland and elsewhere to build similar instruments for solar radio-frequency investigations. (Stewart et al., 2011c: 623).

Some of these facilities are summarized earlier in the afore-mentioned Stewart et al. paper and in Ishiguro et al. (2012), and (apart from RP's Solar Group in Australia) the French and the Japanese were particular active in developing instrumentation and carrying out inspiring research (see ibid.; Orchiston and Ishiguro, 2017; Orchiston et al., 2009; Pick et al., 2011).

When it came to the USA there really was no choice because the Ft Davis field station of Harvard College Observatory was the only major solar radio astronomy facility that was operational at that time (although several other groups would very soon 'join the club'). Consequently, Govind

> … 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 … (Swarup, 2008: 197).

He would spend just one year there.

Leading this small team was the New Zealander Alan Maxwell (b. 1926), who completed an MSc at Auckland University College (as it then was) back in 1948 (see Orchiston, 2016: 645–646). His thesis was titled "Enhanced Solar Radiation at 3 Metre Wavelengths", but

> Despite this being one of the first postgraduate theses on solar radio astronomy ever written anywhere in the world, Maxwell failed to publish his work—it simply was not the custom at this time—and soon after completing his Auckland studies he moved to the dynamic astronomical environment of Jodrell Bank (at the University of Manchester) where he was quickly immersed in new research for a Ph.D. (Orchiston, 2017b: 683).

Figure 31 shows Maxwell adjusting his 100 MHz twin Yagi antennas mounted on the roof of one of the Auckland University College buildings.

Maxwell carried out further solar work for his Manchester doctorate and in 1955 was appointed to lead Harvard College Observatory's new solar radio astronomy program, inspired in part of the International Geophysical Year (1957–1958) and funded (initially, at least) by the U.S. Air Force.

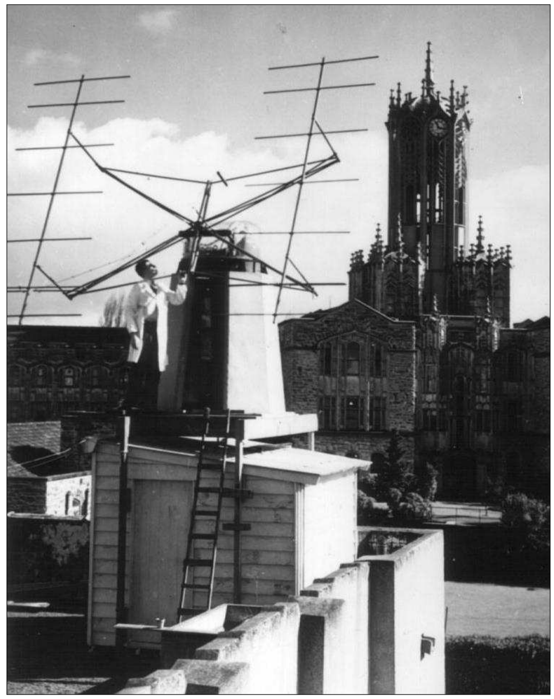

Figure 31: Alan Maxwell and his 100 MHz twin Yagi antenna used for his Auckland University College MSc project (courtesy: Alan Maxwell).

Harvard Professor and respected (optical) solar astronomer Donald H. Menzel (1901–1976) was instrumental in establishing the Harvard solar radio astronomy program, and

> When Maxwell took up his position … orders had already been placed for a 28-ft. diameter equatorially-mounted antenna from D.S. Kennedy Co. of Cohasset, MA, a feed system covering 100–600 MHz from Jasik Labs. of Westbury, NY, and receivers from Airborne Instruments Laboratory Inc. (A.I.L.) of Mineola, NY. (Thompson, 2010: 18)

All that was missing was a site for this equipment and with help from Sacramento Peak and McDonald Observatory colleagues Maxwell found Cook Flat, a small radio-quiet valley near Ft Davis in west Texas, and at the foot of Mt

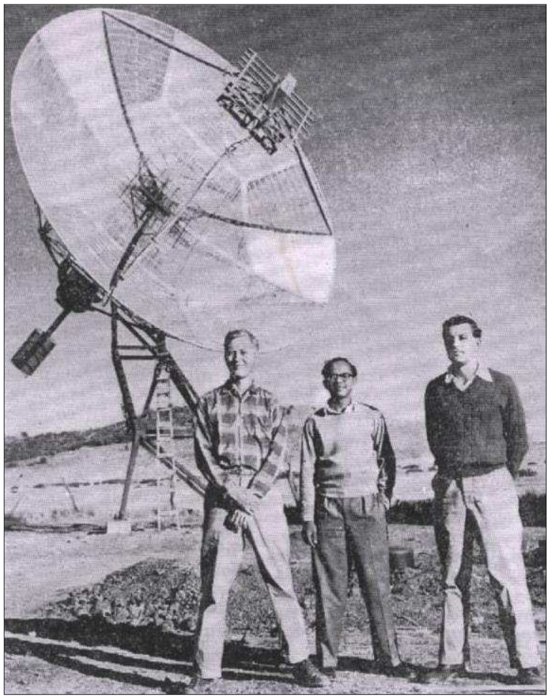

Figure 32: Alan Maxwell, Govind Swarup and Sam Goldstein (left to right) posing in front of the 28-ft dish at Harvard Observatory's Fort Davis field station in Texas (courtesy: Govind Swarup).

Locke (where McDonald Observatory was located).

Given Maxwell's New Zealand pedigree and the considerable local fame of the British explorer Captain James Cook (1728–1779) in New Zealand, not to mention Cook's preoccupation with Queen Charlotte Sound on all three voyages to the Pacific (see Orchiston, 2016: 107–226), his observations of the 1769 transit of Venus (Orchiston, 2017a) and his role as expedition commander *and* astronomer on the First and Third Voyages (Orchiston, 2016: op. cit.), we are bound to wonder if the name 'Cook Flat' resonated in any way with Alan Maxwell and played a part in his decision to site his field station there! Or was this just a happy coincidence?

Be that as it may, when Govind first visited the Ft Davis field station (alias Cook Flat) in August 1956 he found the radiospectrograph already attached to the 28-ft Kennedy Dish and functioning (Thompson, 1961). Figure 32 shows Alan Maxwell, Govind and Sam Goldstein posing in front of the dish.

By mid-1956 Wild's nomenclature of three basic spectral types of bursts (Types I, II and III) was well-known internationally, and the fact that Type II bursts sometimes exhibited harmonic structure, so the quest at Ft Davis (and elsewhere) was to categorize all newly-arriving bursts, identify any new types of bursts, and investigate if radio bursts were associated with flares, prominences and other optical activity (Maxwell, 1957; 1958). While Govind was at Ft Davis, André Boischot (1957) discovered a new variety of burst, the Type IV, and then Wild et al. (1959) added the Type V burst to the list. Typical examples of all of these are shown in Figure 33.

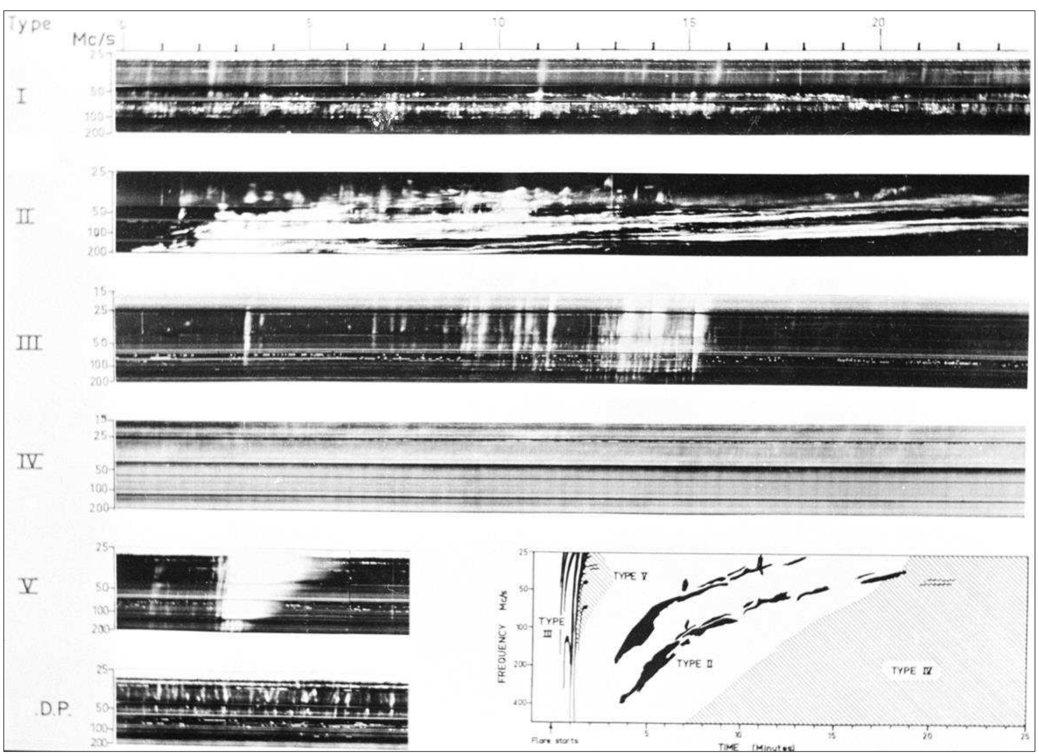

Figure 33: Typical examples of the six different spectral types of solar bursts recorded at Dapto (Types I-V and Drifting Pairs – DPs), with a schematic (bottom right) that summarizes their relative features (RAIA 6317).

For his part, Govind participated in this research at Ft Davis and published several papers (e.g. see Maxwell et al., 1958; Swarup et al., 1960), but his major success was in discovering a new type of solar burst, the U-burst: "In December 1956 I discovered the Type U burst while Maxwell was on a holiday in New Zealand …" This was subsequently reported in *Nature* (Maxwell and Swarup, 1958), and is described by Thompson (2010: 20):

> A type of fast-drift burst, in which the spectrum initially drifts downward in frequency and then turns upward again, was discovered at Fort Davis by Swarup. These appear on the Fort Davis records as an inverted letter U, and are known as 'U-bursts' (Maxwell and Swarup 1958). U-bursts are believed to be generated by excitations that begin to move outward through the solar corona, but are guided by loops in the solar magnetic fields causing them to turn and move down toward the solar surface. They occur much less frequently than the usual Type III bursts.

For a slightly later more detailed account of U-bursts, assembled by two RP radio astronomers, see Labrum and Stewart (1970). For an example of a typical U-burst see Figure 34.

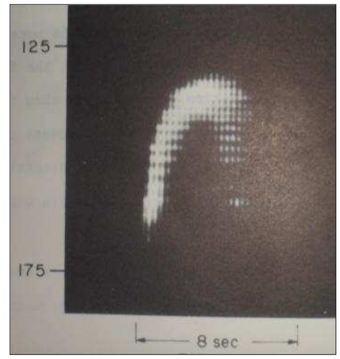

Figure 34: An example of a U-burst recorded with the University of Michigan radiospectrograph on 29 November 1956; time is shown on the x axis and frequency (in MHz) on the y axis (after Kundu, 1964: 408).

In the course of carrying out this solar research at Ft Davis, Govind and Bina also gave thought to their future, and decided it would be their long-term interests if Govind could obtain a PhD Thus

> 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 … 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." (Swarup, 2006: 25 – 26).

With this advice echoing in his mind, Govind chose Stanford, and in September 1957 he began his PhD under the watchful eye of Professor Ron Bracewell. Given his previous Sydney apprenticeship, is it any wonder that Govind chose to be guided by a former Sydney radio astronomer, one of Joe Pawsey's protégés, and a solar radio astronomer to boot! So who was Ron Bracewell?

Ronald Newbold Bracewell (Figure 35) was born in Sydney (Australia) in 1921 and received BSc, BE and ME degrees from the University of Sydney, and a PhD from the University of Cambridge (with a thesis on ionospheric research). In 1949 he joined RP and through sharing a room with Chris Christiansen and Harry Minnett was soon involved in radio astronomy, with interests in interferometry, signal processing and imaging, data analysis and the role of Fourier transforms in radio astronomy (which would later lead to a book: Bracewell, 1965). Pawsey also invited Bracewell to join him in co-authoring a text book, and in 1955 *Radio Astronomy* (by Pawsey and Bracewell) was published by Oxford's Clarendon Press. This was quickly accepted worldwide as *the* standard work on radio astronomy—and many of us find it illuminating reading today, more than half a century later! Bracewell "… later surmised that this [book] was partly a device to get him more involved in the subject." (Thompson and Frater, 2010: 172).

During the 1954 – 1955 US academic year

> Bracewell was invited by Otto Struve (1897–1963) to give a series of lectures on radio astronomy at the University of California, Berkeley. He also lectured at Stanford University, which led to his joining the Electrical Engineering Department at Stanford in December 1955. (ibid.).

Struve also asked Bracewell to suggest a new


Figure 35: A caricature of Ron Bracewell drawn by cartoonist Emile Mercier (after Bracewell, 1984: 187).

