Radio Astronomy and the rise of high energy astrophysics: Two anniversaries

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This essay celebrates the 100th anniversary of the birth of Martin Ryle and the 50th anniversary of the discovery of pulsars by Jocelyn Bell and Antony Hewish. Ryle and Hewish received the 1974 Nobel Prize in Physics, the first in the area of astrophysics. Their interests strongly overlapped, one of the key papers on the practical implementation of the technique of aperture synthesis being co-authored by Ryle and Hewish. The discovery of pulsars and the roles played by Hewish and Bell are described. These key advances were at the heart of the dramatic rise of high energy astrophysics in the 1960s and led to the realisation that general relativity is central to the understanding of high energy astrophysical phenomena.

Keywords: Martin Ryle, Antony Hewish, Jocelyn Bell-Burnell, earth-rotation aperture synthesis, high energy astrophysics, radio sources, neutron stars, supermassive black holes

1. Two Anniversaries

2018 is a cause for celebration in the high energy astrophysical community. The two anniversaries are the centenary of the birth of Martin Ryle (1918-1984) and the 50th anniversary of the announcement of the discovery of pulsars in 1968, associated with the names of Antony Hewish and Jocelyn Bell-Burnell. They were all members of the Radio Astronomy Group in the Cavendish Laboratory. I was present as a graduate student and research fellow through the exciting period from 1963 to 1970.

Martin Ryle and Antony Hewish were awarded the Nobel Prize in Physics in 1974, the first to be awarded in astrophysics. The citation reads:

> 'for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars.'

Their experimental work was central to the realisation that high energy particles and strong magnetic fields play a major role in modern astrophysics and that general relativity is essential in order to understand high energy astrophysical phenomena.

2. The Origins of Radio Astronomy and the Impact of the Second World War

The story begins in 1933 with the discovery of radio waves from our Galaxy by Karl Jansky who was working at the Bell Telephone Laboratories.[1] The discovery arose from the need to understand sources of radio interference in radio communications. Grote Reber followed up Jansky's discovery with his own home-made radio telescope. By 1940, he had succeeded in making the first map of the radio emission from the Galaxy, the results being published in the *Astrophysical Journal.*[2] Little attention was paid to this work by professional astronomers. The only paper was a discussion which showed that the spectrum of the radiation found by comparing Jansky's and Reber's intensity measurements could not be the thermal emission of hot gas clouds.[3]

Immediately after the Second World War, astronomy was about to be changed out of all recognition as compared with the pre-War era. The contributory causes can be summarised as follows:

- The opening up of the whole of the electromagnetic spectrum for astronomical observation was facilitated by huge advances in radio and electronic techniques as well as by the availability of rockets from which observations could be made from above the Earth's atmosphere.
- Investment in pure science increased dramatically as the benefits of basic research for defence purposes and for the benefit of society were appreciated.
- Scientific electronic computation began in earnest and would provide the means for advancing all scientific disciplines dramatically.
- Astronomy became one of the 'Big Sciences'.

These all contributed to many of the great and unexpected astronomical discoveries of the succeeding years.[a]

After the Second World War, a number of University Groups began to investigate the nature of the cosmic radio emission discovered by Jansky. The principal groups involved were at Cambridge, Manchester and Sydney, all of them led by scientists who came from a background in radar. The science of radio communication and detection developed at a great pace during the War under the combined pressures of defending the UK from incoming enemy aircraft and rockets and developing air-borne radar and radio location techniques. The Cambridge efforts were led by Martin Ryle who assembled a brilliant team of young physicists to attack these problems. The Radio Astronomy Group was remarkably tight-knit and everyone contributed to the various technical challenges.

Two of these were of particular importance. The first was the need to achieve higher angular resolution and sensitivity of the antennae and receiver systems. The second was the need to understand the origin and nature of the 'twinkling' or 'scintillation' of the radio sources. Ryle and Hewish worked on both problems, as can be appreciated from a list of some of their joint papers.

[a]For more details, see my book *The Cosmic Century: A History of Astrophysics and Cosmology.* Cambridge: Cambridge University Press (2006). For the high energy astrophysical aspects of the story, see also my book *High Energy Astrophysics: third edition.* Cambridge: Cambridge University Press (2011).

