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The growth of Radio Astronomy

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Abstract. I include a few aspects of the early history of radio astronomy from Karl Jansky and Grote Reber to the developments of radio telescopes and aperture synthesis imaging techniques with specific comments on the developments in India. 50 years ago this year quasars were discovered. It is also 50 years since the beginning of radio astronomy in India and the design of the Ooty lunar occultation telescope was triggered by the lunar occultation observation of the first quasar.

Keywords : radio astronomy: Jansky : aperture synthesis : India :quasars : SKA

1. Introduction

Woody Sullivan's definitive history of radio astronomy pre 1953 provides a comprehensive and insightful study of the emergence of this new branch of astronomy (Sullivan 2009). I will touch on just a few aspects of this history and then follow the developments of radio telescopes and aperture synthesis imaging techniques with specific comments on the early developments in India and the strong links to Australia. This review is limited to developments in continuum radio astronomy at metre and centimetre wavelengths.

In the course of trying to identify the source of interference to trans-Atlantic telephone communications Karl Jansky (1933), working at the Bell Telephone Laboratory, discovered cosmic radio emission. An unexpected source of noise was peaking each day but the peak signal arrived 4 min earlier each day and Jansky realised that it must have extraterrestrial origins. Reaction from Bell Labs was underwhelming and, as Grote Reber later remarked, "*so faint not even interesting as a source of radio interference!*" Once Jansky had determined that the interference was of extraterrestrial

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origin there was little support from the Bell Telephone Laboratory to further pin down the location in space. Sullivan (2009) has noted that while a few astronomers expressed interest, for the majority the world of decibels and superheterodyne receivers was too far removed from their world and Jansky had died before the importance of his discovery was appreciated.

In 1937 Reber built a 32 foot parabolic dish in Wheaton, Illinois and started looking for the radio signals discovered by Jansky. At first he looked at shorter wavelengths than used by Jansky since the only known emission mechanism was for thermal radio emission which would be stronger at shorter wavelengths. Nothing was seen at 3300 MHz or 900 MHz but finally at 160 MHz Reber (1940) detected cosmic static similar to that seen by Jansky. This radio emission was stronger at longer wavelengths so had to be non-thermal but there was no concept of non-thermal astronomical emission at the time. It was not until 10 years later that the synchrotron radiation mechanism was applied to astronomical radio sources (Alvén & Herlofson 1950).

2. The radio stars

Hey, Parsons & Phillips (1946) found a source of radio emission with intensity varying on time scales of seconds to minutes. They correctly concluded that the source must be small diameter. This was the first *radio star*. But what was it? There was no obvious optical counterpart for the strongest radio source in the sky and there was no known emission mechanism. Was the radio emission seen from the whole galactic plane made up of such stars?

In 1946 at Dover Heights near Sydney a telescope was constructed on the cliff to measure the interference between the direct waves and those reflected by the sea (a Lloyd's mirror). This cliff interferometer located the origin of the non-thermal solar radio emission and showed it was coming from sun spots (Pawsey, Payne-Scott & McCready 1946). It was also used to identify three of the brightest radio stars . One was a supernova remnant and two others were extragalactic (Bolton, Stanley & Slee) 1949). We will return to this discussion in Section 5.

3. Indirect imaging and the aperture synthesis radio telescopes

Because of the long radio wavelengths it was realised that interferometers with large separations between the elements would be required to obtain high enough angular resolution to determine the origin of the radio waves. Two of the main pioneering groups were at the University of Cambridge in the U.K., lead by Martin Ryle, and at the CSIRO (then CSIR) Division of Radiophysics in Sydney, Australia, lead by Joe Pawsey. Both groups used the WWII radar technology to build interferometers.

X-ray diffraction in crystals was discovered by von Laue (1914). Bragg (1929) suggested the use of Fourier methods to determine the crystal structure from the observed X-ray diffraction pattern. By 1939 Bragg's X-ray crystallography group was flourishing at the Cavendish Laboratory and this had a strong influence on the development of aperture synthesis in radio astronomy. The van Cittert-Zernike theorem (Zernike 1938) which is now considered the basis of Fourier synthesis imaging was published in the 1930s but it played no role in the early radio astronomy developments. It only appears in the radio astronomy literature after the publication of Born & Wolf's *Principles of Optics* in 1960.

