ANTONY HEWISH

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Elected FRS 1968

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Antony (Tony) Hewish was a pioneer radio astronomer who will always be remembered as the leader of the team in 1967 that discovered the pulsars, which proved to be rapidly rotating, magnetized neutron stars. The discovery resulted from Tony’s programme of systematic all-sky surveys to detect the scintillation, or flickering, of small angular diameter radio sources due to electron density fluctuations in the solar wind flowing out from the Sun. The large low-frequency 4.5-acre array was designed by Tony to find radio quasars, which often display radio scintillations, to estimate the angular sizes of the sources and to study the physics of the interplanetary medium. In the course of commissioning the telescope, his research student, Jocelyn Bell (Jocelyn Bell Burnell, FRS 2003), noted a strange 100% scintillating source unlike anything seen before. Tony and the team soon established that this source was a pulsating radio source, Jocelyn first observing the pulsations with period 1.33 s in November 1967. The discovery paved the way for the rapid development of high energy astrophysics and an appreciation that general relativity plays a key role in the stability of neutron stars. Tony’s contributions spanned a very wide range of pioneering studies in the new discipline of radio astronomy, including telescope and electronic design, cosmological studies of distant radio sources and the physics of the ionospheric, interplanetary and interstellar plasmas. He was awarded the 1974 Nobel Prize in physics for ‘his decisive role in the discovery of pulsars’.

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Antony (Tony) Hewish was born on 11 May 1924 at Fowey, Cornwall. His father, Ernest William Hewish, was manager of Barclay’s Bank at Fowey and then promoted to manager at Newquay, also in Cornwall, where he remained until his retirement. Tony’s grandfather was a draper in Barnstaple and his forebears were well-to-do farmers. His mother, Grace Frances Lanyon Pinch, was the daughter of a Cornish farmer. Tony was the youngest of three brothers; the eldest, Paul, was born in 1918, followed by John in 1921.

Tony recalled a wonderful childhood on the Cornish coast with the freedom to roam from a tender age—rough-riding bikes along cliff paths, spinning for mackerel from a rowing boat and building a canvas canoe with his brother John, his constant companion, which was much used on the nearby Gannel estuary. Other activities included surfing, deep-water swimming in secret coves, beachcombing after gales and so on. John and Tony were encouraged to learn carpentry and model-making and also experimented with fireworks, mixing gunpowder using ingredients from the local chemist. From his earliest years Tony was fascinated by electricity and enjoyed playing with circuits and torch bulbs; an attempt at electrolysis using mains power obtained from a light switch was disastrous and blacked out their home above the bank, as well as the bank itself on the ground floor. He believed that this freedom to find out for himself helped develop an independence of spirit for experimental work that was good preparation for his later career.

After private primary school in Newquay, followed by two years at Newquay County School, John and Tony were sent to King’s College, Taunton, in 1936. Tony regarded his time at the college as moderately enjoyable, but undistinguished as he was not an athlete and of too light a build to make a good hooker in a rugby scrum. After passing his Higher School Certificate in physics, chemistry and mathematics, his physics master suggested that he apply to Gonville and Caius College, Cambridge, where he himself had been a student. Tony was accepted by the college to read for the Natural Sciences Tripos, and subsequently matriculated in October 1942.

At that time, in the middle of World War II, there was an urgent need for scientists for wartime work in radar and radio communications, and bursaries were available to fund two years at university. A new course ‘Physics with Radio’ had been devised, which counted as two experimental sciences, and so Tony took this together with chemistry and mathematics as his Natural Sciences Tripos package. He confessed that he spent too much time rowing, stroking the college second boat, and also spending weekends doing army training with the Senior Training Corps. He ended the year with a third class degree in the preliminary examination and was then drafted into war service at the Royal Aircraft Establishment (RAE) Farnborough. During the long vacation (summer) term of 1943, he attended a crash course on electronics, including soldering, at the Cambridge Engineering Department and joined the RAE in September of that year.

Like many of the future leaders of physics and engineering in the UK, Tony’s wartime experiences of research and development were to have a strong influence on his future career path. Early in 1944, Tony was seconded to the Telecommunications Research Establishment (TRE), then based at Malvern College, Worcestershire, and immediately attended two weeks of lectures on radar techniques. This course had been designed by J. A. (Jack) Ratcliffe (FRS

THE WAR YEARS

Like many of the future leaders of physics and engineering in the UK, Tony’s wartime experiences of research and development were to have a strong influence on his future career path. Early in 1944, Tony was seconded to the Telecommunications Research Establishment (TRE), then based at Malvern College, Worcestershire, and immediately attended two weeks of lectures on radar techniques. This course had been designed by J. A. (Jack) Ratcliffe (FRS
Antony Hewish

1951), who was a lecturer in the Cavendish Laboratory’s Radio Group and was one of the first specialists in electromagnetic theory and experiment to be seconded to the TRE. Tony joined Ratcliffe’s Post Design Services group (PDS).