Figure 36: The completed Stanford 9.2 cm cross-antenna interferometer (courtesy: TIFR Archives).

radio telescope that Stanford could build to launch its radio astronomy research program. After due deliberation, Bracewell recommended a microwave spectroheliograph, and he notes that at the same time

> … I mailed the plan to Joseph L. Pawsey … proposing to build this radio telescope in Sydney [upon his return to Australia]. It comprised NS and EW arms in a cross configuration, each containing sixteen solid metal 10-ft parabolic 'dishes' spaced at 25-ft intervals. It was designed to operate at a wavelength of 9.2 cm, with a pencil beam of 3.1 arcminutes. (Bracewell, 2005: 75).

However, Pawsey advised that Christiansen already planned to build a similar solar grating array near Sydney. Appropriately dubbed the 'Chris Cross', this 1420 MHz radio telescope was completed in 1957 (see Christiansen and Mathewson, 1958; Christiansen et al., 1961; Orchiston, 2004), and its design and research accomplishments are summarised in Orchiston and Mathewson (2009).

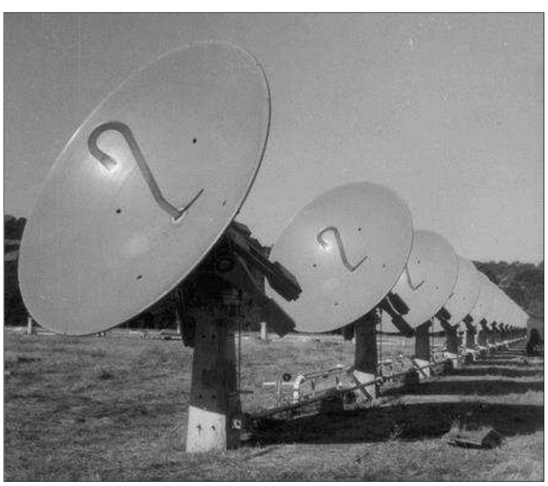

Figure 37: A close-up showing the design of the metal dishes, feeds and mountings (courtesy: TIFR Archives).

Instead, Bracewell chose to build his solar grating array in the USA, and in December 1955 he joined Stanford University's Department of Electrical Engineering. He would later become the Lewis M. Terman Professor of Electrical Engineering and one of the world's most innovative radio astronomers (see Bracewell, 2005; Frater et al., 2017; Thompson and Frater, 2010).[5]

By the time Govind Swarup moved from Fort Davis to Stanford in September 1957, Bracewell was in the process of constructing his 'Solar Radioheliograph' at the 'Heliopolis' radio astronomy precinct on the outskirts of the Stanford University campus (Figure 36), and it became operational in April 1960 (Bracewell, 2005). As indicated above, the radioheliograph comprised two orthogonal arrays, each with

> … 16 parabolic dishes 10 feet diameter, spaced at 25 feet intervals (Bracewell and Swarup, 1961). The voltage outputs of the two arrays were multiplied giving a pencil beam of 3.1 arc minutes. (Swarup, 2008; 197).

Figure 37 provides a close-up of some of the dishes. The array was designed to produce daily maps of solar radio emitting regions at 3.259 GHz (e.g. see Figure 38).

The solar array was first described in Bracewell (1957), but this was later followed by a detailed account, penned by Bracewell and Swarup (1961). Govind's co-authorship of this important paper was fully justified because of his input to the design: the waveguide path to each antenna feed horn had to be kept constant to within one millimeter, but

> … the phase length to individual antenna feeds was found to vary from month to month, largely as a result of activity of spiders and birds. To measure these shifts a novel scheme was developed that became the forerunner for adjustment of interferometer arrays elsewhere. At each feed horn a very small fluorescent tube developed by Govind Swarup was inserted across the waveguide. A signal injected into the NS waveguide terminal in the control room would undergo successive subdivisions at the seven tee junctions and radiate into space. But if one discharge tube was switched on, it caused almost total reflection from its feed horn. A slotted waveguide section between the signal generator and the transmission wave-guide terminal indicated, for each feed horn in turn, the location of a standing wave minimum and the amount of the necessary adjustment, if any. Phase compensation was carried out with calibrated half-wavelength slivers of copper inserted on the waveguide floor at a junction. (Bracewell, 2005: 77; cf. Swarup and Yang, 1961).

Govind elaborates on the background to this innovative idea:

> After more than six months of hard work we [i.e. Govind and fellow graduate student K.S. Yang] 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.! (Swarup, 2008: 197–198).

This is why Govind came up with the idea of inserting small fluorescent tubes across the waveguide and injecting a signal into the N-S waveguide terminal! Furthermore,

> 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! (Swarup, 2008: 198).

After Pawsey heard about this he wrote Govind:

> 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. (Pawsey, 1960).

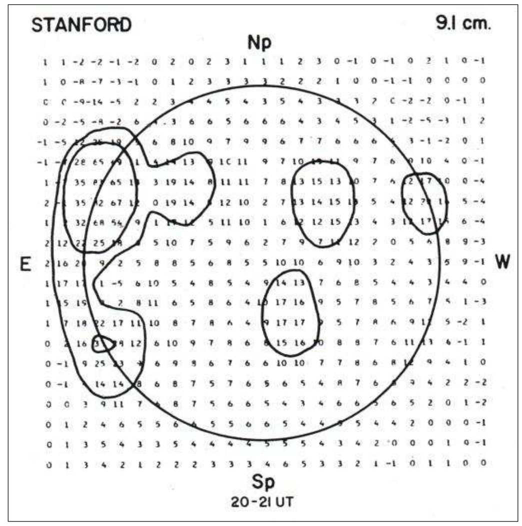

Figure 38: A map of 3.224 GHz solar radio emission on 3 January 1969 (after Bracewell, 2005: 76).

Upon looking through the list assembled by Ron Bracewell (2005: 85–86) of research publications based on observations made with the Stanford radioheliograph it is—at first sight—strange to see no papers by Govind, given that the array "… was astronomically productive in the field of solar physics." (Bracewell, 2005: 77). But we must remember that Govind was busy helping design, construct and test the array for his PhD (see Figure 39), which he completed in 1960[6] just a few months after the array became operational in April 1960.

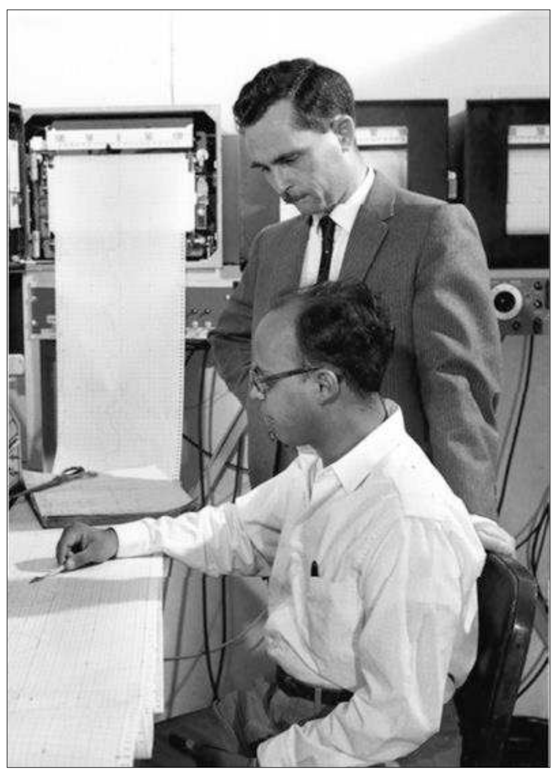

Figure 39: Ron Bracewell and Govind Swarup examining solar records (courtesy: Stanford University News Service).

We do know that Govind later suggested a new way of converting the strip scans into two-dimensional maps of quiet Sun emission. Writing about his Potts Hill days, he reveals that

> … 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. (Swarup, 2006: 23).

Govind remarks (2008) that since he was about to return to India he did not pursue the idea, but later it was developed and published by Bracewell and Riddle (1967).

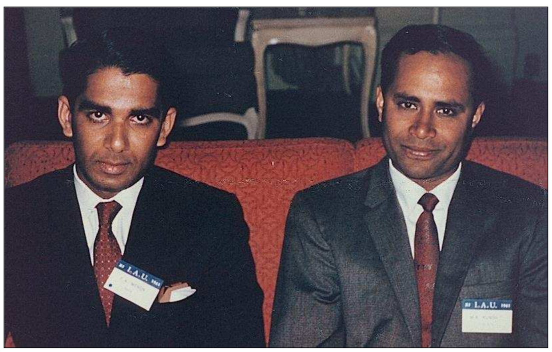

Figure 40: T.K. Menon (left) and M.R. Kundu (right) at the Berkeley IAU General Assembly in 1961 (Menon Collection).

One interesting solar radio astronomy project that Govind did initiate while at Stanford was a collaboration involving colleagues from Canada, Japan and Australia. Inspired by an earlier successful project published by Christiansen et al. (1960), Govind's study focused on the sizes, heights in the solar atmosphere, and brightness temperatures of radio plages observed at 3.2, 7.5, 9.1, 10.7 and 21 cm, and their association with photospheric features (see Swarup et al., 1963b).

Once the grating array was operational, what Ron Bracewell's team did was to look at modifying the design so that for the first time in his comparatively short astronomical career Govind could research discrete radio sources—rather than continue to focus solely on solar radio emission. This was achieved by adding two further antennas to the E-W arm of the array so that it could function as a compound interferometer.[7] This produced fan beams with widths of 52 arcsec, and east-west scans of several strong radio sources were obtained with this angular resolution (Swarup et al., 1963a; Thompson and Krishnan, 1965).

The aforementioned Swarup et al. 1963a paper was Govind's first research publication on a non-solar topic. Little could he have imagined at the time that this paper would set the pattern for much of his subsequent career, after he returned to India.

One other paper Govind would co-author while at Stanford, also would fore-shadow his later interest in designing and constructing novel radio telescopes. During the 1960s, apart from the solar array there were two equatorially-mounted 30-ft parabolic dishes at Heliopolis that were used as a two-element variable baseline interferometer, but they were only useful for observations of the strongest discrete sources. Therefore

> Bracewell considered building an instrument with a much larger collecting area, using several long cylindrical reflectors. He envisaged an instrument that would grow with time, by the addition of more elements as funding allowed (Bracewell, Swarup, and Seeger, 1962). However, funds for a large instrument proved to be unavailable, and the development of Earth-rotation synthesis by Martin Ryle (1918–1984) showed the advantage of fully steerable antennas.

Obviously Govind also was captivated by the concept of a large cylindrical antenna for this would feature prominently in his later plans—as we shall see in Sections 8 and 9, below.

6 PLANNING A POSSIBLE RETURN TO INDIA

Although Govind accepted an Assistant Professorship in Electrical Engineering at Stanford on 1 January 1961, soon after being awarded his doctorate, from time to time he had contemplated returning to India and launching a radio astronomy program there.

At several meetings of the American Astronomical Society and the American chapter of URSI Govind proceeded to discuss these ideas with M.R. Kundu and T.K. Menon, two Indian colleagues then working in the USA. Mukul Kundu (1930–2010; Figure 40) had completed a doctorate in radio astronomy in France (see Orchiston et al., 2009) before joining Fred Haddock's group at the University of Michigan in 1958, while T.K. Menon (Figure 40) completed MS and PhD degrees at Harvard University and worked in the Astronomy Department there until 1959 when he joined the (U.S.) National Radio Astronomy Observatory. Kundu was interested in solar radio emission, while Menon's field was galactic HI clouds and HII regions.

As Govind remarks (2006), in 1960 and 1961, he raised the idea of the three of them returning to India in letters he wrote to Pawsey, Christiansen and fellow-Australian Frank Kerr.

They were supportive, but suggested adding T. Krishnan (Figure 41), to the group. At that time Krishnan was at RP in Sydney, and was involved in solar work with the Chris Cross (see Orchiston and Mathewson, 2009).

Christiansen wrote Govind on 22 September 1960:

> … you two [i.e. Swarup and Krishnan] and Menon and Kundu should get together for a united attack on the monolith of Indian bureaucracy – separately I can't see you getting anywhere in radioastronomy very fast … I know you all, and feel that [the four of you] would make a very fine team.

Meanwhile, in his letter penned one month later Pawsey (1960) was equally supportive, but he also was concerned about group dynamics and the types of research the group might pursue:

> It will probably happen that different ones want different things. You must all try to sink your personal preferences in favour of the whole project and judge objectively. Remember that strength lies in unity … keep off fashionable stuff as far as possible. Be original. Try, if possible, to develop ideas which one or more of you have originated. The small groups bring in the radical new thoughts. They are not tied up with inherited large programmes. The other point for me to emphasize is the importance of good experimental technique.

In commenting on the dynamism of small groups Pawsey was clearly reflecting on the successes of those at the RP field stations in and near Sydney.

It is also clear that issues of group dynamics and leadership continued to worry Pawsey, as on 18 April 1961 he wrote:

> If the scheme comes off, you are a key person. Your practical ability and direct approach will be most important ... A real difficulty is the question of leadership of the group. It could well lead to jealousies and failure. The position is that there are several of you, each with something different to contribute, and no one alone is likely to be able to make things go by himself ... [The] problem ... can be met if the individuals of the group are each willing to subordinate their individual interests to some extent … (Pawsey, 1961a).