3.1 Ratcliffe, Pawsey, Bhabha and the Cambridge links

Joe Pawsey from Australia did his PhD with Ratcliffe at Cambridge from 1934 to 1940. While in Cambridge Pawsey met Homi Bhabha and this friendship was a critical step towards the eventual formation of a radio astronomy group in India [Section 4]. In 1940 Pawsey returned to Australia and joined CSIRO Radiophysics Laboratory in Sydney but maintained strong links with Ratcliffe in Cambridge. By 1945 Pawsey was investigating radio emission from the sun. He introduced Bracewell to the duality of physical and mathematical descriptions following Ratcliffe's style and sent Bracewell to work with Ratcliffe in Cambridge. Bracewell later went to Stanford and eventually became Govind Swarup's supervisor.

3.2 Australian group

The first published suggestion that it would be possible to synthesise an image of the radio sky by measuring a range of Fourier components was made by Pawsey and Ruby Payne-Scott (McCready, Pawsey & Payne-Scott 1947). However, obtaining a range of spacings was impractical with the cliff interferometers they were using and changing frequency was not suitable for imaging solar bursts which were strongly variable in both time and frequency. The first observations using a range of Fourier components measured with an interferometer with moveable elements were made at the Cavendish Laboratory in Cambridge (O'Brien 1953). The sun is a strong and variable radio source so this required instantaneous measurements of many Fourier components but they could be made with small antennas. This lead the Australians down a different evolutionary path building arrays with a large numbers of relatively small elements. In 1951 Christiansen built the Potts Hill grating array with 32 6-foot diameter dishes near Sydney and the first 2D earth rotation synthesis image was obtained Christiansen & Warburton (1955). Chris noted: *"The way in which a 2D radio brightness distribution may be derived from a number of 1D scans is not obvious. However rather similar 2D problems have arisen in crystallography and solutions for these problems, using methods of Fourier synthesis have been found."* To make a 2D image of the quiet sun they took the 1D FT of each strip distribution providing a line of visibilities in the Fourier plane. They then drew contours of the visibility amplitude before making the 2D Fourier transform. In this way they had overcome the problem of correcting weights in back projections, see Section 4. Govind Swarup who was working in Christiansen's group in 1953 calculated the Fourier Transforms, taking more than 1 month using Lipson Beevers strips and an electronic calculator.

Wild (1967) later went on to build a 3 km diameter circle of 96 3-metre dishes which between 1967 and 1984 made moving images of the sun and resolved most of the questions about the nature of solar bursts.

3.3 Martin Ryle and the Cavendish Laboratory in Cambridge

In 1945 Ryle joined the Cavendish laboratory and used WWII radar technology for radio astronomy. Ryle & Vonberg (1946) were also making interferometric measurement of sunspots and introduced the use of a Michelson (1891) interferometer fringe visibility to measure the angular diameter of the source of the radiation.

After early experiments observing the sun Ryle's group in Cambridge moved their focus to the observation of "radio stars". These sources were static but much weaker than the sun so the arrays evolved along a different path with moveable antennas and earth rotation to build up the Fourier components over time and much larger elements to achieve the sensitivity required for the fainter sources (Ryle & Hewish 1960). In June 1961 an earth-rotation aperture synthesis image of the North pole using 4C aerials at 178 MHz was obtained by Ryle & Neville (1962). This evolution culminated in the construction of the One-Mile Telescope in 1963 . The use of this telescope and the later 5-kilometre aperture synthesis telescope to study the structure of radio galaxies was a great success and resulted in the award of the Nobel prize to Sir Martin Ryle in 1974.

3.4 Calculating the Fourier transforms

Computation of the Fourier transforms was a key technology for the development of aperture synthesis imaging. The use of Lipson-Beevers strips to calculate "large" 2D Fourier transforms, which had been introduced by the crystallographers (see Beevers & Lipson (1985)), was in common practise in 1953. A 25x25 array to 2 digits took 1 person 24 hours. Punched card tabulators provided an alternative automatic solution with a 25x25 array to 3 digits taking 8 hours but requiring 4 operators! In 1949 Wilkes had programmed the EDSAC I to do a 1D transform. In 1954 was used by Blythe (1957) and it took 15 hrs for 360 38 point transforms, however, it was not considered practical for radio astronomy at the time (Bracewell private communication). By 1958 EDSAC II was operating and was applied to Fourier inversion problems in both crystalography and radio astronomy at Cambridge. The Ryle and Neville (1962) North Pole image was a 240 x 240 pixel image and took a full night using EDSACII.