Fig. 1. The Cambridge Radio Astronomy Group in the early 1950s. Those seated in the middle row are (left to right) Francis Graham Smith, Martin Ryle and Antony Hewish. (Courtesy and copyright the Cavendish Laboratory, University of Cambridge.

- Ryle, M. and Hewish, A. (1950), The Effects of the Terrestrial Ionosphere on the Radio Waves from Discrete Sources in the Galaxy.[4]
- Ryle, M. and Hewish, A. (1955), The Cambridge Radio Telescope.[5]
- Ryle, M. and Hewish, A. (1960), The Synthesis of Large Radio Telescopes.[6]
- Scott, P. F., Ryle, M. and Hewish, A. (1961), The First Results of Radio Star Observations using the Method of Aperture Synthesis.[7]

Immediately after the Second World War, there was very little money, but Ryle and his colleagues were able to make very good use of surplus war equipment, including high quality radio antennae, a large amount of coaxial cable and other items brought back to the UK as German war booty. It was quickly understood that the way to achieving the goals of higher angular resolution and greater sensitivity was to use radio interferometry and, in particular, to implement the techniques of aperture synthesis in which both the amplitude and phase of the interferometric observations are preserved. Martin Ryle's contribution of genius was the practical implementation of Earth-rotation aperture synthesis which resulted in both high angular resolution and high sensitivity images of the radio sky.

Optical telescopes reflect the light of a distant object from a parabolic mirror which has the property that the signals from a distant object reflected from all parts of the mirror surface travel the same distance to the focus. The radio astronomers realised that the reflecting surfaces do not need to be part of the same surface. If the path lengths to the focus from the source are the same, the interferometric data provide the necessary amplitude and phase information to begin the reconstruction of the image on the sky. To ensure that the waves travel the same distance, delay lines needed to be introduced so that the signals from the two telescopes were combined in phase. Increasing the number of antennae increases the number of possible pairings of antennae, the short baselines providing the large-scale structure and the long baselines the fine detail.

These techniques were exploited in a series of radio interferometers constructed, first of all, at the Rifle Range site just behind the Cambridge University Rugby Ground and then at the Lord's Bridge Observatory which was opened in 1957 once the full significance of radio astronomy for astrophysics and cosmology had become apparent. Radio astronomy hit the headlines in 1955 with the first results of the Second Cambridge (2C) Survey. The dramatic result was that there is a large excess of extragalactic radio sources at large distances, implying that these objects had evolved strongly with cosmic epoch. This was initially a controversial result but it led to the need for deeper surveys and the continued development of radio interferometric techniques. The first large interferometer on the Lord's Bridge site was the 4C radio telescope completed in about 1960. The surveys of the Northern sky carried out by the telescope showed convincingly the evolutionary nature of the radio source population. These radio surveys were carried out with fixed telescopes which mapped the sky by allowing the Earth's rotation to provide a scan of the sky above the telescope.

To sample the two-dimensional structure of the sources, Ryle and his colleagues pioneered the concept that it is simplest to build a one-dimensional interferometer and then use the Earth's rotation to carry one telescope about another as viewed from a point on the sky. In this way information is obtained corresponding to the annulus of a large telescope with diameter equal to the maximum separation of the elements of the interferometer. By adding together a number of baselines with different spacings, the equivalent of a single large telescope with diameter equal to the longest baseline separation can be synthesised with much improved sensitivity. Ryle and Ann Neville used the 4C telescope system in 1962 to create the first fully two-dimensional map of a region about the North Celestial Pole using the Earth-rotation synthesis technique.[8] Every available receiver in the Observatory was needed to make the observations.

The implementation of fully-steerable aperture-synthesis radio telescopes was realised with the construction of the Cambridge One-Mile Telescope (OMT). It required a great deal of innovation in electronics, path compensation and computation. The new generation of electronic computers, the Cambridge EDSAC-1 and 2 machines, was essential to carry out the Fourier transforms to convert the interferometric data into two-dimensional maps. The Fast Fourier transform was implemented to make these computations feasible in a reasonable time.

Fig. 2. The Cambridge One-Mile Telescope, the world's first fully-steerable, general purpose, Earth-rotation aperture synthesis radio telescope.