New equipment was being introduced to the RAF so rapidly that there was no time to organize specialist training courses. Instead, members of the PDS group worked alongside the scientists who designed the prototypes, then joined the manufacturers responsible for production versions, and finally spent time at the RAF stations where the equipment was first used. They oversaw the installation of the equipment and trained the ground crews in their maintenance. Tony was assigned to ‘Airborne Grocer’, a 50 cm radar jammer against German night fighters. Martin Ryle (FRS 1952), the future head of the Cambridge Radio Astronomy Group, was head of the design team and this is where Tony and Martin first met. After production at GEC Wembley, the devices were installed at RAF Oulton, a Bomber Command station near Norwich used by 100 Group, which flew American B-17s, the famous ‘Flying Fortresses’. Tony insisted that flight tests were required to check the tuning and he had some exciting flights over East Anglia while the pilots practised evasive action. Airborne Grocer was mounted at the tail of the aircraft and consisted of four Yagi antennae radiating noise signals directed rearwards. He recalled how checking the radiation pattern of the antennae on the ground required crouching in the slipstream of the Flying Fortress ‘while bombarded with gravel, dead rabbits, etc.’ (42)*.

Returning to the RAE in late 1944, Tony rejoined the radio group and became involved with Sonobuoy, a submarine tracking device in which floating transmitters attached to submerged hydrophones were dropped successively to mark the course of the submarine. Initial trials were made at a swimming pool in West Kirby and later off the south coast, where he enjoyed outings in an Air–Sea Rescue launch, based at Newhaven, to monitor the action of Sonobuoys dropped from a Lysander aircraft. Following the end of the war in Europe, attention turned to the Far East, and he attended a course at Cranwell on the tropicalization of radio equipment. This consisted mainly of masking certain sensitive components prior to spraying the equipment with quick-setting varnish.

For the remainder of his time at RAE Tony worked on two projects. The first was ‘Talking Beacon’, a navigational aid in which a rotating antenna transmitted bearings so that a pilot receiving the signal would hear the vector required to head towards the beacon. Finally he worked with an American blind-landing device known as ILS (Instrument Landing System). This was installed at the far end of the main runway, and Tony checked the alignment, flying in an ancient Avro Anson aircraft that followed the beam down to a near-collision with the main administration block. During the summer of 1946 Tony successfully applied to Gonville and Caius College to complete his degree. Besides his good fortune in working with Ratcliffe and Ryle at TRE, he had time during his three years of war service to assimilate some of the physics he had found difficult in his first year at Cambridge.

RETURN TO CAMBRIDGE

With his improved understanding of physics, Tony obtained a second class degree in Part I in 1947, and a first in Part II in 1948, completing his BA degree and also making him eligible for a

* Numbers in this form refer to the bibliography at the end of the text.
Department of Scientific and Industrial Research (DSIR) research studentship. He commented that his success was undoubtedly aided by the excellent course on electromagnetism given by Ratcliffe, now back in Cambridge as head of the Radio Group in the Cavendish Laboratory. His director of studies at Caius was David Shoenberg (FRS 1953), who urged him to visit group leaders at the Cavendish before making any final career decision. It turned out that Ratcliffe was seeking a graduate student to work with Martin Ryle. Although totally ignorant of radio astronomy, this offer was too good to resist.

Another strong reason for staying in Cambridge was that he had just met Marjorie Richards, a primary school teacher. In June 1948, while awaiting the results of his finals, they fell into conversation on the bank of the Cam near Grantchester. The die was cast when she later came to tea in his rooms at Caius and he was able to offer an excellent orange sponge cake from the famous Cambridge cakeshop Fitzbillies, very hard to come by at the time. They were married in 1950 at Kelston, Somerset, where Marjorie’s father, Edgar Richards, was the Anglican vicar. Tony and Marjorie had two children. Their daughter, Jennifer Anne, was born in 1954 and became a teacher of modern languages. She married Richard Hookham and they had three children, Rebecca, Elizabeth and Emma. Tragically, Jenny died of ovarian cancer in 2004. Their son, Nicholas, was born in 1956. He obtained a first class degree in physics at Cambridge and then a PhD at Bristol on neutron diffraction and the structure of liquids. He is the lead software consultant at Plextek, a company specializing in communications systems. He married Katherine Welford in 1983 and they have two children, Sarah and John.

The Ionosphere, the Solar Corona and the Solar Wind

Tony’s PhD programme centred on studies of the ionosphere by observing the scintillation, or ‘twinkling’, of the ‘radio stars’, as they were known at the time. He discovered that scintillation was a nocturnal phenomenon, strongly correlated with the occurrence of a type of irregular reflection of radio waves from the F-region of the ionosphere known as ‘Spread-F’ (1). In contrast to reflection methods for studying these phenomena, the scintillation technique was not limited to regions below the level of maximum ionization. A major part of this research was a theoretical analysis of the diffraction of radio waves by an irregular, transparent layer. Ratcliffe was impressed by Tony’s diffraction theory and encouraged him to submit his analysis for publication by the Royal Society (2). The theory showed how the intensity variations developed with distance from the screen, and defined what became known as the Fresnel distance. His practical application of this approach led to information about the scale-size of the electron density fluctuations and their height within the ionosphere, as well as measurements of their wind speeds of 100–200 m s\(^{-1}\) in the F-region (3). These impressive results led to Tony becoming the Radio Astronomy Group’s authority on all types of radio scintillation phenomena.