Pawsey returned to the leadership question in his next letter, dated 29 June 1961:

> ... you, I think stand out in practical experience and ability. Menon has the astronomical knowledge. Who then will be the leader? This is the sort of situation which can be made to work if the members have a real urge to make the project a success and are willing to subjugate their individualities to a reasonable extent. Not all men can do this and you do not want to pick up members who won't fit in. On the other hand, you must get a few key people. My own feeling is that there are only two essential key men: (1) a good practical physicist combining radio skill and common sense (you are my choice here); and (2) an organizer with drive and good external contacts (Krishnan stands out here). (Pawsey, 1961b).

Govind finally responded to Pawsey's concerns in a letter dated 25 July 1961:

> It would be desirable for me to devote all my limited energies to the construction and development of the apparatus. I personally would not care who would be the leader. But the overall scientific program should be mutually decided so as to make everybody in the group feel his importance. (Swarup, 1961).

It is not clear how widely Govind discussed the issues Pawsey raised with the other Indian radio astronomers, but in August 1961 all four of them met during the Berkeley General Assembly of the IAU. On 23 September 1961 they completed a 3.5-page proposal titled "Proposal for the Formation of a Radio Astronomy Group in India" (Krishnan et al., 1961) and they wrote about at first setting up a solar radio astronomy program using the thirty-two ex-Potts Hill dishes, and then

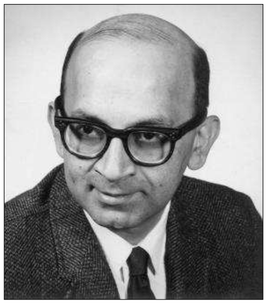

Figure 41: T Krishnan in India in 1970 (Krishnan Collection).

> … 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 ... (ibid.).

The proposal was then send 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." (Swarup, 2006: 26). Goss (2014: 12) lists the five recipients:

(1) The Atomic Energy Commission (through the Tata Institute of Fundamental Research)
(2) The Council of Scientific and Industrial Research
(3) The Ministry of Natural Resources and Scien-

tific Research, Director General of Observatories

(4) The University Grants Commission

(5) The Physical Research Laboratory

Copies of the proposal also were sent to Bart Bok (Director of Mt Stromlo Observatory in Australia and Professor of Astronomy at the Australian National University in Canberra), J.-F. Denisse (leader of the Paris Observatory radio astronomy group), Jan Oort (Professor of Astronomy at Leiden University in the Netherlands), Joe Pawsey and Harlow Shapley (Director of Harvard College Observatory and Professor of Astronomy at Harvard). All were asked to send confidential assessments to the Indian authorities. Govind (ibid). notes that copies of the supporting letters from Bok, Oort and Pawsey to Dr Homi Bhabha, Director of the Tata Institute of Fundamental Research in Mumbai are available in the TIFR archives. He also mentions that Bok's (1961) recommendation was very supportive:

Figure 42: Dr Homi Bhabha (1911–1966), founding Director of the Tata Institute of Fundamental Research, Mumbai (courtesy: TIFR Archives).

> 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 scientific development of a nation, which scientifically, is obviously coming of age.

Pawsey (1961c) was equally flattering:

> I have a very high opinion of the scientific talent in this group ... a group chosen from among them should have an excellent chance of building up a first class scientific institution ... I regard this spontaneous movement among the young Indians who have initiated this proposal as a most encouraging sign and strongly urge you, in the interests of science in India, to try to assist them in their efforts to work out something worthwhile.

What is a little surprising is that there is no letter of support on file from J.-F. Dennise (though this does not automatically mean that he did not send one). Like Pawsey, he was an internationally respected solar radio astronomer, and he certainly knew Mukul Kundu who had carried out his DSc research using facilities located at Paris Observatory's Nançay field station (see Orchiston et al., 2009).

Nonetheless, according to Govind,

> 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 … (Swarup, 2006: 27).

Born in 1909, Homi Bhaba (Figure 42) was particularly interested in cosmic rays, so it is easy to understand his support for radio astronomy. But it goes deeper than that: he was quick to recognise research opportunities that could consolidate India's place on the world stage. In 1935 he had completed a PhD at the Cavendish Laboratory in Cambridge at the same time that Pawsey was there; his thesis was titled: "On Cosmic Radiation and the Creation and Annihilation of Positrons and Electrons". Four years later he joined the Physics Department at the Indian Institute of Science, but he left in 1945 in order to found the Tata Institute of Fundamental Research in Bombay, which he built into a major international centre for cosmic ray research (see Sreekantan, 1998). Homi Bhabha died unexpectedly in an Air India crash in the Alps on 24 January 1966, and apart from his cosmic ray research he is known today as 'The Father of India's Atomic Energy Programme'. For further biographical details of this remarkable man, who strongly supported early Indian radio astronomy, see Chowdhury and Dasgupta (2010) and Venkataraman (1994).

On 20 January 1962 Homi Bhabha sent a cable to the four radio astronomers: "We have decided to form a radio astronomy group stop letter follows with offer …" (Bhabha, 1962a). Over the next two months Homi Bhabha somehow was able to formalize the establishment of the new radio astronomy group at the Tata Institute of Fundamental Research, and on 3 April 1962 he wrote Govind:

> 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 can foresee at present. (Bhabha, 1962b).

7 TATA INSTITUTE OF FUNDAMENTAL RESEARCH AND THE KALYAN RADIO TELESCOPE

Govind then resigned from Stanford, and he and Bina headed for India, via Europe. In Leiden (Holland) Govind visited Professor Jan Oort (1900–1992), one of the world's leading

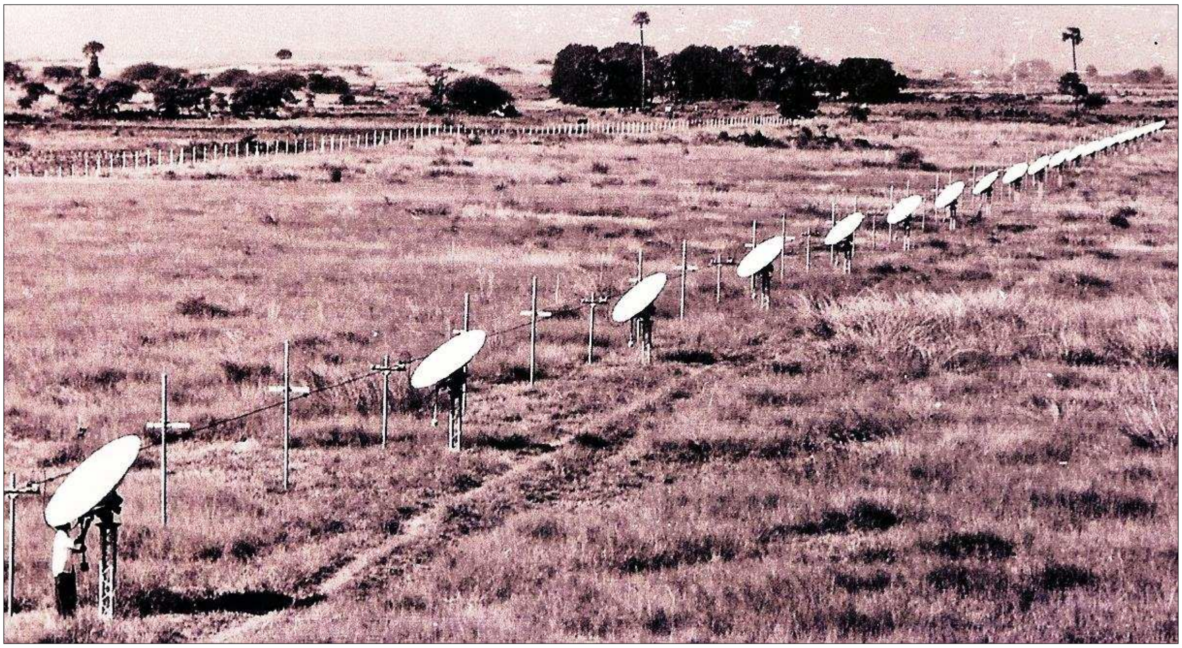

Figure 43: View of part of the east-west grating array, consisting of twenty-four 1.8-m diameter dishes and built at Kalyan, near Mumbai, in 1965 (courtesy: TIFR Archives).

authorities on galactic and extragalactic astronomy, who

> … showed him was a model of a 25 m diameter parabolic dish antenna that they were in the process of building. The great Jan Oort suggested to Swarup that he might build one such dish and use it to study the distribution of neutral hydrogen gas in the southern part of the sky, which is not accessible from Europe but would be easily accessible from the southern latitudes. Such a study would complement the survey they had done of the northern sky. Since Oort knew Bhabha, he was willing to provide TIFR with all the engineering drawings. The 21 cm line radiation from hydrogen atoms had been discovered only a few years earlier – one of the most momentous discoveries in the entire history of astronomy – and mapping the distribution of hydrogen was the hottest problem in astronomy. (Srinivasan, 2015: 621).

But Swarup recalled Pawsey's warning to keep away from the "… fashionable stuff … [and] Be original." So he diplomatically chose not to accept Oort's tantalizing offer, and it was left to Pawsey's group at Radiophysics to pick up the collaboration (see Wendt et al., 2011b).

On 31 March 1963 he returned to India. Shortly afterwards the ex-Potts Hill dishes were transferred to the TIFR, and Govind was joined by two recent graduates, J.D. Isloor and V.K. Kapahi. The following year, two more recent graduates, D.S. Bagri and R.P. Sinha, joined the group, along with N.V.G. Sarma and M.N. Joshi (both of whom transferred from the NPL in New Delhi). Collectively, they constructed India's first radio telescope, which was completed in April 1965 (see *Nature*, 1966). This solar grating array was sited at Kalyan, near Mumbai, and consisted of the thirty-two 1.8-m diameter ex-Potts Hill parabolas:

> … 24 of them were placed along a 630-m east-west baseline and 8 along a 256-m north-south baseline, giving an angular resolution of 2.3 × 5.2 arcmin … (Swarup et al., 1991b: 79).

Part of the E-W arm is shown in Figure 43 and in Figure 44 one of the radio astronomers is adjusting the transmission line.

The idea of using a T-array rather than a cross (as at Stanford) was something that Govind

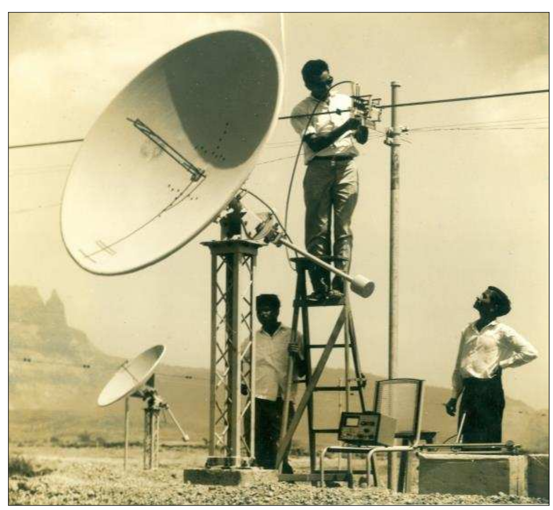

Figure 44: A close-up of two of the Kalyan array antennas, with R.T. Kapahi adjusting the transmission line (courtesy: TIFR Archives).

already decided on years earlier, when the Kalyan array was all but a distant dream:

> 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. (Swarup, 2008: 197).

Over the next three years Govind's group used the Kalyan Radio Telescope "… to investigate properties of the quiet and active radio Sun at 610 MHz …" (Swarup, 2006: 27). Even though this period extended from sunspot minimum towards what would prove to be a relatively weak maximum (see Figure 45), the young TIFR radio astronomy group "… found that the Sun showed considerable limb brightening, and that the solar corona had a temperature of around one million degrees." (ibid.). These findings, and others, were discussed in a series of

Figure 45: A plot showing sunspot numbers from about 1912 to 2003. The Kalyan solar observations were carried out at, and soon after, sunspot minimum (courtesy: Mt Wilson Observatory).

research papers (see Sinha and Swarup, 1967; Swarup et al., 1966a; 1966b; 1968) that built on or confirmed the results published by Govind and Parthasarathy during their Potts Hill sojourn. Meanwhile, technical details of the Kalyan array were provided in Swarup and Kapahi (1970: 404–406). Collectively, these publications—and particularly the *Nature* paper (Swarup et al., 1966b)—marked the start of India's attempt to place its name of the world stage as a serious radio astronomical nation.

Govind noted that Mukul Kundu joined the TIFR radio astronomy group in early 1965, but returned to the USA three years later. In the interim, he "… contributed a great deal to the growth of the group during its critical formative years." (Swarup, 2006: 29). He also featured as a co-author of one of the Kalyan papers (Swarup et al., 1968).

8 THE OOTY RADIO TELESCOPE (ORT)

With a functioning solar grating array (shades of Potts Hill and 'Heliopolis'), we could be forgiven for thinking that Govind's next move would be to expand his solar observatory by adding one or more radiospectrographs (shades of Cook Flat, alias Ft Davis), but no. Admittedly, he did briefly consider adding 20-ft dishes to the E-W grating array in order to have access to a compound interferometer, and discrete radio sources (Swarup, 2006). But as early as June 1963—immediately after starting construction of the Kalyan array—he was already thinking seriously about the second phase of Indian radio astronomy mentioned in the 1961 proposal document that was sent to the TIFR and other agencies, namely, after a solar array the group would construct "... a very high resolution radio telescope of a novel design …" (Krishnan et al., 1961).