In 1965, the first radio images from the One-Mile Telescope, the world's first fully-steerable, general purpose, Earth-rotation aperture synthesis radio telescope (Fig. 2), were made of the radio galaxy Cygnus A and the supernova remnant Cassiopaeia A.[9] I was there in the EDSAC control room when the first maps came out of the computer printer. The next step was to extend these techniques to higher frequencies with larger numbers of telescopes and this was achieved with the 5-kilometre (Ryle) in the early 1970s. This resulted in much higher angular resolution and sensitivity. The success of these telescopes led to the construction of even more powerful instruments such as the Very Large Array in the USA.

It is remarkable that over the 25 year period from the end of the Second World War, the sensitivity of radio astronomical observations increased by a factor of about one million and the imaging capability of the telescope system improved from several degrees to a few arcseconds, comparable to that of ground-based optical telescopes. This was Martin Ryle's legacy to radio astronomy. After 1972, his health declined and his interest changed to wind power, sustainability and opposition to nuclear power.

The major impact of radio astrophysics upon astrophysics and cosmology in general cannot be overstated. The discovery of Galactic and extragalactic radio sources revealed the importance of relativistic astrophysics for astronomy in general. To summarise the change of perspective:

- Enormous energies in relativistic particles and magnetic fields were needed to account for the synchrotron radio emission of the radio sources and involved the conversion of $10^6\, M_\odot c^2$ of mass into these forms of energy, at the same time ejecting them far beyond the confines of the host galaxy.
- The role of relativistic jets in powering the huge energies in relativistic particles and magnetic fields became apparent.
- The discovery of the quasars and the BL-Lac objects opened up quite new challenges for the astrophysics of these objects in all wavebands.
- The extreme variability of some of the quasars and BL-Lac objects led to the realisation that supermassive black holes had to be involved in the most extreme active galactic nuclei.
- Evidence for the cosmological evolution of extragalactic radio sources, both radio galaxies and quasars, showed that major changes had taken place in the properties of these objects over the last 75% of the age of the Universe.

These discoveries were first reviewed internationally at the first Texas Symposium on *Relativistic Astrophysics* held in Dallas, Texas in 1963. At the closing dinner, Thomas Gold remarked:

> 'Everyone is pleased: the relativists who feel they are being appreciated, who are suddenly experts in a field which they hardly knew existed; the astrophysicists for having enlarged their domain, their empire by the annexation of another subject - general relativity.'

This was the beginning of high energy astrophysics in its modern guise.

3. The Discovery of Pulsars

The discovery of pulsars in 1967 is associated with the names of Antony Hewish and Jocelyn Bell-Burnell, but the seeds of their achievement were sown long before during the immediate post-War years. During that period, part of Hewish's research involved understanding the nature of the scintillations of the intensities of radio sources caused by intervening moving plasma clouds. Just as stars twinkle even on the clearest nights, so point sources of radio emission are observed to scintillate, particularly at long radio wavelengths. Their cause is the deflections of radio rays when they pass through irregularities in the ionospheric plasma.

The theory of the process of scintillation was worked out in detail by Hewish in 1951 in a paper entitled 'The diffraction of radio waves in passing through a phase-changing ionosphere'.[10] The paper set out the theoretical background needed to understand the short-term fluctuations in the intensities of radio sources due to irregularities in an ionised plasma. The same concepts could be used to understand the physics of fluctuations due to ionospheric, interplanetary and interstellar electron density fluctuations. This theoretical paper was followed in 1952 by another entitled 'The Diffraction of Galactic Radio Waves as a Method of Investigating the

Irregular Structure of the Ionosphere'.[11] Applying these concepts to observations of the fluctuating radio signals, Hewish showed that the scale of the irregularities ranged from 2 to 10 km, that the variation of the electron content was about 5×10^9 electrons cm^{-2} and that the irregularities are at a height of about 400 km. These irregularities moved with a steady wind-like motion at a velocity of the order 100 to 300 m s^{-1}.

The same technique could be used to study the solar corona, the region of hot plasma surrounding the Sun. The radio source Taurus A (the Crab Nebula) was observed at varying angular distances from the Sun and the variability of the signal could be accounted for by scattering because of the presence of fluctuations of the electron density in the solar corona. In his paper of 1955 'The Irregular Structure of the Outer Regions of the Solar Corona', Hewish derived the sizes and electron densities of coronal irregularities in the distance range 5 to 15 solar radii.[12]

In 1954, Hewish had remarked in his notebooks that, if the angular sizes of the extragalactic radio sources were small enough, they would illuminate the solar corona with a coherent radio signal and so give rise to rapid time variations in their intensities. This idea was forgotten until about 1962 when Margaret Clarke showed that two of the compact 3CR radio sources ($\theta \lesssim 2$ arcsec) varied very rapidly in intensity. Hewish realised that his old idea was the answer.