These successes led naturally to investigations of the solar corona, the very high temperature region extending from just above the Sun’s surface far out into interplanetary space. The strong radio source associated with the Crab Nebula could be observed at a small angle to the Sun, and in 1953 it was shown that radio waves traversing the corona did not reveal the expected large-scale spherical refraction. It was suggested that random scattering might be the cause. Tony made interferometric observations at different wavelengths and baselines, which confirmed that random diffraction by small-scale density structures was the dominant
cause (4). With a succession of graduate students, interferometers with baselines up to 10 km were built, and they succeeded in studying the solar corona out to about half the Sun–Earth distance (6, 7, 11).

In his notebook for 1953, Tony noted the possibility that scattering of the radiation of point sources by electron density fluctuations in the solar corona might give rise to scintillations analogous to ionospheric scintillations. In 1962–63, Margaret Clarke noted that one or two radio sources showed significant intensity fluctuations, while others did not (see the opening paragraph of (12)). It was soon clear that the newly discovered radio quasars were compact radio sources and that Tony’s suggestion of a decade earlier that coronal scintillation were responsible for the fluctuations was indeed a possibility. Paul Scott and Derek Wills made repeated observations of a number of these sources using the 4C Telescope with the necessary short receiver time constant, and the presence of scintillation due to fluctuations in the electron density in the interplanetary medium flowing out from the Sun, what is known as the solar wind, was soon confirmed (12) (figure 1). Interplanetary scintillation (IPS) became a major field of study.

The next application of the IPS technique was to map out the structure of the solar wind. In 1966, Tony and his graduate student Paul Dennison set up a triangular arrangement of three simple interferometers with baselines of 50–80 km in length. From the time delays of the scintillations at the three sites they established that the solar wind existed far above the plane of the ecliptic (16). Of particular interest was the much faster wind found when the line of sight through the corona sampled regions above heliolatitudes of 60°. This was the first observation of the high-speed wind from solar polar coronal holes, and it was not until 1995 that direct sampling by the Ulysses spacecraft confirmed the existence of such streams. Further measurements of the solar wind on longer baselines, with outstations at Jodrell Bank and Defford, and observing more sources, were carried out with M. D. Symonds (19).
Radio Scintillation and the Angular Sizes of Radio Sources

The first application of IPS for angular size measurements was a study of the compact source within the Crab supernova remnant. The observations had already been made with Samuel Okoye, prior to the discovery of IPS, during measurements of coronal scattering on a baseline of 10 km. Since the start of this project, which was designed to detect the corona at the greatest distance from the Sun, the intensity variations seen in the Crab source were a puzzle, since they were not observed in several other sources regularly observed in the same way. Tony was well aware of the fact that, on a 10 km baseline, the Crab Nebula is largely resolved (13), and he suggested that the fluctuating source might be the active remnant of the supernova explosion. Following the discovery of IPS it became clear that scintillation explained the fluctuations and it was deduced that the Crab Nebula contained a source of angular size about 0.1 arcsec, which could only be the remnant of the original supernova explosion (14).

The 4.5-acre array was designed to carry out a sky survey using IPS to estimate angular sizes, and this was completed in 1967. The first results, over a restricted range of declination, are described in Jocelyn Bell’s (Jocelyn Bell Burnell, FRS 2003) dissertation (Bell-Burnell 1968). A more complete survey was carried out by Tony’s graduate student Anthony Readhead (23). This survey showed clearly, for the first time, a source-broadening effect caused by scattering due to density fluctuations in the interstellar plasma, particularly near the galactic plane (20). Having a fairly large sample of angular sizes, the angular size versus redshift relation was investigated and it was shown that there was a deficit of small-diameter sources at the largest redshifts (24,25).

Following the success of angular size surveys with the 4.5-acre array, its collecting area was doubled, the design and construction being directed by Peter Duffett-Smith. Preamplifiers were inserted at each group of 16 dipoles, and the two halves of the array were connected as a north–south interferometer. After completion in 1978, much-improved surveys of angular sizes were carried out, listing over 1000 sources (26,36).

This catalogue proved to be a useful astronomical resource and led to the discovery of the first millisecond pulsar. Listed in the Cambridge 4C catalogue as 4C21.53, this source was unusual in that it exhibited strong IPS despite the fact that it was situated in the galactic plane, where interstellar scattering causes extragalactic sources to have apparent angular sizes too large for IPS to occur. Hence, the source had to be relatively nearby within the Galaxy, its small angular size suggesting that it might be a pulsar. Duffett-Smith made special measurements, showing that the period must be less than 10 ms. He then contacted Jodrell Bank, where even shorter periods could be measured, and it was shown that any period was less than 2 ms. Finally, in 1982, a period of 1.6 ms was measured by Don Backer at Berkeley (Backer et al. 1982).

Radio Telescopes and Radio Surveys

Returning to the early years of Tony’s activities as a member of the Radio Astronomy Group, his experience of designing antennae and electronic systems was invaluable to Martin Ryle and members of the group as they began the construction of more and more powerful radio telescopes and, in particular, in the practical realization of the principles of aperture synthesis. As he recalled (42), as soon as he arrived in the group in 1948:
Figure 2. Two of the four elements of the 2C array, each consisting of fixed cylindrical reflectors, located at the Rifle-range site. (Courtesy of the Cavendish Laboratory, University of Cambridge.) (Online version in colour.)