This is when Govind

> … 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. (Swarup, 2006: 27).

As we know, this marked the discovery of quasars (see Kellermann, 2014) and opened up a whole new way of viewing the Universe.

Govind describes what happened next:

> 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 [Cambridge] 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. (Swarup, 2006: 27; our italics).

This was an ingenious idea (Srinivasan, 2015: 621 calls it "Exceedingly clever!"), and it certain-

Figure 46: 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 (courtesy: TIFR Archives).

ly qualified as a high resolution radio telescope of novel design. Not surprisingly, Govind quickly 'sold' the idea to Homi Bhabha.

Actually, initially Govind wanted to set up a synthesis radio telescope in India, and in late 1963 he discussed this option with Chris Christiansen who visited the TIFR while *en route* to the Netherlands. But

> An even less ambitious synthesis radio telescope [than the Westerbork Shynthesis 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 … (Swarup, 2008: 199).

Govind and Ramesh Sinha then went in search of a suitable site, and in early 1965 they found one, at Ooty in the Nilgiri Hills (see Figure 2). In late 1965 Dr Bhabha enthusiastically approved the establishment of the Ooty Radio Telescope (Swarup, 1991), and through Prime Minister Nehru accessed funding science education funding; the Tamil Nadu State Government provided the land. Sadly, Homi Bhabha died in an air crash in January 1966, before the ORT could be built, but his successor at the TIFR continued to provide strong support for the project.

The Ooty Radio Telescope (ORT) was completed at the end of 1969 (Swarup, 1986), and it is still in operation today. Back then it consisted of

> … a parabolic cylindrical 530 m long × 30 m wide antenna … The reflecting surface is made of 1100 stainless steel wires, each 530 m long and 0.38 mm in diameter. This surface is supported by 24 parabolic frames … placed 23 m apart. The unique feature of the telescope is that its long axis is aligned in the north-south direction along a hill with a natural slope of about 11°, which is equal to the latitude of the observatory. This enables ORT to track a celestial object for about 9.5 hours every day by rotation of the telescope mechanically in the east-west direction about its long axis. The pointing in the north-south direction is achieved by electronic phasing of the 1056 dipoles placed along the 53-m-long focal line of the parabolic reflector. A useful declination range of ±40° can thus be covered.
>
> The telescope operates in a band centred on 326.5 MHz (λ = 92 cm). (Swarup et al., 1991b: 79).

With a total collecting area of 8,700 m^2, the ORT was one of the largest steerable radio telescopes in the world at the time, and could detect sources down to 0.2 jansky. Two different views of the ORT are shown in Figures 46 and 47, and further technical details are provided in Swarup et al. (1991a).

Although the ORT was completed in December 1969, the first occultation was only observed on 18 February 1970 (see Swarup et al., 1971a). By the time the research paper "Lunar occultation observations of 25 radio sources made with the Oooty Radio Telescope: List 1" (Swarup et al., 1971b) was published, Govind's team had already used the occultation method to observe more than 300 sources. At this time (i.e. early

Figure 47: Another view of the Ooty Radio Telescope; reflections of sunlight by 1,100 stainless steel wires are seen on the right. The inset bottom left shows an Indian stamp featuring the ORT (courtesy: TIFR Archives).

1971), the TIFR radio astronomy group comprised 16 researchers, plus several engineers and technicians. One of the researchers was Dr T.K. Menon (but he would return to the USA in 1974). Later, Govind would pay tribute to his team:

> 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 … (Swarup, 2006: 29).

Srinivasan (2015: 622) elaborates:

> A telescope like that was not easy to build in the late 1960s. The technological capabilities were still primitive in India. While the Tata Consulting Engineers (known then as Tata Ebasco) did the structural and mechanical design, and the Calcutta Firm Bridge and Roof were identified to do the mechanical construction, the group itself lacked experienced engineers. Since foreign exchange was virtually impossible those days, the entire electronics had to be fabricated in India. The indigenous manufacture of critical components like coaxial cables, ultra-high frequency connectors, etc. was just starting. So it was a challenge to build a large telescope like that. The remote location of the site was an added complication.
>
> Nonetheless,
>
> 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. (Swarup, 2006: 30).

Srinivasan (2015: 622–623) would go further, and he contrasts Govind's students who worked on construction of the ORT with present-day graduate students:

> The entire electronics had to be built in-house by the handful of students, guided by Sarma and Joshi. This included the phase shifters, the 1024 dipoles along the focal line, the control system and the back end electronics. The students … worked incredibly hard, often 18 hours a day. Contrast this with the present-day trend where students refuse to dirty their hands ... The 'publish or perish' syndrome has overtaken science. One can only be nostalgic about the days when students had a pioneering spirit; they were not obsessed with getting a 'quick Ph D'. Of course, they needed to be motivated and inspired by an inspired leader. Govind Swarup was certainly one of them!

The ORT was very productive as a research instrument:

> During the 1970s, lunar occultation observations of more than 1,000 radio sources were made … 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 sources, and to reveal their angular structure with arc-second resolution. The data provided inde-

> pendent support to the Big Bang model (Kapahi, 1975; Swarup, 1975). Detailed physiccal properties of many Galactic and extragalactic sources 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. (Swarup, 2006: 30).

By 1984 the Ooty radio astronomers had

> … 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. (ibid.).

It was now time to move on, and the Ooty Radio Telescope evolved into the Ooty Synthesis Radio Telescope (OSRT), which was designed to provide 2-D images of radio sources. The OSRT consisted of the original ORT, plus

> … seven small and inexpensive parabolic cylinders of size 22 m × 9 m at distances of up to 4 km from the ORT. The pointing of these cylinders in both east-west and north-south directions was controlled from the central observatory by means of radio telemetry. In order to achieve a wide field of view of 2° by 40′ arc, ORT was itself divided into five sections and the signals received from the 12 antennas were mutually combined to form a total of 66 interferometer pairs. The resulting image had a resolution of about 1 arcmin at 327 MHz. (Swarup et al., 1991b: 80).

The configuration of the ORT and the 'satellite antennas' is shown in Figure 48.

The OSRT operated at a much lower frequency than any of the other synthesis radio telescopes in existence in 1984, and it also had the advantage of accessing both the northern and southern skies (see Sukumar et al., 1988).

Initially. the OSRT was used to search for new galactic supernova remnants; and to map galactic sources, edge-on and face-on spiral galaxies, including the nearby radio galaxy Fornax A, giant radio galaxies and selected very-steep-spectrum sources in clusters of galaxies (Swarup, 1984). Sukumar et al. 1988: 108) elaborate on the importance of the galaxy clusters research program:

> The OSRT with its high sensitivity and resolution, large field of view and operation at meter wavelength is well suited for a survey of clusters of galaxies which are known to contain very steep spectrum (VSS) radio sources with spectral indices α > 1.2 and head-tail radio galaxies with extended diffuse steep spectrum tails. The VSS sources are remnants of old radio galaxies confined by hot thermal gas. The head-tail sources owe their morphology to the motion of their parent galaxies through the intra-cluster medium leaving behind a trail of relativistic electrons which are confined by the hot ICM gas. Such sources can be used as probes to study the dynamics of ICM.

Further details are provided in Swarup (1991).

Srinivasan (2015: 625) is in an excellent position to make an unbiased assessment of the ORT and OSRT. Here is his 'report card':

> The 'balance sheet' after the exercise to build the Ooty radio telescope read[s] something like this.
>
> - A large number of talented young people were attracted to Swarup's 'crazy idea' (to quote one of his illustrious students) to build a novel world class telescope in the middle of no-where. This included both students of science as well as engineering. The cream of the TIFR/ Atomic Energy Training School wanted to work with Swarup.

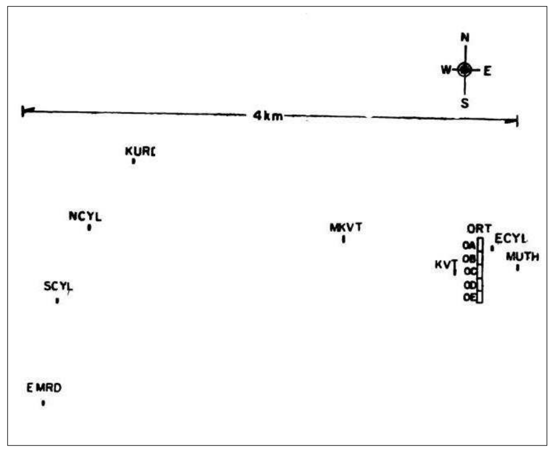

Figure 48: An OSRT map showing the location of the ORT and the satellite antennas (after Sukumar et al., 1987: 97).

> - The project helped several engineering firms – such as Tata Consulting Engineers – to reach the next plateau in their capability and sophistication.
> - The successful indigenous design and construction of the Ooty Radio Telescope led to the development of a large microwave antenna industry in India, starting with the construction of the ARVI satellite earth station north of Pune in 1971.
> - The Ooty telescope produced not only good science; it produced a number of outstanding astronomers and engineers, endowed with leadership qualities.
> - There was tremendous cohesion and camaraderie within the group.
> - This group was to stay together and design and build the GMRT – the world's largest low frequency telescope.

More on the aforementioned GMRT later, in Section 10.

9 INTERNATIONAL SCIENCE AND THE PROPOSED GIANT EQUATORIAL RADIO TELESCOPE (GERT)

Flushed with success experienced with the Oorty Radio Telescope, in 1976 Govind began thinking about constructing a radio telescope of similar design but about four times the length of the ORT, and sited on the Earth's equator—where flat terrain would facilitate rapid construction of the antenna and make it relatively easy to operate (and track sources for up to 12 hours per day).

In 1978 this formally became known as the 'Giant Equatorial Radio Telescope' (GERT), and would consist of a single cylindrical antenna 2 km long and 50 m wide, and operating "… at a few discrete [protected] bands in the range of about 38 and 328 MHz." (Swarup, 1981: 269).

As part of his overall proposal, Govind also envisioned a second phase:

> … to construct an aperture synthesis interferometer around GERT at a relatively small additional cost by adding 14 parabolic cylinders of smaller dimensions (say 50 m × 15 m) on a baseline measuring 14 km east-west and 12 km north-south. (Swarup, 1981: 272).

The GERT Synthesis Telescope was thought to be ideal for the investigation of steep-spectrum sources with low surface brightness, and as the largest and most powerful low frequency radio telescope in the world would improve our understanding of the evolution of galactic and extragalactic radio sources. Furthermore, by including the GERT Synthesis Telescope in existing VLBI networks, it would be useful in studying galactic nuclei, compound components in galactic objects and proper motions of pulsars.

The science case for a fully-developed GERT was overwhelming, but more than this, Govind (1981) pointed to the inevitable technology spin-offs for countries involved in this venture.

In April 1979 a workshop attended by scientists from Egypt, India, Indonesia, Iraq, Kenya and Nigeria, and Professors W.N. Christiansen from Australia and T. Hewish from England (representing UNESCO) was held on India to "… consider the technical feasibility and scientific merits of the project." (Swarup, 1981: 276). There was over-whelming support for the proposal, and for the establishment of the International Centre for Space Sciences and Electronics (INISSE), with the GERT as its flagship research facility (see Swarup et al., 1979).

Finding a suitable site for the GERT was not difficult. Although the Earth's Equator traverses various nations in South America (Ecuador, Colombia and Brazil), Africa (Gabon, Congo, the Democratic Republic of Congo, Uganda, Kenya and Somalia) and Asia (Indonesia) as shown in Figure 49, potential sites in Kenya and Indonesia were quickly settled on. The Kenyan site was then selected, but although the Kenyan Government was supportive and the Indian Government agreed to fund half of the all-up cost of US$20 million, the project fell through after President Kenyatta died (in August 1978) and Kenyan scientists were not able to follow up on the project.