Wild (1965) invented J2 synthesis which involved the electronic summation of Bessel functions. This was able to produce a 60 x 48 dual polarisation 2D image from the solar heliograph every second in real time. In the same year the efficient implementation of the Fast Fourier transform algorithm was published by Cooley & Tukey (1965) and since then increasingly powerful general purpose digital computers have dominated the Fourier transform computations.

4. Radio astronomy in India

Swarup (2006) has provided detailed chronology of the development of radio astronomy in India, including the strong early links between India and Australia.

K.S. Krishnan (NPL) attended the 1952 URSI meeting in Sydney and became aware of the remarkable discoveries in radio astronomy. With his support Govind Swarup went to Australia on a Columbo Plan Fellowship and worked with the CSIRO radio astronomy groups from 1953-1955. During this period he met Homi Bhabha who was in Australia visiting his friend Joe Pawsey whom he had known since they were students in Cambridge in 1935. In 1955 CSIRO agreed to give to India the original Potts Hill array of dishes that Govind had used and these eventually became the Kalyan array.

In 1957 Swarup joined Bracewell, who was now at Stanford, to do his PhD. Stimulated by the difficulty of doing 2D Fourier transforms, see Section 3.2, Swarup suggested a back projection correction which was later published by Bracewell & Riddle (1967). This had a major impact on medical imaging; before this the analogue devices they used could not remove the "fog" due to over-weighting the short spacings.

In 1963 Homi Bhabha (TIFR) encouraged the expat Indians: Swarup, Menon, Kundu, and T. Krishnan, to return to India to form a radio astronomy group in India. Swarup returned and, motivated by the discovery of quasars based on a lunar occultation, proposed an equatorially mounted cylinder to do even fainter occultations. This is the Ooty Radio Telescope which became operational by 1970. It was extended to form the Ooty Synthesis Radio Telescope (OSRT) in 1984.

In 1971 Radhakrishnan started a new radio group at RRI with big ideas rather than big facilities. In 1976 Govind Swarup's conceived a Giant Equatorial Radio Telescope (GERT) involving India, Kenya, Nigeria, and Indonesia. This multinational project was too hard to pull together but it laid some of the foundations for the international SKA project. The Giant Metrewave Radio Telescope (GMRT) was proposed by Swarup in 1984, built in India and completed in 1996. Govind retired in 1994 and was succeed by Vijay Kapahi (deceased 1999) as second director of NCRA. With 30 45-metre dishes it now occupies a special niche for very high sensitivity at intermediate and lower radio frequencies (Swarup 1990).

5. Radio source identification and the discovery of quasars

Bolton, Stanley, Slee (1949) had identified the brightest two objects in the radio sky, Centaurus A and Virgo A, with external galaxies far outside our own Milky Way. This discovery lead to the eventual identification of the strongest of all the radio sources, Cygnus A. It was found to be a very faint galaxy so incredibly distant that it was immediately obvious that these new radio telescopes were probing the most distant reaches of the universe (Baade & Minkowski 1954).

Prior to 1963 the extragalactic radio sources were almost all identified with giant elliptical galaxies. The most distant known object in the Universe at that time was 3C295, identified with a faint elliptical galaxy with $z = 0.46$. This was all to be changed in a very unexpected way by the Lunar occultation of 3C273 using CSIRO's Parkes Observatory (Hazard, Mackey,& Shimmins 1963). The occultation showed a core and jet structure, clearly identifying it with a bright 13 magnitude star with a wisp (jet) of optical emission. Schmidt (1963) obtained an optical spectrum of the star and interpreted the lines as having a redshift of 0.158 , implying unprecedented optical luminosity from a very small volume.