Following the Rutherford tradition of making your own apparatus, he directed me towards a large pile of brass tubing and asked me to saw it into dipoles for his antenna arrays.

He goes on (42):

For the next ten years I was to continue to work on antenna arrays for a succession of Ryle’s telescopes. Without this experience, alongside my own research, I would never have built the 4.5 acre array with which we discovered pulsars, so I am eternally grateful to Ryle for this background.

During the 1950s and early 1960s, Tony was involved in the construction of all the major survey radio telescopes, initially on the Rifle-range site behind the Cambridge University Rugby Club pitch just off Grange Road. In 1952, he designed the dipole arrays suspended at the line-foci of each of the four trough reflectors of the one-acre telescope for the 2C and 3C surveys (figure 2). Light structures were required, and he designed folded dipoles constructed from heavy-gauge copper wire, which provided sufficient bandwidth. Impedance matching was achieved with quarter-wavelength transformers of variable spacing, which required manual adjustment at the top of each mast (5). He spent much time aloft during this work.
In 1955, the search began for a new site for the radio observatory, and Tony visited many disused airfields within 30 miles of Cambridge, accompanied by a colleague from the University Department of Estate Management. It was finally concluded that Lord’s Bridge, located about three miles from the city, was the optimum location. The site was still owned by the Air Ministry when he set up simple interferometers, both for studies of the solar corona and to confirm that the level of radio interference was suitably low.

Dipole arrays were again used at the focus of the first large aperture-synthesis telescope at Lord’s Bridge, what became known as the 4C survey radio telescope (figure 3). In addition to adjusting all the transformers, Tony was responsible for protecting the end-towers of the 1450 foot long reflector in the event of damaging ice-loads forming on the wires of the reflecting screen. Experiments on de-icing single wires using DC currents made it clear that huge currents would be needed to protect the screen and so he designed a simple quick-release system to free the wires from one end of the telescope. During a period of severe icing one night at the end of December 1961, it was necessary to activate this device and to his great relief it worked perfectly. He also designed 2 : 1 transformers for the branched-feeder network of the long fixed reflector of the telescope, before realizing that the same aperture-distribution could be achieved more simply computationally with the university’s pioneering computer, EDSAC, by cross-correlating the recorded signal with a Gaussian-type function. Tony was the author with Martin Ryle of a description of the telescope (8) and also of the paper on the first survey carried out with the new synthesis interferometer (9).

During the early development of the aperture-synthesis technique, Tony devised, with assistance of David Wheeler (FRS 1981) of the Computer Laboratory, some of the first computer programs for Francis Graham-Smith’s (FRS 1970) 38 MHz array—this was in fact the first synthesis antenna completed at Lord’s Bridge.

THE RADIO SOURCE COUNTS

The central figure in this story was Martin Ryle. Initially, he had been strongly wedded to the idea that most of the radio sources were radio stars belonging to our own Galaxy, but by early 1954 he had been converted to the idea that most of the radio sources observed at high galactic latitudes are extragalactic. The second Cambridge (2C) survey of radio sources was published in the following year by Shakeshaft et al. (1955). They found that the small-diameter radio sources were uniformly distributed over the sky and that the numbers of sources increased enormously as the survey extended to fainter and fainter flux densities. Ryle found a huge excess of faint radio sources, the slope of the source counts between 20 and 60 Jy being described by \( N ( \geq S) \propto S^{-3} \), compared with the much flatter relation expected for a uniform distribution of sources in Euclidean space, \( N ( \geq S) \propto S^{-1.5} \). He concluded that the only reasonable interpretation of these data was that the sources were extragalactic and that there was a much greater comoving number density of radio sources at large distances than there are nearby. As Ryle expressed it in his Halley Lecture in Oxford in 1955 (Ryle 1955):

This is a most remarkable and important result, but if we accept the conclusion that most of the radio stars are external to the Galaxy, and this conclusion seems hard to avoid, then there seems no way in which the observations can be explained in terms of a Steady-State theory.
These remarkable conclusions came as a surprise to the astronomical community. There was enthusiasm and also some scepticism that such profound conclusions could be drawn from the counts of radio sources, particularly when their physical nature was not understood and only the brightest 20 or so objects had been associated with relatively nearby galaxies.

The Sydney group led by Bernard Mills carried out similar radio surveys of the southern sky at about the same time with the Mills Cross, and they found that the source counts could be represented by the relation $N(\geq S) \propto S^{-1.65}$, which they argued was not significantly different from the expectation of uniform world models—Mills stated (Mills & Slee 1957):

We therefore conclude that discrepancies, in the main, reflect errors in the Cambridge catalogue, and accordingly deductions of cosmological interest derived from its analysis are without foundation. An analysis of our results shows that there is no clear evidence for any effect of cosmological importance in the source counts.

Relations between Martin Ryle, the Sydney radio astronomers and the proponents of steady-state cosmology became increasingly fraught.