Attention then switched to Indonesia, and

> … 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 [which needed to provide fin-

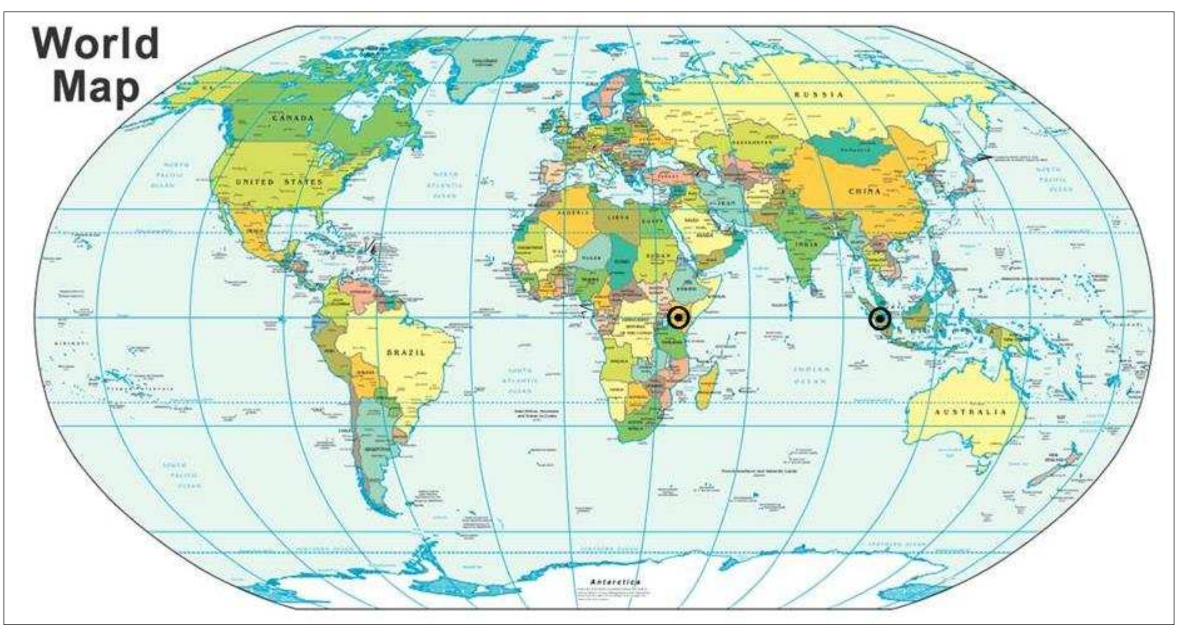

Figure 49: Map showing the equator and sites selected for the GERT in Kenya (left) and Indonesia (right) (map: Wayne Orchiston).

ancial or other support for the project]. 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.

Notwithstanding President Suharto's invaluable support and a financial commitment from the Indian Government, the seismic concerns sent shock waves through the project. Apparently they were 'the last straw', for by the end of 1983 Govind had decided to abandon the GERT altogether and champion another major project in its place. Thus, the GMRT was born.

10 THE GIANT METREWAVE RADIO TELESCOPE (GMRT)

By early 1982 Govind was already aware that

> … 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.

It was apparent that the TIFR radio astronomers would not be able to use the GERT to study proto-clusters, "… the postulated condensates of neutral hydrogen existing at very high redshifts prior to the formation of galaxies in the Universe." (Swarup, 2006: 30). What was needed was a major new low frequency radio telescope … and once again Govind had a brainwave:

> 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 … (Swarup, 2006: 30).

Re the SMART concept, Srinivasan (2015: 626) explains:

> The reflecting surface – a stainless steel mesh – is attached to these rope trusses. This is what gives the 'see-through-look' to the dish. This ingenious invention by Swarup greatly reduced the cost of the dish, by reducing the wind load, and has been acclaimed internationally.

Srinivasan (2015: 627) notes that when Govind first came up with this clever design "… he called it '*The Great Indian Rope Trick*'! Later he nicknamed it SMART."

Govind's research objective, plus

> … experience gained in designing and building the ORT, and the dynamism of the younger members of our group propelled me to propose the Giant Metre-wave Radio Telescope on 1 January 1984. (Swarup, 2006: 30).

Chris Christiansen also believed this was the right path for Govind (and India) to follow. On 30 July 1984 he wrote:

> 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, 1984).

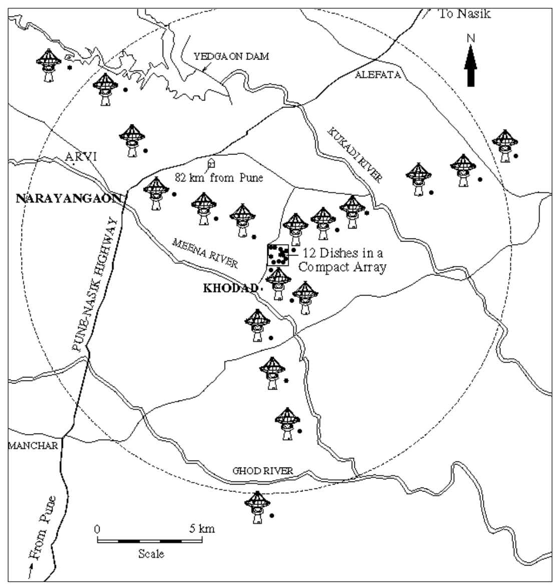

Figure 50: Map showing the location of the thirty 45-m fully steerable parabolic dishes of the GMRT, located near Khodad in western India (courtesy: TIFR Archives).

The Government of India gave its approval in March 1987, "… after the Prime Minister, Rajiv Gandhi—who was an active radio ham—was satisfied after asking three penetrating questions." (Swarup, 2008: 200). The GMRT was no longer a dream, and Govind's group moved from Mumbai to Pune and formed the National Centre for Radio Astrophysics (NCRA), but still under the TIFR umbrella.

The GMRT is a synthesis radio telescope consisting of thirty parabolic dishes each 45 m in diameter each, spread in an approximate Y-shaped configuration across a region of about 25 km diameter (see Figure 50). There are fourteen antennas in a central array of about 1 km × 1 km (Figures 51 and 52), while the remaining

Figure 51: Some of the GMRT dishes in the central array (courtesy: TIFR Archives).

Figure 52: A close up of one of the 45-m antennas, with six others in the background (courtesy: TIFR Archives).

sixteen dishes—as Figure 50 indicates—are situated along the three 14 km long arms (Swarup et al., 1991a). The GMRT operated at the following radio frequency bands: 120–180, 225–245, 300–360, 580–650, and 1000–1430 MHz. It takes about 10 hours of observations to build up an image of a discrete source. The GMRT became fully operational in 2000.

Country	Nos
Argentina	13
Austria	5
Australia	75
Belgium	7
Brazil	11
Canada	50
China	19
Chile	1
Denmark	6
France	66
Germany	40
India	847
Iran	2
Italy	49
Ireland	7
Japan	21
Korea	6
Malaysia	3
Mauritius	3
Mexico	7
Netherlands	75
Nigeria	1
Poland	55
Portugal	3
Russia	13
Spain	14
South Africa	16
Sweden	2
Taiwan	20
UK	163
USA	169
Total	1769

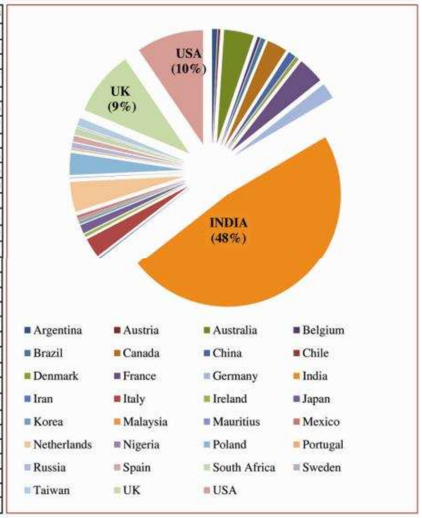

Figure 53: A pie diagram showing successful GMRT observing proposals 2002–2015 by country (after Srinivasan, 2015: 628).

Figure 54: The November 2016 ICOA-9 Conference featured one Public Lecture, which was presented by Professors Wayne Orchiston (Thailand) and Govind Swarup (India), who are shown in the foreground. Their topic was the early development of radio astronomy in Asia, with emphasis on Australia, China, India, Japan and New Zealand (after Orchiston et al., 2018: xxii).

The GMRT is the world's largest and most powerful low frequency array and has been popular with Indian and overseas radio astronomers from the time it became operational. As Figure 53 illustrated, between January 2002 and September 2015 there were 1769 successful research proposals submitted by astronomers from 31 different countries. Just under half of all proposal came from India.

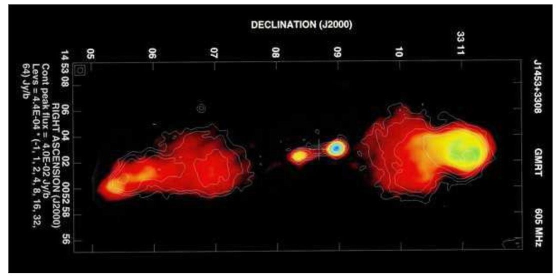

Figure 55: A false-colour image of the unusual radio galaxy J1453+3304 (courtesy: TIFR Archives).

During the November 2016 Ninth International Conference on Oriental Astronomy, which was held in Pune, Govind Swarup and the first author of this paper stepped in at the last-minute (Figure 54) to present a Public Lecture when the scheduled speaker could not attend. In their review of the historical development of Asian radio astronomy, Govind discussed the many research accomplishments of the GMRT and singled out three of special interest (Orchiston and Swarup, 2018: 204–205). They were (but with revised figure numbers for this paper):

> (1) Observations made with the GMRT have have led to the discovery of the new and interesting double-double radio galaxy (J1453+3304) (Saikia et al. 2006), which is shown in [Figure 55]. The outer-most lobes are remnants of an earlier epoch of the radio source when the supply from the central engine was stopped; millions of years later the central engine was activated again, giving rise to another double radio source.
>
> (2) The GMRT is being used to search for giant radio galaxies and probe the inter-galactic medium. The giant radio galaxy J1420-054 [shown in Figure 56] is identified

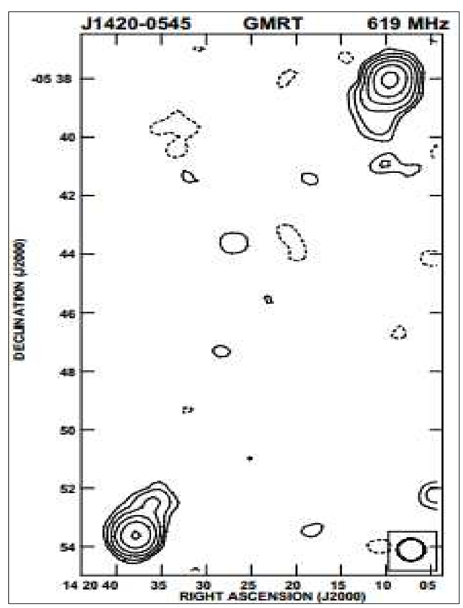

Figure 56: The radio source J1420-054, bottom left, is currently the largest-known giant radio galaxy (courtesy: TIFR Archives).

with an optical galaxy at z = 0.3067, and has a projected linear size of 4.69 Mpc (15 million light years). This is currently the largest known radio galaxy (see Machalski et al., 2007).

(3) A recent outstanding result relates to the formation of structure in the Universe by the merging of galaxies and clusters of galaxies, and is the discovery of a giant double radio relic in the Planck Sunyaev-Zel'dovich Cluster [Figure 57].

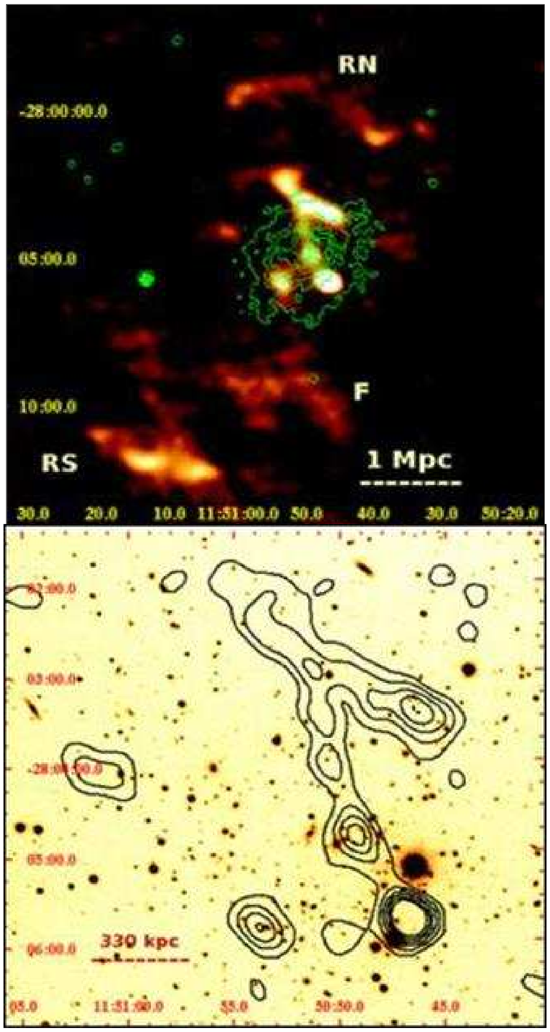

Figure 57, Top: XMM-Newton contours in X-rays (green) superimposed on the 150 MHz GMRT radio map of the cluster (orange and yellow). Bottom: The 150 MHz GMRT radio map near the cluster centre, superimposed on the R-band optical image (after Bagchi et al., 2011: 3).

Professor Srinivasan (2015: 627) has the last word about the GMRT:

> The GMRT should become the benchmark for many things in Indian science. It demonstrates that self-reliance in instrumentation is possible. It is true that far more complicated things, such as Fast Breeder Reactors, advanced satellites, giant rockets like the PSLV and GSLV, have been made. But they were made by large organizations with large budgets. GMRT was made with a shoestring budget, at a fraction of what it would have cost elsewhere in the world. And it was made by a small team of scientists and engineers working in unison.