By 1964, a number of radio quasars were known and some of these radio sources had small angular sizes. With Paul Scott and Derek Wills, Hewish showed that the radio scintillations were due to scattering of the radio waves by inhomogeneities in the ionised plasma flowing out from the Sun, the Solar Wind. This wind had been predicted by Eugene Parker in 1958 and observed by the Soviet Luna satellites in 1959 and by the US Mariner-2 satellite in 1962. The paper by Hewish, Scott and Wills showed how radio source scintillations could be used to map the outflowing Solar Wind.[13]

Hewish realised that a large, low-frequency array dedicated to the measurement of the scintillations of compact radio sources would provide a new approach to the study of three important astronomical areas:

- it would enable many more quasars to be discovered,
- their angular sizes could be estimated,
- the structure and velocity of the Solar Wind could be determined.

In 1965, he designed a large array to undertake these studies and was awarded a grant of £17,286 by the UK Department of Scientific and Industrial Research to construct it, as well as outstations for measuring the velocity of the Solar Wind. To obtain adequate sensitivity at the low observing frequency of 81.5 MHz (3.7 m wavelength), the array had to be large, 4.5 acres (1.8 hectares) in area, in order to record the rapidly fluctuating intensities of bright radio sources on time-scales as short as one tenth of a second.

Jocelyn Bell joined the 4.5 acre array project as a graduate student in October 1965. She was involved in the construction of the telescope, including knocking the posts into the ground, and then became responsible for the network of cables connecting the dipoles. The telescope was commissioned during July 1967 with the objective of mapping the whole sky once a week so that the variation of the scintillation of the sources with solar elongation could be studied. The array consisted of 2,048 full-wave dipoles arranged in 16 rows of 128 elements. Each row was 470 m long and the north-south extent of the array was 45 m.

A key aspect of the array was that it had to measure the fractional scintillations of the radio sources in real time. Before the days of high speed digital computers, this was achieved by electronic processing of the incoming signals. On a strip chart, the top trace showed the intensity of the source as it passed through the beam of the telescope. This signal was then passed through a high-pass filter so that only the fluctuating component was registered in the middle trace, from which the noise power in the fluctuating component could be displayed in the bottom trace.

While the array was being constructed, Leslie Little and Hewish carried out a theoretical investigation of the strength of the scintillations as a function of heliocentric coordinates. They demonstrated how the angular sizes of the sources could be estimated from measurements of the amplitudes of the scintillations when sources were observed at different solar elongations.[14] A key point was that the scintillations decrease to very small amplitudes when observed at large angles from the Sun.

The commissioning of the 4.5 acre array proceeded through the summer of 1967. Hewish suggested that Bell create sky charts for each strip of the sky each day, noting all the scintillating sources. If the scintillating sources were present on successive weeks at the same astronomical coordinates, they were likely to be real sources, whereas if they were simply interference, for example caused by a nearby unsuppressed tractor or motorcycle, they would not recur at the same astronomical coordinates. This was a very demanding task requiring great persistence, patience and attention to detail on Bell's part since she had to keep up with the very high rate at which the charts were being produced by the telescope, over 200 metres per week.

The discovery of the pulsar CP 1919 was made by Bell on 6 August 1967, the story of the discovery being contained in Appendix 1 of her PhD dissertation. The remarkable feature of CP1919 was that the source scintillated at roughly the 100% level in the anti-solar direction, quite contrary to the expectations of the scintillation models of Little and Hewish. Furthermore, the source was highly variable and not always present. It was not observed again until 28 November 1968, this time with a much short time-constant in the receiver system – the pulses were detected separately for the first time. To everyone's astonishment, the signal consisted entirely of a sequence of pulses with repetition period 1.33 sec, the period being stable to better than one part in 10^6.