The problem with the Cambridge number counts was that they extended to surface densities of radio sources such that the flux densities of the faintest sources were overestimated because of the presence of faint sources in the beam of the telescope, a phenomenon known as
confusion. Peter Scheuer, who was Martin Ryle’s research student from 1951 to 1954, devised a statistical procedure for deriving the number counts of sources from the survey records themselves without the need to identify individual sources (Scheuer 1957). The technique, which he referred to as the $P(D)$ technique, where $D$ is the deflection on the survey records, showed that the slope of the source counts was $-1.8$. Ironically, this result was not trusted, partly because the mathematical techniques used by Scheuer were somewhat forbidding and also because his result differed from the prejudices of both Ryle and Mills. The dispute reached its climax at the Paris Symposium on Radio Astronomy in 1958 and the conflicting positions were not resolved (Bracewell 1959).

In 1960–61 Martin asked Tony to carry out some numerical calculations based on Scheuer’s statistical method of analysing interferometric observations. The records showed a continuous background of overlapping fringes between the individual sources of large fringe amplitude. One problem with Scheuer’s method was the difficulty of calculating $P(D)$ analytically for different model universes. With his now well-honed expertise in programming the EDSAC II computer, Tony evaluated the $P(D)$ distributions numerically using a Monte Carlo technique. This approach made the results of Scheuer’s analysis much more accessible to the general community of radio astronomers and showed that Scheuer’s conclusion about the slope of the source counts were correct (10). Tony confirmed that the observations were not consistent with the steady-state model of the Universe.

THE DISCOVERY OF PULSARS

By 1964 Tony realized 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 astronomical areas: (a) it would enable many more quasars to be discovered; (b) their angular sizes could be estimated; and (c) the structure and velocity distribution 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 DSIR 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 very large, 3.5 acres (1.8 hectares) in area, in order to record the rapidly fluctuating intensities of bright radio sources on timescales as short as one-tenth of a second.

Tony was the head of the project for all aspects of the construction and operational phases of the array, including specifying the observing programme and the method of data analysis. In addition to listing every source that showed significant scintillation, the weekly observations were plotted on a sky chart so that repeated detections in the same position on the sky would signify genuine sources, rather than random events caused by radio interference—interference is unavoidable at metre wavelengths, and it had to be fully understood as early as possible.

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 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 2048 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 (figure 4).
While the array was being constructed, Leslie Little and Tony had carried out a theoretical investigation of the strength of the scintillations as a function of heliospheric coordinates (15). 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. The scintillations decrease to small values when observed at large angles from the Sun, as they demonstrated in the plot of the scintillation index as a function of heliocentric coordinates, the term scintillation index meaning the ratio of the scintillating to total intensity.

The commissioning of the 4.5-acre array proceeded through the summer of 1967. Tony suggested that Jocelyn create sky charts for each strip of the sky each day, noting all the scintillating sources. Jocelyn was responsible for carrying out the day-to-day running of the survey and analysis of the records. This was a very demanding task, requiring great persistence, patience and attention to detail on Jocelyn’s part. Under Tony’s supervision, she meticulously analysed the huge amount of data arriving each day entirely by hand. On 6 August 1967 she discovered a strange 100% scintillating source in a region of sky where the scintillations were expected to be small (figure 5a). The trace was rather odd, not showing the usual envelope in right ascension, and on some days it was not present. Nevertheless, it appeared several times on the sky charts, Jocelyn referring to it as her ‘piece of scruff’.
Figure 5. (a) Discovery record of the strange scintillations of CP 1919 on 6 August 1967. (b) First observations of the pulses of CP 1919 recorded on 28 November 1967. (Courtesy of the Churchill Archives Centre (ref. HWSH Acc 355) and the Hewish family.) (Online version in colour.)
Tony took the decision to make daily observations of the source using a more sensitive recorder running at a faster chart speed to determine the nature of the signal in more detail. Jocelyn installed the recorder and began daily observations at the faster chart speed, but frustratingly the source had disappeared. Towards the end of November the source reappeared and, during a period when the source was bright, Jocelyn observed the first pulses on 28 November (figure 5b).

Tony described the following two months as the most exciting of his scientific career. Nothing like this had been observed in astronomy before and the team had to be absolutely certain of the correctness of the observations. First of all, accurate timing of the pulses was needed, and Tony began these measurements using the time pips from the Rugby MSF broadcast time service and was amazed at the day-to-day regularity of the pulses, which had a stable period of 1.33 s. The pulse period was so stable that Doppler shift measurements could be made to investigate possible orbital motion of the source, which might have indicated an alien origin of the signals, the infamous ‘little green men’. The motion of the Earth about the Sun was clearly observed, but no orbital motion of the source itself. By inspecting all the past records Tony identified phase-reversals, which gave a more accurate measurement of right ascension, and showed that the source had a fixed position on the sky.