11 DISCUSSION

11.1 Unique Educational Initiatives

Govind and the Indian physicist and educationist Professor V.G. Bhide promoted an all-inclusive approach to teaching science. Their proposal led to a 5 year integrated program for intensive education in science and the setting up of the Indian Institute of Science Education and Research (IISER) in Pune and Kolkata in 2005 and later in other places in India. Govind considers this as one of this important achievements (Srinivasan, 2015).

In addition, with the assistance of villagers Govind was able to form the Khodad Rural Science Center (Figure 58). This was another of his dreams: to encourage rural students to study science by offering them hands-on experiments. This is a wonderful example of how a world-famous scientist can influence Indian education at the grass-roots level and help change society (Phakatkar, 2015).

11.2 Recognition and Rewards

Over the years, Govind has received many national and international prizes and awards, and we can do no better than to once again quote Srinivasan (2015: 629), a personal friend and self-proclaimed admirer:

> I would be doing an injustice to him [to Govind] if I were to dwell on these at any length, for he never aspired for any awards. Nevertheless, I would like to mention a few of them.
>
> Govind Swarup is immensely proud of the fact that C. V. Raman elected him to the Fellowship of the Indian Academy of Sciences in 1967. Subsequently, he was elected to the Royal Society of London, and to the Pontifical Academy in the Vatican.
>
> The astronomical community bestowed on him the Grote Reber Medal, the most coveted award for achievement in radio astronomy.

11.3 Other Indian Radio Astronomy Initiatives

In science, often the outstanding achievements of one group serve as a catalyst that leads to the emergence of other like-minded groups, and this is precisely what happened in India once Govind Swarup's group at the TIFR became prominent internationally. Eventually, this led to radio astronomy research being launched at the Raman Research Institute and the Indian Institute of Astrophysics (in Bengalaru) and the Physical Research Institute (in Ahmedabad).

Figure 58: The Khodad Rural Science Center is located in the village of Khodad, close to the central cluster of GMRT radio telescopes. With a population of about 5,000, Khodad is mainly an agricultural centre, but because of the GMRT it has also become a tourist destination (photograph: Sudhir Phakatkar).

Scientists at some of these facilities (especially at the Raman Research Institute) established close collaborations with Govind's group at the TIFR.

12 CONCLUDING REMARKS

Govind Swarup is a child of modern India but a man of two worlds. He was born and part-educated in colonial India, but grew up as India gained its independence. He remembers hearing Mahatma Gandhi's scintillating speeches when he was still an impressionable school boy, and this instilled in him a patriotic spark that has lasted a lifetime. Govind could so easily have built an international career as a radio astronomer in Australia or in the USA—indeed in any country —but he chose India (to its eternal gain and their loss).

Jawahar Lal Nehru was a great visionary Prime Minister, and in the early years of independence he saw the newly-established scientific laboratories as the 'temples' of modern India. One such temple was the Tata Institute of Fundamental Research in Bombay/Mumbai, but all temples are useless and internationally invisible unless sustained by suitable 'high priests'. There is no doubt that Govind Swarup has filled that role admirably for more than half a century, and in the process he has built the Institute's radio astronomy group into one of its flagship accomplishments (see Sreekantan, 2006).

In this regard, we wholeheartedly agree with Srinivasan (2015: 630) that Govind Swarup's career "… personifies the stuff legends are made of." It has been our pleasure and privilege to know Govind, and we applaud his intellect, his inspirational leadership, his remarkable inventions that have helped reshape astronomical instrumentation—and the role that India has been able to play—and lastly, his countless achievements as a scientist and a researcher.

In the 'Concluding Remarks' in their 2016 Asian history of radio astronomy review paper, Orchiston and Swarup (2018: 207) noted that

> Over the last sixty years, there has been a succession of remarkable scientific discoveries made by radio astronomers in the USA, in European countries and in three different Asian nations: Australia, India and Japan. (Orchiston and Swarup, 2018: 207).

What is particularly remarkable is that most of the Indian scientific discoveries were the direct or indirect result of the achievements of just one remarkable man: Govind Swarup. What is more, he never tires—even though he is supposedly retired he continues to contribute to science and technology and build India's international reputation in radio astronomy.

Govind, we salute you for all that you have accomplished for Indian astronomy, and we hope that you will enjoy and cherish this little memento. We had hoped to formally present this paper to you on your birthday, during 'The Metre Wavelength Sky II' conference" (Figure 59), but—as you know—unfortunate last minute visa problems prevented the first author of this paper from visiting India. We hope, nonetheless, that you will enjoy reading this belated birthday present and that it will bring back many fond memories.

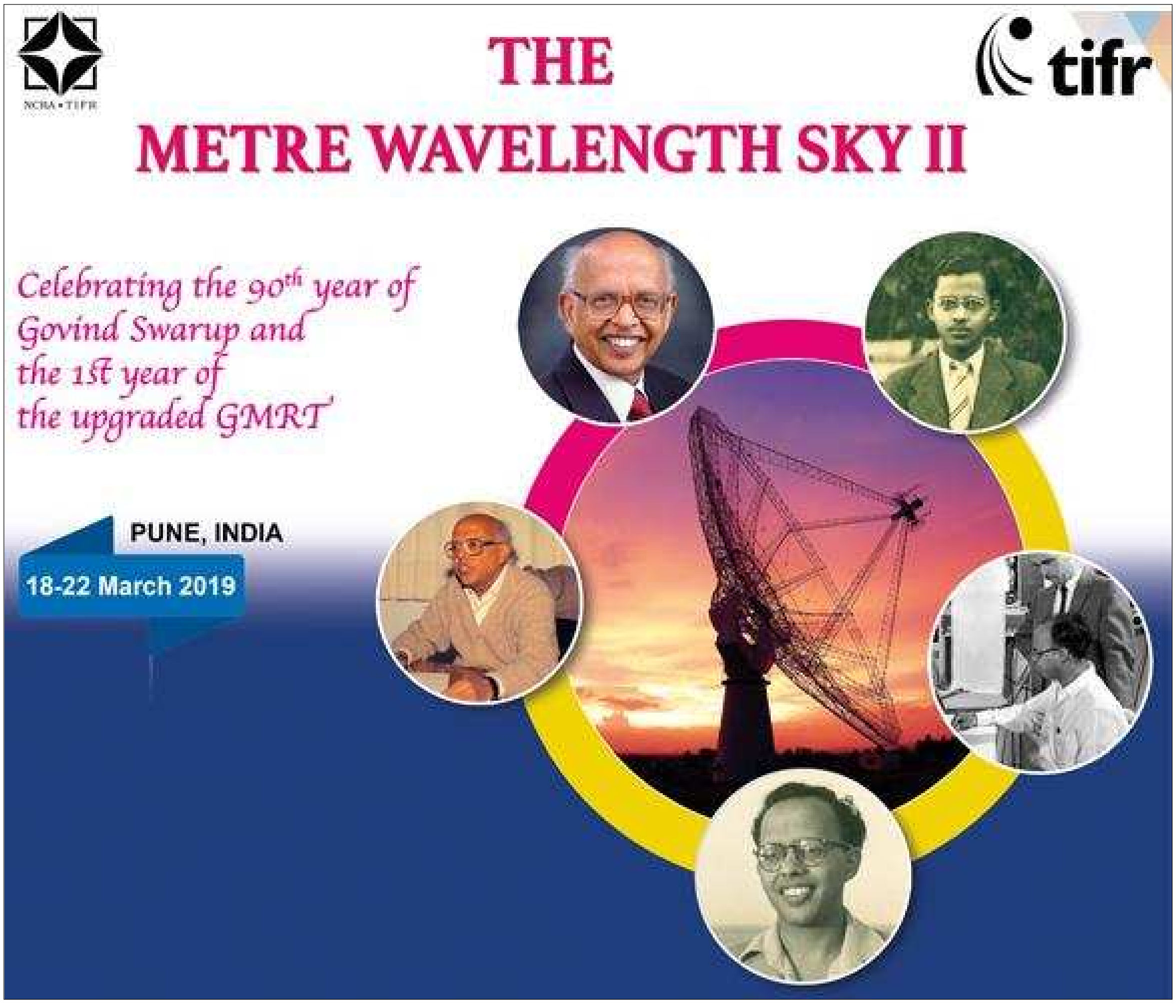

Figure 59: The attractive poster about 'The Metre Wavelength Sky II' conference.

13 NOTES

1. At that time, Kodaikanal had a vibrant optical solar astronomy program (see Kochhar and Orchiston, 2017), but was keen to expand and include radio astronomy. This would be Parthasarathy's responsibility upon his return to India.
2. RP began as a Division of the Government's Council for Scientific and Industrial Research (CSIR), which in 1949 was reconstituted as a new organisation with a similar name, the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
3. For an example of the use of this 'discarded' equipment see Wendt and Orchiston (2018).
4. But this was a 'two-way street' for at first most optical astronomers viewed radio astronomers with suspicion, and it would take time before they were accepted as part of the international astronomy community (e.g. see Jarrell, 2005).
5. Bracewell retired from teaching in 1991, but continued his research, and by the time he died in 2007 he was an acknowledged authority not only on radio astronomy but also on Fourier transforms and medical imaging (e.g. see Bracewell, 1984; 2005; Frater et al., 2017; Thompson and Frater, 2010). In the twilight years of his life Ron also cultivated an interest in astronomical history, and he published two papers in this journal (Bracewell, 2002; 2005).
6. Govind was only the second student to complete a Stanford radio astronomy PhD under Ron Bracewell. His degree was awarded in 1961 for a thesis titled "Studies of Solar Micro-wave Emission Using a Highly Directional Antenna".
7. Note that Christiansen's 'Chris Cross' also was modified by the addition of the 60-ft (18-m) 'Kennedy Dish' near the eastern end of the E-W arm of the array so that it too could be used as a compound interferometer. The Kennedy Dish was relocated to Parkes in 1963, but between

> … August 1961 and October 1962 … the FCI [Fleurs Compound Interferometer] was used to determine the right

ascensions and angular sizes of eight well-known discrete sources. (Orchiston and Mathewson, 2009: 25).

As at Stanford, two papers were published on this work (Labrum et al., 1963; 1964).

14 ACKNOWLEDGEMENTS

We wish to thank the late Professor Ron Bracewell, the late Professor Rod Davies, Professor Alan Maxwell, and the late Edward Waluska for kindly supplying Figures 39, 14, 31, and 26 respectively; Mt Wilson Observatory for Figure 45; The National Physical Laboratory (New Delhi) for Figure 30; The Tata Institute of Fundamental Research Archives for Figures 36, 37, 42–44, 46, 47, 50–52, and 55–57; CSIRO Astronomy and Space Sciences (Sydney, Australia) for Figures 1, 7, 10–13, 15, 16, 18, 21–25, 27 and 33; and finally, Professor Govind Swarup, for Figures 3, 32, 40 and 41, and the original version of Figure 2.

15 REFERENCES

Bagchi, J., Sirothia, S.K., Werner, N., Pandge, M.B., Kantharia, N.G., and 3 coauthors, 2011. Discovery of the first giant double radio relic in a galaxy cluster found in the Planck Sunyaev-Zel'dovich Cluster Survey: PLCK G287.0+32.9. *Astrophysical Journal Letters*, 736(1), article id. L8, 6 pp.

Bhabha, H.J., 1962a. Western Union telegram to T. Krishnan, M.R.. Kundu, T.K. Menon and G. Swarup, dated 20 January. Original in the NCRA Library, Pune.

Bhabha, H.J., 1962b. Letter to G. Swarup, dated 3 April. Original in the NCRA Library, Pune.

Boischot, A., 1957. Caractères d'un type d'émission hertzienne associé à certaines éruptions chromosphériques. *Comptes Rendus de l'Académie des Sciences*, 244, 1326–1329.

Bok, B., 1961. Letter to Dr Homi J. Bhabha, dated 5 October. Copies in the TIFR Archives, Mumbai, and the NCRA Library, Pune.

Bolton, J.G., 1953. Radio astronomy at U.R.S.I. *The Observatory*, 73, 23–26.

Bracewell, R.N., and Swarup, G., 1961. The Stanford Microwave Spectroheliograph Antenna, a microsteradian pencil beam antenna. *Institute of Radio Engineers, Transactions on Antennas and Propagation*, AP-9, 22–30.

Bracewell, R.N., Swarup, G., and Seeger, C.L., 1962. Future large telescopes. *Nature*, 193, 412–416.

Bracewell, R.N., 1965. *The Fourier Transform and its Applications*. New York, McGraw Hill.

Bracewell, R.N., and Riddle, A.C., 1967. Inversion of fan beam scans in radio astronomy. *Astrophysical Journal*, 150, 427–434.

Bracewell, R.N., 1984. Early work on imaging theory in radio astronomy. In Sullivan, 167–190.

Bracewell, R.N., 2002. The discovery of strong extragalactic polarization using the Parkes Radio Telescope. *Journal of Astronomical History and Heritage*, 5, 107–114.

Bracewell, R., 2005. Radio astronomy at Stanford. *Journal of Astronomical History and Heritage*, 8, 75–86.

Christiansen, W.N., 1953. A high-resolution aerial for radio astronomy. *Nature*, 171, 831–833.

Christiansen, W.N., and Warburton, J.A., 1953a. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part I. A new highly directional aerial system. *Australian Journal of Physics*, 6, 190–202.