The following two months were what Hewish described as the most exciting of

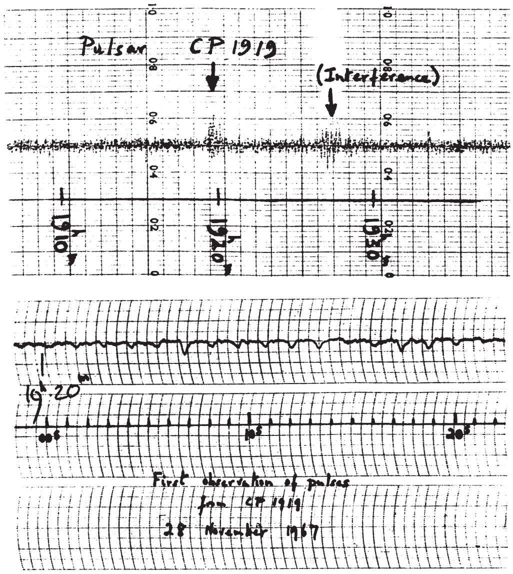

Fig. 3. The discovery record of CP 1919 taken on 6 August 1967. (Courtesy and copyright the Cavendish Laboratory, University of Cambridge and Churchill College Archives.)

his scientific career. Nothing like this had been observed in astronomy before and Hewish and his colleagues had to be absolutely certain of the correctness of the observations. It was essential to carry out follow-up observations and experiments:

- All sources of terrestrial inference had to be excluded.
- If the source was associated with extraterrestrial emissions, including the notorious 'Little Green Men (LGM)', the motion of a planet about the parent star would be easily detectable. The motion of the Earth about the Sun was observed, but no orbital motion of the source.
- The low frequency signals displayed dispersion, the high frequency signals arriving earlier than the low frequencies. This enabled a rough distance of 65 parsec (about 200 light years) to be estimated for the source.
- Three other similar sources were discovered by Bell including one with a period of only 0.25 seconds.

The discovery was kept under tight wraps until Hewish and his colleagues were absolutely convinced that they had discovered a new type of astronomical phenomenon. I was in the next door office to Hewish at the time and I knew nothing about what was going on until he gave a lecture about the discovery in the week before the *Nature* paper was published. The paper 'Observation of a Rapidly Pulsating Radio Source' was submitted for publication in *Nature* on 9th February 1968 and published on 24th February 1968.[15]

Within a few months, Thomas Gold convincingly associated the pulsars with magnetised, rotating neutron stars.[16] The radio pulses are caused by beams of very high energy particles emitting coherent radiation of extraordinarily high brightness temperature escaping from the poles of a magnetised rotating neutron star. When the beam passes across the line of sight to the observer, an intense burst of radio emission is observed.

Very soon after the discovery, large numbers of pulsars were discovered. By now, well over 2000 radio pulsars are known and they are of the greatest astrophysical importance as the last stable stars before collapse to a black hole ensues. The neutron stars represent matter in bulk at nuclear densities and offer many challenges for physicists and astrophysicists. Perhaps most significant was the fact that relativistic stars really exist in nature — general relativity is essential in working out their stability.

In 1972, neutron stars were discovered as the compact X-ray emitting sources in X-ray binary systems by Riccardo Giacconi and his colleagues from observations with the UHURU X-ray observatory.[17] In these sources, the energy source is the accretion of matter from the normal primary star onto the poles of the neutron star.

In 1975, Russell Hulse and Joseph Taylor discovered that the pulsar PSR 1913+16 is a member of a binary neutron star system.[18] This was a fabulous gift to relativists since it can be considered to be a perfect clock in a rotating frame of reference. The binary neutron star system loses energy by the radiation of gravitational waves and one of the great discoveries was the measurement of the speeding up of the binary due to this process. The remarkable agreement between theory and experiment shows that general relativity is the best theory of relativistic gravity we possess.

The discovery of the pulsars resulted in the award of the Nobel prize to Hewish in 1974. Hewish continued his research on the use of the scintillation technique to chart 'interplanetary weather', work which is of the considerable importance because of its impact upon the GPS system. Bell went on to become a distinguished member of the UK scientific community and has received many awards recognising her role in the discovery of pulsars, most recently the $3 M Special Breakthrough Prize in Fundamental Physics in 2018 — she has generously donated this remarkable prize to the Institute of Physics to support research studentships. In June 2007, she was created Dame Jocelyn Bell-Burnell in the UK honours list. She has been President of the UK Institute of Physics and of the Royal Society of Edinburgh. She has recently been appointed Chancellor of the University of Dundee.

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