Further information was obtained by John Pilkington, Paul Scott and his student Robin Collins. The large 4C reflector could track the source for up to 30 min and showed the large intensity variations that caused the ‘scruffiness’. Observations at two frequencies showed the time delay due to dispersion of the radio waves by the plasma along the line of sight to the source. With rough assumptions of the density of the interstellar gas, Tony estimated a minimum distance of approximately 60 pc for the source. Meanwhile Jocelyn painstakingly scoured the survey records for evidence of further pulsing sources, and just before Christmas, on 20 December 1967, confirmed the existence of a second pulsar, CP 1133. Two more pulsars were discovered on 6 January 1968—including CP 0950, which had a short pulse period of only 0.25 seconds. These observations left no doubt that the pulsars were a new class of astronomical object (18).

From the measured pulse duration, the source could not be larger than a small planet and so stellar oscillations of white dwarf stars or neutron stars seemed to provide an explanation for the stability of the periodicity. The discovery paper was received by Nature on 9 February 1968 and published two weeks later (17). The discovery was kept under tight wraps until Tony and his colleagues were absolutely convinced that they had discovered a new astronomical phenomenon. I was in the next door office to Tony’s in the Old Cavendish Laboratory in Free School Lane at the time and knew nothing about what was going on until he gave a lecture about the discovery in the week before the Nature paper was published.

Within a few months, Thomas Gold FRS convincingly associated the pulsars with magnetized, rotating neutron stars (Gold 1968). The radio pulses are caused by beams of very high energy particles escaping from the poles of a magnetized, rotating neutron star. When the beam of intense radio emission associated with streaming particles passes across the line of sight to the observer, an intense burst of radio emission is observed.

Soon after the discovery, large numbers of pulsars were discovered. By now, more than 2000 radio pulsars are known, and the associated neutron stars are of the greatest astrophysical importance as the last stable stars before collapse to a black hole ensues—their radii are only about three times that of the ‘surface’, or event horizon, of a black hole of the same mass. Neutron stars represent matter in bulk at nuclear densities and offer many challenges for
physicists and astrophysicists. Neutron stars were discovered as the compact X-ray sources in X-ray binary systems by Riccardo Giacconi and his colleagues (Giacconi et al. 1971) from observations with the UHURU X-ray observatory. Russell Hulse and Joseph Taylor (Hulse & Taylor 1975) discovered that the pulsar PSR 1913 + 16 is a member of a binary neutron star system. This was a wonderful 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 major discoveries was the measurement of the speeding up of the binary owing to this process. The remarkable agreement between theory and experiment showed complete consistency with Einstein’s prediction of the existence of gravitational waves according to his theory of general relativity (Hulse & Taylor 1975).

The discovery of the pulsars resulted in the award of the Nobel Prize to Tony and Martin Ryle in 1974, the citation stating:

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.

A shadow was cast over Tony’s achievement by claims that Jocelyn should have shared the Nobel Prize with him. This was fomented by Fred Hoyle FRS, with whom Martin Ryle had particularly poor relations. The animosities had a long history; Ryle had initially assumed the radio stars were galactic objects, whereas Hoyle and others correctly inferred that they were extragalactic. In the 2C radio survey, Ryle claimed to have shown that the steady-state cosmology of Hermann Bondi FRS, Thomas Gold and Fred Hoyle could not account for the radio source counts. In fact, the excess of faint sources had been exaggerated because of the effects of confusion. The subsequent debate was acrimonious, and the result was that the next catalogues, derived from the 3C and 4C surveys, were kept under close wraps until Ryle and his colleagues were absolutely sure of the reliability of the results.

Tony was not party to these debates, except insofar as his statistical simulations of the $P(D)$ distribution showed that there was indeed an excess of faint radio sources. According to the science correspondent of The Times, Hoyle allegedly remarked during a press interview that ‘the senior members of the team were busy pinching it [her discovery] from the girl’. The Nobel Prize nomination did not come from Cambridge. The widespread dissemination of this allegation is illustrated in Tony’s autobiographical notes:

In 1997, at a reception in the University Combination Room prior to the award of Honorary ScDs to Jocelyn and myself, the Duke of Edinburgh, then Chancellor of the University, remarked to me “Ah yes, Jocelyn did all the work and you got all the credit”.

The remark may have been intended in jest, but it was hurtful and did not reflect Tony’s central leadership role, without which the 4.5-acre array would never have been built and the discovery could not have been made. Throughout this sad business, Tony and Jocelyn both behaved impeccably.

INTERSTELLAR SCINTILLATION

Following the discovery of pulsars, Tony’s interests reverted to the original scientific objectives of the 4.5-acre array, the use of the scintillation technique for studies of compact
radio sources and the properties of the intervening media. These included studies of irregularities in the solar wind and the resulting opportunities to study ‘space weather’. One relic of the pulsar discovery followed from Peter Scheuer’s pioneering analysis of the use of pulsar variability to understand *interstellar* scintillation (Scheuer 1968). Scheuer showed convincingly that some of the temporal variations in intensity of pulsars could be attributed to scintillation caused by fluctuations in the ionized component of the interstellar gas, providing a probe of the distribution of density irregularities in the interstellar medium.