Christiansen, W.N., and Warburton, J.A., 1953b. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part II. The quiet Sun—one-dimensional observations. *Australian Journal of Physics*, 6, 262–271.

Christiansen, W.N., and Warburton, J.A., 1955a. The distribution of radio brightness over the solar disk at a wave-length of 21 cm. Part III. The quiet Sun, two-dimensional observations. *Australian Journal of Physics,* 8, 474–486.

Christiansen, W.N., and Warburton, J.A., 1955b. The Sun in two-dimensions at 21 cm. *The Observatory*, 75: 9–10.

Christiansen, W.N., and Mathewson, D.S., 1958. Scanning the Sun with a highly directional array. *Proceedings of the Institution of Radio Engineers*, 46, 127–131.

Christiansen, W.N., 1960. Letter to G. Swarup, dated 22 September. Original in the NCRA Library, Pune.

Christiansen, W.N., Mathewson, D.S., Pawsey, J.L., Smerd, S.F., Boischot, A., Denisse, J.F., Simon, P., Kakinuma, T., Dodson-Prince, H., and Firor, J., 1960. A study of a solar active region using combined optical and radio techniques. *Annales d'Astrophysique*, 23, 75–101.

Christiansen, W.N., Labrum, N.R., McAlister, K.R., and Mathewson, D.S., 1961. The cross-grating interferometer: a new high-resolution radio telescope. *Proceedings of the Institution of Electrical Engineers*, *108B*, 48–55.

Christiansen, W.N., and Högbom, J.A., 1969. *Radio Telescopes*. Cambridge, Cambridge University Press.

Christiansen, W.N., 1976. Taped interview with Woody Sullivan, 27 August. Tape and transcript in the Sullivan Collection, National Radio Astronomy Observatory Archives, Charlottesville.

Christiansen, W.N., 1984. Letter to G. Swarup, dated 30 July. Original in the NCRA Library, Pune.

Chowdhury, I., and Dasgupta, A., 2010. *A Masterful Spirit: Homi J. Bhabha 1909–1966*. New Delhi, Pen-guin.

Davies, R.D., 2005. A history of the Potts Hill radio astronomy field station. *Journal of Astronomical History and Heritage*, 8, 87–97.

Davies, R.D., 2009. Recollections of two and a half years with 'Chris' Christiansen. *Journal of Astronomical History and Heritage*, 12, 4–10.

Frater, R.H., and Goss, W.M., 2011. Wilbur Norman Christiansen 1913–2007. *Historical Record of Australian Science*, 22, 215–228.

Frater, R.H., and Ekers, R.D., 2012. John Paul Wild 1923–2008. *Historical Record of Australian Science*, 23, 212–227.

Frater, R.H., Goss, W.M., and Wendt, H.W., 2013. Bernard Yarnton Mills 1920–2011. *Historical Records of Australian Science*, 24, 294–315.

Frater, R.H., Goss, W.M., and Wendt, H.W., 2017. *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*. Cham (Switzerland), Springer.

Goss, W.M., 2014. Origins of radio astronomy at the Tata Institute of Fundamental Research and the role of J.L. Pawsey. India. arXi:1408.3734v1 [physics.hist-ph]

Hazard, C., 1963. Investigation of the radio source 3C273 by the method of lunar occultation. *Nature*, 197, 1037.

Illustrated Weekly Times of India, 14 September 1954.

Ishiguro, M., Orchiston, W., Akabane, K., Kaifu., N., Hayashi, M., Nakamura, T., Stewart, R., and Yokoo, H., 2012. Highlighting the history of Japanese radio astronomy. 1: An introduction. *Journal of Astronomical History and Heritage*, 15, 213–231.

Jarrell, R., 2005. "Radio Astronomy, whatever that may be". The marginalization of early radio astronomy. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth*. Dordrecht, Springer. Pp. 191–202.

Kapahi, V.K., 1975. Cosmology from angular size counts of extragalactic radio sources. *Monthly Notices of Royal Astronomical Society*. 172, 513–533.

Kellermann, K.I., 2014. The discovery of quasars and its aftermath. *Journal of Astronomical History and Heritage*, 17, 267–282.

Kerr, F.J., 1953. Radio astronomy at the URSI Assembly. *Sky and Telescope*, 12, 59–62.

Kochhar, R.K., and Orchiston, W., 2017. The development of astronomy and emergence of astrophysics in India. In Nakamura and Orchiston, 705–770.

Krishnan, K.S., 1955. Letter to G. Swarup, dated 22 February. Original in the NCRA Library, Pune.

Krishnan, T., Kundu, M.R.., Menon, T.K.., and Swarup, G., 1961. Proposal for the Formation of a Radio Astronomy Group in India. Dated 23 September. Copies were sent to H.J. Bhabha (Director, TIFR), D.S. Kothari (Chairman, University Grants Commission), M.S. Thacker (Director General of CSIR) and Vikram Sarabhai (Director, PRL and Director General of Observatories). Copy in the NCRA Library, Pune.

Kundu, M., 1964. *Solar Radio Astronomy*. *Volume II* Ann Arbor, The University of Michigan Radio Astronomy Observatory.

Labrum, N.R., Harting, E., Krishnan, T., and Payten, W.J., 1963. A compound interferometer with a 1.5 minute of arc fan beam. *Proceedings of The Institution of Radio Engineers*, *Australia*, 2, 148–155.

Labrum, N.R., Krishnan, T., Payten, W.J., and Harting, E., 1964. Fan-beam observations of radio sources at 21cm wavelength. *Australian Journal of Physics*, 17, 323–339.

Labrum, N.R., and Stewart, R.T., 1970. The solar U-burst at metre wavelengths. *Proceedings of the Astronomical Society of Australia*, 1, 316–318.

Lovell, A.C.B., 1964. Joseph Lade Pawsey 1908–1962. *Biographical Memoirs of Fellows of the Royal Society*, 10, 229–243.

McLean, D.J., and Labrum, N.R. (eds.), 1985, *Solar Radiophysics*, Cambridge, Cambridge University Press.

Machalski, J., Koziel-Wierzbowska, D., and Jamrozy, M., 2007. Giant radio galaxies as a probe of the cosmological evolution of the IGM. I. Preliminary deep detections and low-resolution spectroscopy with SALT. *Acta Astronomica*, 57, 227–248.

Maxwell, A., 1948. *Enhanced Solar Radiation at 3 Metre Wavelengths*. M.Sc. Thesis, Physics Department, Auckland University College.

Maxwell, A., 1957. Radio emissions from the Sun. *Proceedings of the National Electronics Conference*, 13, 374–376.

Maxwell, A., 1958. Solar radio astronomy in Texas. *Sky and Telescope*, 17, 388–393.

Maxwell, A., and Swarup, G., 1958. A new spectral characteristic in solar radio emission. *Nature*, 181, 36–38.

Maxwell, A., Swarup, G., and Thompson, A.R., 1958. The radio spectrum of solar activity. *Proceedings of the Institute of Radio Engineers*, 46, 142–148.

Mills, B.Y., and Little, A.G., 1953. A high-resolution aerial system of a new type. *Australian Journal of Physics*, 6, 272–278.

Mills, B.Y., Little, A.G., Sheridan, K.V., & Slee, O.B., 1958. A high resolution radio telescope for use at 3.5m. *Proceedings of the Institute of Radio Engineers*, 46, 67–84.

Mills, B.Y., 1963. Cross-type radio telescopes. *Proceedings of the Institution of Radio Engineers Australia*, 24, 132–140.

Mills, B.Y., 2006. An engineer becomes astronomer. *Annual Review of Astronomy and Astrophysics*, 44, 1–15.

Nakamura, T., and Orchiston, W. (eds.), 2017. *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe.* Cham (Switzerland), Springer.

Orchiston, W., 2001. Focus on the history of Australian radio astronomy. *ATNF News*, 45, 12–15.

Orchiston, W., and Slee, B., 2002. Ingenuity and initiative in Australian radio astronomy: the Dover Heights hole-in-the-ground antenna. *Journal of Astronomical History and Heritage*, 5, 21–34.

Orchiston, W., 2004. The rise and fall of the Chris Cross: a pioneering Australian radio telescope. In Orchiston, W., Stephenson, R., Débarbat, S., and Nha, I-S. (eds.). *Astronomical Instruments and Archives From the Asia-Pacific Region*. Seoul, Yonsei University Press. Pp. 157–162.

Orchiston, W., Chapman, J., and Norris, B., 2004. The ATNF Historic Photographic Archive: documenting the history of Australian radio astronomy. In Orchiston, W., Stephenson, F.R., Débarbat, S., and Nha, I.-S. (eds). *Astronomical Instruments and Archives from the Asia-Pacific Region*. Seoul, Yonsei University Press. Pp. 41–48.

Orchiston, W., Slee, B., and Burman, R., 2006. The genesis of solar radio astronomy in Australia. *Journal of Astronomical History and History*, 9, 35–56.

Orchiston, W., and Kellermann, K.I., 2008. Bolton, John Gatenby. In *Dictionary of Scientific Biography*. New York, Gale. Pp. 332–337.

Orchiston, W., and Mathewson, D., 2009. Chris Christiansen and the Chris Cross. *Journal of Astronomical History and Heritage*, *12*, 11–32.

Orchiston, W., Steinberg, J.-L., Kundu, M., Arsac, J., Blum, É.-J., and Boischot, A., 2009. Highlighting the history of French radio astronomy. 4: Early solar research at the École Normale Supérieure, Marcoussis and Nançay. *Journal of Astronomical History and Heritage*, 12, 175–188.

Orchiston, W., Nakamura, T., and Strom, R. (eds.), 2011. *Highlighting the History of Astronomy in the*

Asia-Pacific Region: Proceedings of the ICOA-6 Conference. New York, Springer.

Orchiston, W., 2014a. Mills, Barnard Yarton. In Hockey et al., 1482–1484.

Orchiston, W., 2014b. Smerd, Stefan Friedrich. In Hockey, et al., 2019–2020.

Orchiston, W., Slee, B., George, M., and Wielebinski, R., 2015. The history of early low frequency radio astronomy in Australia: 4: Kerr, Shain, Higgins and the Hornsby Valley field station near Sydney. *Journal of Astronomical History and Heritage*, 18, 285–311.

Orchiston, W., 2016. *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits*. Cham (Switzerland), Springer.

Orchiston, W., 2017a. Cook, Green, Maskelyne and the 1769 transit of Venus: the legacy of the Tahitian observations. *Journal of Astronomical History and Heritage*, 20, 35–68.

Orchiston, W., 2017b. The early development of New Zealand radio astronomy. In Nakamura and Orchiston, 675–702.

Orchiston, W., and Ishiguro, M., 2017. The early development of Japanese radio astronomy. In Nakamura and Orchiston, 129–149.

Orchiston, W., and Robertson, P., 2017. The origin and development of extragalactic radio astronomy: the role of the CSIRO's Division of Radiophysics Dover Heights field station in Sydney. *Journal of Astronomical History and Heritage*, 20, 289–312.

Orchiston, W. and Slee, B., 2017. The early development of Australian radio astronomy: the role of the CSIRO Division of Radiophysics field stations. In Nakamura and Orchiston, 497–578.

Orchiston, W., and Wendt, H., 2017. The contribution of the Georges Heights experimental radar antenna to Australian radio astronomy. *Journal of Astronomical History and Heritage*, 20, 313–340.

Orchiston, W., and Swarup, G., 2018. The emergence of radio astronomy in Asia: opening a new window on the Universe. In Orchiston, et al., 185–210.

Orchiston, W., Sule, A., and Vahia, M. (eds.), 2018. *Growth and Development of Astronomy and Astrophysics in India and the Asia-Pacific Region. Proceedings of the 9th International Conference on Oriental Astronomy*. Mumbai, Tata Institute of Fundamental Research and the Hindustan Book Agency.

Pawsey, J.L., and Bracewell, R.N., 1955. *Radio Astronomy*. Oxford, Clarendon Press.

Pawsey, J.L., 1957. Letter to G. Swarup, dated 8 February. Original in the NCRA Library, Pune.

Pawsey, J.L., 1960. Letter to G. Swarup, dated 26 October. Original in the NCRA Library, Pune.

Pawsey, J.L., 1961a. Letter to G. Swarup, dated 18 April. Original in the NCRA Library, Pune.

Pawsey, J.L., 1961b. Letter to G. Swarup, dated 29 June. Original in the NCRA Library, Pune.

Pawsey, J.L., 1961c. Letter to Homi Bhahba, dated 6 October. Original in the NCRA Library, Pune.

Phakatkar, S., 2015. *Vidnyanyatri Dr. Govind Swarup* (*Biography of Dr. Govind Swarup*). Pune, Rajhans (in Marathi, the language of Maharashtra State).

Pick, M., Steinberg, J.-L., Orchiston, W., and Boischot, A., 2011. Highlighting the history of French radio astronomy. 6: The multi-element grating ar-rays at Nançay. *Journal of Astronomical History and Heritage*, 14, 57–77.

Robertson, P., 1992. *Beyond Southern Skies*: *Radio Astronomy and the Parkes Radio Telescope*. Cambridge, Cambridge University Press.