This discovery of the QSOs was the trigger for the first Texas Symposium *Gravitational Collapse and Relativistic Astrophysics*, held in Dallas, Texas, 16-18 Dec 1963 (Robinson et al. 1964). Only a massive condensed object could provide the energy required from such a small volume and black holes rapidly emerged as the likely candidates. Subrahmanyan Chandrasekhar had argued the case for the existence of black holes as early as 1931 but their existence was not widely accepted until the discovery of quasars. When Chandra received the 1983 Nobel Prize the citation included *for his theoretical studies of the physical processes of importance to the structure and evolution of the stars. . . For the heaviest stars having a mass in excess of 2-3 Solar masses, the force of gravity becomes so strong that the matter simply disappears in the form of a so-called black hole*.

6. The large dishes

Grote Reber's dish was the forerunner of a series of ever larger and more precise parabolic dishes. A short summary of the world's largest cm dishes follows. For a more detailed and more complete summary see Ekers & Wilson (2013).

The 76m Lovell Telescope at Jodrell Bank has been an internationally renowned landmark in the world of astronomy. It has been operating since the summer of 1957. The Lovell telescope, used as an interferometer with small telescopes, found the small angular size radio sources that led to the identificaion of the quasars. The Parkes 64-metre parabolic dish, built in 1960 by the CSIRO Radiophysics group in Australia, observed the lunar occultation of 3C273, which was the first quasar (Hazard et al. 1963). In 1963 at Arecibo, Puerto Rico, the US constructed the largest single aperture reflecting dish ever built. This has a 1000 foot diameter but is a fixed spherical reflector with a moveable focus. Originally designed for prime focus with a line feed, it was modified to a Gregorian with a 22-metre correcting sub-reflector (Goldsmith 1996). The Max Planck Institute, 100-metre dish in Effelsberg near Bonn is a classical steerable parabolic dish completed in 1972. The Robert C. Byrd 100-metre Green Bank Telescope (GBT), replacing an older transit dish, is the last of the giant dishes to be built. It commenced operation in 2000. Unlike its predecessors, the GBT is an off-axis segment of a parabola with offset focus (both prime and Gregorian) which provides an unblocked aperture for high efficiency and minimum spectral ripple.

7. The major centimetre radio telescope arrays

Professor Jan Oort was so impressed by the Cambridge image of the North Pole that he initiated the Benelux Cross Project (1958) to use the radio astronomy source counts for cosmology. The design was drastically modified under the influence of Jan Hogbom, a recent PhD graduate from Ryle's group in Cambridge, and Chris Christiansen, from CSIRO in Sydney. The Benelux Cross was transformed into the Westerbork Synthesis Radio Telescope (WSRT) which was opened in 1970.

A huge step forward in sensitivity was the US constructed VLA which was formally inaugurated in 1980 (Napier, Thompson & Ekers 1983). The VLA has been the most productive ground based telescope ever built at any wavelength in both its number of publications and number of citations. After 30 years with only minimal upgrades the VLA has had a major upgrade and the JVLA is now coming into operation with 5 to 20 times the sensitivity, almost complete frequency coverage, and greatly enhanced spectral capability. This illustrates the impact of improved technology even though the collecting area has not changed (Perley et al. 2011).

The Australian Telescope Compact Array (ATCA), opened in 1988, has 6 22-metre moveable dishes and a 6 km baseline (Frater, Brooks & Whiteoak 1992). It is the premier Southern Hemisphere aperture synthesis telescope. Although it has only modest collecting area it now has multiple simultaneous frequencies extending up to 100 GHz, very wide bandwidth (8 GHz) and low system temperature (Wilson et al. 2011). Finally, we have the GMRT, already discussed in Section 4.

8. Future developments - the SKA and its precursers

8.1 Origin of the SKA

The following summary emphasises the Indian involvement in the genesis of the SKA. For a more detailed discussion see Ekers (2013) and Noordam (2013).