A great deal of observational data were accumulated by large steerable radio telescopes, and Tony was particularly intrigued by the characteristic quasi-periodic patterns that were often revealed by dynamic spectra of scintillation, meaning continuous observations of the intensity plotted as a function of time versus radio frequency. Tony showed how these could be explained as the combined effect of diffraction by small-scale irregularities and refraction by much larger irregularities (27). This led a fruitful collaboration with Aleksander Wolszczan, who had obtained excellent observational data using the 100 m Effelsberg Telescope. They showed how Tony’s theory could be used to place constraints on the spatial power spectrum of the density irregularities in the interstellar medium; in particular, the widely-assumed Kolmogorov spectrum was an oversimplification (32,40). As a footnote to this story, Tony was asked to referee a paper submitted to *Nature* by an American group who had discovered unusual intensity variations exhibited by a few radio galaxies, which they attributed to lens-like refraction by ionized interstellar clouds. In his report, Tony suggested a simpler explanation, based on irregular refraction, which the authors adopted, and his name was added to the paper (37).

**Space weather**

The 4.5-acre array was not the ideal instrument for follow-up studies of pulsars. These were vigorously pursued by the worldwide community of radio astronomers with access to large single-dish radio telescopes. Tony continued to use scintillation techniques to study ‘space weather’. Early observations with the array had shown large-scale, systematic day-to-day variations of scintillation across the sky, which were strongly correlated with *in situ* spacecraft measurements of the plasma density (22). A detailed study using observations of strongly scintillating sources confirmed that the progress of the high-density compression regions, formed ahead of long-lived, high-speed solar wind streams emitted from large coronal holes, could be tracked (21).

When the 4.5-acre array was doubled in size to 9 acres (3.6 hectares), which became operational in 1978, it provided a superior grid of sources across the sky that could be observed routinely on a daily basis, and it became possible to track both short-lived radially travelling disturbances, such as coronal mass ejections and interplanetary shocks, and long-lived corotating structures associated with coronal holes (28,29,30). This opened a new era of ground-based space research, with potential for predicting the occurrence of major geomagnetic storms (35,39).

The team identified what seemed to be a new kind of interplanetary disturbance, which they called ‘erupting streams’. These were radially travelling shocks followed by streams of fast solar wind, which typically persisted for several days. This contrasted with the conventional view that shocks are caused by fast coronal mass ejections, for which there is no known
mechanism for generating the sustained post-shock outflow. They found that erupting streams originated from coronal holes (33) and suggested that when coronal holes are located near active regions on the Sun they can generate sporadic outflows with exceptionally fast winds (31,34,38,41).

In the late 1980s the Space Environment Laboratory (SEL) in Boulder, Colorado, became interested in the predictive potential of synoptic maps of space weather. To achieve this, an upgrade in the data recording system was required, and this was carried out by Duffett-Smith in collaboration with SEL. Routine observations commenced in 1990 and continued until 1994, with data analysis by Graham Woan and transmitted to Boulder via the internet. It turned out that the arrival of corotating high-speed streams could be predicted one or two days in advance, but this was not generally possible for strong interplanetary shocks. With Tony’s retirement in 1991, and Woan’s move to Glasgow in 1996, the scintillation programme came to an end.

ADVISORY BODIES, TEACHING AND OUTREACH

Tony did his fair share of committee work throughout his career: the Council of the Royal Astronomical Society for several years; various committees of, successively, the DSIR, the Science Research Council (SRC) and the Science and Engineering Research Council, as well as visiting committees for Jodrell Bank and the Royal Observatories. Of significance for the Radio Astronomy Group was his chairmanship of the SRC Millimetre Wave Committee, beginning in 1974. He initiated a design study for what ultimately became the James Clerk Maxwell Telescope in Hawaii. On the international scene, he served on the advisory committees for the National Radio Astronomy Observatory and the Arecibo Observatory in the USA, the Observatoire de Paris (Meudon) and a committee to review the Physical Research Laboratory at Ahmedabad, India. He was a member and then chairman of the Fachbeirat of the Max Planck Institute for Radioastronomy at Bonn, and was chairman of Commission 49 (the Heliosphere) of the International Astronomical Union.

Teaching was always a major interest. Throughout his career he usually taught one major undergraduate course each year, including advanced optics, oscillations and waves, electrodynamics and relativity, and observational cosmology. In 1976, when a major revision of the first-year physics courses was undertaken, it was decided to abandon the usual custom of two streams, one for those intending to specialize in physics and a less demanding option for those moving on to other subjects. Tony, as a very recent Nobel Prize winner, accepted the major challenge of addressing a class of 450 students on the new course, entitled ‘Concepts in physics’. His brief was to introduce basic mechanics, relativity and particle physics at a level that would not baffle the weaker students, while not boring the brightest and best. The course was a success. On one occasion, during the final lecture, a pyjama-clad figure emerged from the back of the auditorium with a breakfast tray and served toast and coffee. Tony was also presented with a Christmas card painted on a square metre slab of York paving stone.

Throughout his career, he gave numerous named lectures, as well as popular lectures to university societies, schools and astronomical societies, typically two to four per year. In 1965 he gave one of the Royal Institution Christmas lectures on radio telescopes, the other speakers being Martin Ryle, Bernard Lovell FRS and Francis Graham-Smith.
Tony Hewish

Figure 6. Tony and Marjorie with their children, their children’s spouses and their grandchildren in 1990. Left to right: Jenny, Richard Hookham, Tony, Marjorie, Katherine holding John, and Nicholas. The children in front are Rebecca, Elizabeth and Emma Hookham and Sarah Hewish. (Photograph courtesy of the Hewish family.) (Online version in colour.)