Robertson, P., 2017. *Radio Astronomer: John Bolton and a New Window on the Universe*. Sydney, NewSouth Publishing.

Robinson, B., 2002. Recollections of the URSI Tenth General Assembly, Sydney, Australia, 1952. *Radio Science Bulletin*, 300, 22–30.

Saikia, D.J., Konar, C., and Kulkarni, V.K., 2006. J0041+3224: a new double-double radio galaxy. *Monthly Notices of the Royal Astronomical Society*, 366, 1391–1398.

Schmidt, M., 1963. A star-like object with large redshift. *Nature*, 197, 1040.

Sinha, R.P., and Swarup, G., 1967. Radio studies of the quiet Sun at decimetre and metre wavelengths. *Proceedings of the Astronomical Society of Australia*, 1, 41–42.

Smerd, S.F., 1950. Radio-frequency radiation from the quiet Sun. *Australian Journal of Scientific Research*, A3, 34–59.

Sreekantan, B.V., 1998. Homi Bhabha and cosmic ray research in India. *Resonance*, 3(7), 18–27.

Sreekantan, B.V., 2006. Sixty years of the Tata Institute of Fundamental Research 1945–2005: The role of young men in the creation and development of this institute. *Current Science*, 90, 1012–1025.

Srinivasan, G., 2015. Govind Swarup: radio astronomer, innovator *par excellence* and a wonderfully inspiring leader. *Current Science*, 109, 618–630.

Stanier, H. M, 1950. Distribution of radiation from the undisturbed Sun at a wavelength of 60 cm. *Nature*, 165, 354–355.

Stanley, G.J., and Slee, O.B., 1950. Galactic radiation at radio frequencies. II. The discrete sources. *Australian Journal of Scientific Research*, A3, 234–250.

Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2010. The Radiophysics field station at Penrith, New South Wales, and the world's first solar radiospectrograph. *Journal of Astronomical History and Heritage*, 13, 2–15.

Stewart, R., Orchiston, W., and Slee, B., 2011a. The contribution of the Division of Radiophysics Dapto field station to solar radio astronomy, 1952–1964. In Orchiston et al., 481–526.

Stewart, R., Orchiston, W., and Slee, B., 2011b. The Sun has set on a brilliant mind: Paul Wild (1923–2008). In Orchiston et al., 527–542.

Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2011c. A retrospective view of Australian solar radio astronomy 1945 to 1960. In Orchiston et al., 589–629.

Sullivan, W.T. III, 1984. *The Early Years of Radio Astronomy: Reflections Fifty Years after Jansky.* Cambridge, Cambridge University Press.

Sullivan, W.T. III, 2009. *Cosmic Noise: An Early History of Radio Astronomy*. Cambridge, Cambridge University Press.

Sullivan, W.T. III, 2017. The beginnings of Australian radio astronomy. In Nakamura and Orchiston, 453–496.

Swarup, G., 1955. Proposed Investigation: Study of Solar Radiation Using a 2100 ft. long 32-element Interferometer to Operate Simultaneously at 60 cm and 1,8 m Wavelengths. Dated 23 January. Submitted to K.S. Krishnan, Copy in the NCRA Library, Pune.

Swarup, G., and Parthasarathy, R., 1955a. Evidence of limb-brightening of the Sun at 60cm wavelength. *Observatory*, 75, 8–9.

Swarup, G., and Parthasarathy, R., 1955b. Solar brightness distribution at a wavelength of 60 centimetres. I: the quiet Sun. *Australian Journal of Physics*, 8, 487–497.

Swarup, G., and Parthasarathy, R., 1958. Solar brightness distribution at a wavelength of 60 centimetres. II: localized radio bright regions. *Australian Journal of Physics*, 11, 338–349.

Swarup, G., Stone, P.H., and Maxwell, A., 1960. The association of solar radio bursts with flares and prominences. *Astrophysical Journal*, 131, 725–738.

Swarup, G., 1961. Letter to J. Pawsey, dated 25 July. Copy in the NCRA Library, Pune.

Swarup, G., and Yang, K.S., 1961. Phase adjustment of large antennas. *Institute of Radio Engineers, Transactions on Antenna and Propagation*, AP-9, 75–81.

Swarup, G., Thompson, A.R., and Bracewell, R.N., 1963a. The structure of Cygnus A. Astrophysical Journal, 138, 305–309.

Swarup, G., Kakinuma, T., Covington, A.E., Harvey, G.A., Mullaly, R.F., and Rome, J., 1963b. High resolution studies of ten solar active regions at wavelengths of 3-21 cm. *Astrophysical Journal*, 137, 1251–1267.

Swarup, G, Kapahi, V.K., Isloor, J.D., and Sinha, R.P. 1966a. High resolution studies of the Sun at a frequency of 612 Mc/s. In Daniel, R.R. (ed.), *Proceedings of the Ninth Symposium on Cosmic Rays, Elementary Particle Physics and Astrophysics; Bom-bay December 13–17, 1965.* Government of India. Pp. 774–781.

Swarup, G, Kapahi, V.K., Isloor, J.D., and Sinha, R.P. 1966b. Radio observations of the quiet Sun at 49 cm. *Nature*, 212, 910–911.

Swarup, G., Kundu, M.R., Kapahi, V.K., and Isloor, J.D., 1968. Some properties of the sources of slowly varying component and of bursts at 612 Mc/s. In Kiepenheuer, K.O. (ed.), *Structure and Development of Solar Active Regions. Symposium No. 35 Held in Budapest, Hungary, 4–8 September 1967*. Dordrecht, Reidel. Pp. 581–584.

Swarup, G., and Kapahi, V.K., 1970. A simple image forming technique suitable for multifrequency observations of solar burst. *Solar Physics*, 14, 404–413.

Swarup, G., Sarma, N.V.G., Joshi, M.N., Kapahi, V.K., Bagri, D.S., Damle, S.H., Ananthkrishnan, S., Balasubramanian, V., Bhave S.S., and Sinha, R.P. 1971a. Large steerable radio telescope at Ootacamund, India. *Nature*, 230, 185–188.

Swarup, G., Kapahi, V.K., Sarma, N.V.G., Krishna, G., Joshi, M.N., and Rao, A.P., 1971b. Lunar occultation observations of 25 radio sources made with the Oooty Radio Telescope: List 1. *Astrophysical Letters*, 9, 53–59.

Swarup, G., 1975. Angular size flux density relation for extragalactic radio sources. *Monthly Notices of Royal Astronomical Society*, 172, 501–512.

Swarup, G., Odhiambo, T.R., and Okoye, S.E., 1979. Report of a UNESCO Workshop on Proposals for an International Institute of Space Sciences and Electronics and Giant Equatorial Radio Telescope. Ootacamund, UNESCO. Pp. 103. Copy in the NCRA Library, Pune.

Swarup, G., 1981. Proposal for an International Institute for Space Science and Electronics and for a Giant Equatorial Radio Telescope as a collaborative effort of the developing countries. *Bulletin of the Astronomical Society of India*, 9, 269–277.

Swarup, G., 1984. The Ooty Synthesis Radio Telescope: first results. *Journal of Astrophysics and Astronomy*, 5, 139–148.

Swarup, G., 1986. The story of Ooty Radio Telescope. In Cowsik, R. (ed.). *Cosmic Pathways*. New Delhi, Tata McGraw Hill. Pp. 349–360.

Swarup, G., 1991. An international telescope for radio astronomy. *Current Science*, 60, 106–108.

Swarup, G., Ananthkrishnan, S., Kapahi, V K., Rao, A.P., Subrahmanyan, C.R., and Kulkarni, V.K., 1991a. The Giant Metrewave Radio Telescope. *Current Science*, 60, 95–105.

Swarup, G., Kapahi, V.K., Velusamy, T., Ananthkrishnan, S., Balasubramanian, V., Gopal-Krishna, Pramesh Rao, A., Subrahmanyan, C.R., and Kulkarni, V. K., 1991b. Twenty-five years of radio astronomy at TIFR. *Current Science*, 60, 79–94.

Swarup, G., 2006. From Potts Hill (Australia) to Pune (India): the journey of a radio astronomer. *Journal of Astronomical History and Heritage*, 9, 21–33.

Swarup, G., 2008. Reminiscences regarding Professor W.N. Christiansen. *Journal of Astronomical History and Heritage*, 11, 194–202.

Swarup, G., 2014. Growth and development of radio astronomy in India. In Padmanabhan, T. (ed.), *Astronomy in India: A Historical Perspective*. New Delhi, Springer. Pp. 73–110.

Swarup, G., 2017. The early development of Indian radio astronomy: personal perspective. In Nakamura and Orchiston, 815–839.

Thompson, A.R., 1961. Spectral observations of solar radio bursts. I. Receiving equipment. *Astrophysical Journal*, 133, 643–648.

Thompson, A.R., and Krishnan, T., 1965. Observations of the six most intense sources with a 1.0′ fan beam. *Astrophysical Journal*, 141, 19–33.

Thompson, A.R., 2010. The Harvard radio astronomy station at Fort Davis, Texas. *Journal of Astronomical History and Heritage*, 13, 17–27.

Thompson, A.R., and Frater, R.H., 2010. Ronald N. Bracewell: an appreciation. *Journal of Astronomical History and Heritage*, 13, 172–178.

Venkataraman, G., 1994. *Bhabha and his Magnificent Obsessions*. Hyderabad, Universities Press

Wang, S., 2017. The early development of Chinese radio astronomy: the role of W.N. Christiansen. In Nakamura and Orchiston, 245–254.

Wendt, H., Orchiston, W., & Slee, B., 2008a. The Australian solar eclipse expeditions of 1947 and 1949. *Journal of Astronomical History and Heritage,* 11, 71–78.

Wendt, H., Orchiston, W., and Slee, B., 2008b. W.N. Christiansen and the development of the solar grating array. *Journal of Astronomical History and Heritage*, 11, 173–184.

Wendt, H., Orchiston, W., and Slee, B., 2008c. W.N. Christiansen and the initial Australian investigation of the 21cm hydrogen line. *Journal of Astronomical History and Heritage*, 11, 185–193.

Wendt, H., Orchiston, W., and Slee, B., 2011a. An overview of W.N. Christiansen's contribution to Australian radio astronomy, 1948–1960. In Orchiston et al., 547–587.

Wendt, H., Orchiston, W., and Slee, B., 2011b. The contribution of the Division of Radiophysics Potts Hill field station to international radio astronomy. In Orchiston et al., 379–431.

Wendt, H., and Orchiston, W., 2018. The contribution of the AN/TPS-3 radar antenna to Australian radio astronomy. *Journal of Astronomical History and Heritage*, 21, 65–80.

Wild, J.P., and McCready, L.L., 1950. Observations of the spectrum of high-intensity solar radiation at metre wavelengths. Part 1. The apparatus and spectral types of solar bursts observed. *Australian Journal of Scientific Research*, 3, 387–398.

Wild, J.P., 1953. Investigation of Cygnus fluctuations at Dapto. Report dated 17 April. National Archives of Australia, 972807 Series: C3830-B2/2 Part 2.

Wild, J.P., and Roberts, J.A., 1956a. Regions of the ionosphere responsible for radio star scintillations. *Nature*, 178, 377–378.

Wild, J.P., and Roberts, J.A., 1956b. The spectrum of radio-star scintillations and the nature of irregularities in the ionosphere. *Journal of Atmospheric and Terrestrial Physics*, 8, 55–75.

Wild, J.P., Sheridan, K.V., and Trent, G.H., 1959. The transverse motions of the sources of solar radio bursts. In Bracewell, R.N. (ed.). *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press. Pp. 176–185.

Wild. J.P., 1980. The Sun of Stefan Smerd. In M.R. Kundu, M.R., and Gergely. T.E. (eds.), *Radio Physics of the Sun*. Dordrecht, Reidel. Pp. 5–21.

Professor Wayne Orchiston was born in New Zealand in 1943. He works at the National Astronomical Research Institute of Thailand in Chiang Mai, and is also an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 was founding Chairman of the IAU Working Group on Historic Radio Astronomy. Through James Cook University and the University of Southern Queensland he has supervised six PhD or Masters theses on historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, India, Japan, New Zealand and the USA. He also has published extensively on ethnoastronomy, the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroidal astronomy. In 2016 and 2017 Springer published his books, *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* and *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (co-editored by Tsuko Nakamura), both of which contain various chapters on early radio astronomy. At the moment, Wayne is working on a book about early Australian radio astronomy, co-authored by Peter Robertson and Woody Sullivan, and this will be published by Springer in 2020. Currently, Wayne is the President of IAU Commission C3 (History of Astronomy), and he is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*. He also is the Series Editor for Springer's books on Historical and Cultural Astronomy. In 2013 the IAU named minor planet 48471 Orchiston after him.

Sudhir Phakatkar worked at the GMRT from 29 years as a Technical Assistant in Electronics for Telescope Receiver system. Simultaneously he worked on popularizing science among students and laypersons. In the process, he wrote two books in the vernacular language (i.e. Marathi), one about the GMRT and the other a biography of Professor Govind Swarup. Sudhir writes on science and technology for Marathi newspapers, magazines and radio stations, and he works as a guide at the Khodad Rural Science Center.