Between 1988 and 1990 Robert Braun, Ger de Brujn and Jan Noordam proposed a

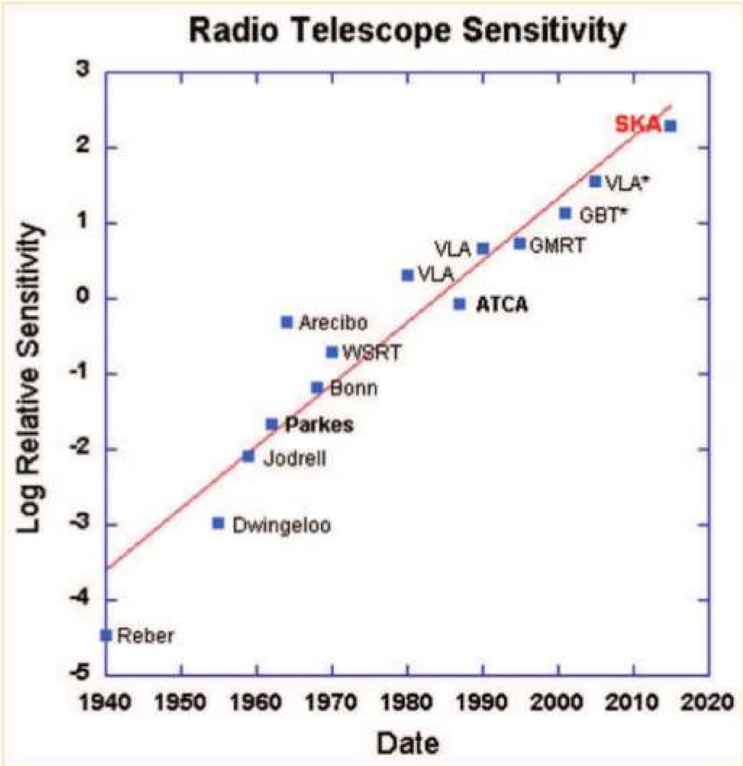

Figure 1. Radio Telescope Sensitivity vs. time. Points are the relative continuum sensitivity when the telescopes were built, or after major upgrades. VLA* is the JVLA upgrade. SKA is the proposed sensitivity for a telescope which has not yet been built.

Dutch extragalactic HI telescope. Their key idea was to build a telescope with enough collecting area to detect HI at high redshift. Independently, but at about the same time, Govind Swarup in India was already planning a next generation cm radio telescope based on the GMRT (Swarup 1990). Swarup (1991) proposed an International Radio Astronomy telescope (ITRA) with 160 75m dishes, centrally concentrated with baselines up to 200km.

IAU colloquium 131, *"Radio-Interferometry"*, was held in New Mexico, USA, 8 October 1990, to celebrate the first 10 years of observations with the VLA. Many ideas for a future telescope came together and the international SKA project was born (Wilkinson 1991).

Figure 1 plots the point source continuum sensitivity of telescopes used for radio astronomy since the first discovery of extra-terrestrial radio emission in 1940. It has been exponential with an increase in sensitivity of 10^5 since 1940, doubling every three years. The growth of radio astronomy facilities has been exponential but how do we maintain this exponential growth? If the improvement in sensitivity has reached a ceiling the rates of new discoveries will decline and the field will stagnate. On the other hand, if we can shift to new technology or find new ways to organize our resources the exponential increase in sensitivity can continue (Ekers 2010).

8.2 The new era of low frequency arrays

Radio astronomy started with telescopes operating at the lower radio frequencies but ionospheric irregularities and the inflexibility of the analogue beam forming electronics, which were the only way to combine the array elements at the time, limited their imaging capability. The improvements in high speed computing have dramatically changed the situation and a number of new low frequency arrays are now being brought into operation. Most notable is the just completed European LOFAR (Vermeulen 2012) array centred in the Netherlands and the international Murchison Widefield Array (MWA) (Tingay et al. 2013) located in the radio-quiet Western Australia outback which is now in its final commissioning phase. We will hear much more about these two new telescopes during this meeting.

8.3 The Square Kilometre Array (SKA) project

The SKA is the next generation radio telescope with a total collecting area of approximately one square kilometre, a frequency range from 70MHz to 25GHz and baselines up to at least 3,000 km from a concentrated central core. The SKA will be built in the Southern Hemisphere, partly in South Africa and partly in Western Australia. The design will use aperture array technology for the lower frequencies and arrays of dishes at the higher frequencies. To provide a square kilometre of aperture at an acceptable cost, the SKA must make a revolutionary break with current radio telescope design. Some aspects of the technology needed are still in the development stage and the new low frequency arrays and the SKA precursors ASKAP and Meerkat are now exploring the key technologies.

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