Personality

Tony was a modest, almost shy, individual who did not seek the limelight. He was a friendly and helpful colleague and a dedicated supervisor. He and Marjorie were devoted parents, grandparents and great grandparents (figure 6). In the late 1970s, they moved to a splendid sub-mediaeval thatched house in the village of Kingston, not far from the Lord’s Bridge Observatory. This was a rural idyll where Tony enjoyed to the full his passion for horticulture. His grandchildren remember him as a kind, warm, funny, generous and unassuming presence, but very much the patriarch of the family supported in equal measure by Marjorie (figure 7a). Tony was most revered for growing the most incredible carrots, fruits and fresh vegetables in his remarkable vegetable garden, where he spent much of his retirement teaching the grandchildren the perfect time to pick a ripe tomato and how to ride a lawn mower.

The grandchildren fondly remember standing outside the house, ringing an enormous bell to lure Tony back from the vegetable garden for supper with a basket of spoils from the day. He made fresh bread for breakfast every day and his fudge was incredible, really the platonic ideal of fudge. Tony was not a scientist at home, unless the grandchildren helped with the washing up, which was a great time to encourage him to talk about the theory of relativity. His
engineering skills were evident in the thatched summer house he built and the roofed treehouse capable of holding quite a crowd of grandchildren playing games and stringing beans.

Tony served as churchwarden of St Edward’s church in central Cambridge for several years and, from 1985, was churchwarden of the village church in Kingston (figure 7b). He saw no major conflict between science and religion, provided that the latter does not demand belief in rigid dogmas. For this reason he felt it a duty to support the Anglican church, in which he was brought up at school and at home. He stated that he could never be an atheist, accepting that mankind, and our Universe, are simply flukes of nature in which the physical constants just happened to be favourable. He accepted invitations to talk on science and religion in churches, college chapels and schools.

APPRECIATION

There is no doubt that Tony Hewish was a major pioneer of radio astronomy. He had the great fortune to enter the subject in its infancy and made full use of the opportunities for opening up completely new perspectives in astronomy. He was also fortunate to work with Martin Ryle, a driven and visionary leader whose brilliance as an electrical engineer made possible the rapid ascent of radio astronomy as an essential waveband for astronomical discovery, despite being quite different from classical astronomy and led by physicists rather than astronomers. The achievements described in this memoir bear testimony to Tony’s outstanding abilities as a physicist in making a new science out of the study of the scintillation properties of radio sources.

The discovery of pulsars will ensure that his name will be a permanent fixture in the history of breakthrough discoveries in science. The months from August 1967 to February 1968 exemplify how something totally unexpected turned out to be pure gold, showing that neutron stars exist and in turn leading to the extraordinary explosion of interest in the new
Antony Hewish

discipline of high energy astrophysics and the role of general relativity in astrophysics. The route to being wholly convinced that a new astronomical phenomenon had been discovered involved a brilliant series of observations using all the telescopes and facilities available to the group. Tony’s leadership of the whole programme was exemplary.

AWARDS AND RECOGNITION

1952 Hamilton Prize, Cambridge
1968 Fellow of the Royal Society of London
1969 Eddington Medal, Royal Astronomical Society
1970 Charles Vernon Boys Prize, Institute of Physics and Physical Society
1971 John Howard Dellinger Gold Medal, International Union of Radio Science
1972 Hopkins Prize, Cambridge Philosophical Society
1973 Michelson Medal, Franklin Institute, USA
1974 Nobel Prize for physics, jointly with Martin Ryle
1974 Holweck Medal and Prize, Société Française de Physique
1976 Honorary Fellow, Gonville and Caius College
1977 Hughes Medal, Royal Society
1982 Foreign Honorary Member, American Academy of Arts and Sciences
1982 Foreign Fellow, Indian National Academy of Sciences
1985 Honorary Fellow, Institution of Electronics and Telecommunications Engineers, India
1990 Foreign Member Belgian Royal Academy
1996 Honorary Citizen, Kwangju, S Korea
1996 Vainu Bappu Medal, Indian National Academy of Sciences

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AUTHOR PROFILE

Malcolm S. Longair CBE FRS FRSE is Jacksonian Professor emeritus of natural philosophy and Director of Development, Cavendish Laboratory, University of Cambridge. He was appointed the ninth Astronomer Royal of Scotland in 1980, as well as Regius Professor of astronomy, University of Edinburgh, and the Director of the Royal Observatory, Edinburgh. He was head of the Cavendish Laboratory from 1997 to 2005. He has served on and chaired many international committees, boards and panels, working with both NASA and ESA. His main research interests are in high-energy astrophysics, astrophysical cosmology and the history of physics and astrophysics. The third edition of his book, Theoretical concepts in physics, was published in 2020.
He is currently working on the third edition of his book *Galaxy formation*. He has continued to enhance the online digital archive of historic photographs illustrating the history of the Cavendish Laboratory. A major task is preparing for the move of the Cavendish collection of historical scientific instruments to the new Cavendish Laboratory in 2022.

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