Robert Hanbury Brown, 1916-2002

John Davis and Sir Bernard Lovell, FRS

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Numbers in square brackets refer to the notes at the end of the text.

1 Introduction

Robert Hanbury Brown was born on 31 August 1916 in Aruvankadu, Nilgiri Hills, South India; son of an Officer in the Indian Army, Col. Basil Hanbury Brown, and of Joyce Blaker. From the age of three Hanbury was educated in England, initially at a School in Bexhill and then from the age of eight to fourteen at the Cottesmore Preparatory School in Hove, Sussex. In 1930 he entered Tonbridge School as a Judde scholar in classics. Hanbury's interests turned to science and technology particularly electrical engineering and after two years he decided that he would seek more appropriate education in a technical college. His decision was accelerated by the fact that after the divorce of his parents his mother had re-married Jack Lloyd, a wealthy stockbroker, who in 1932 vanished with all his money and thus Hanbury felt he should seek a career that would lead to his financial independence. For these reasons Hanbury decided to take an engineering course at Brighton Technical College studying for an external degree in the University of London. At the age of 19 he graduated BSc with first class honours taking advanced Electrical Engineering and Telegraphy and Telephony. He then obtained a grant from East Sussex and in 1935 joined the postgraduate department at the City & Guilds, Imperial College. In 1936 he obtained the Diploma of Imperial College (DIC) for a thesis on oscillators.

He intended to continue his course for a PhD but a major turning point in his career occurred when he was interviewed during his first postgraduate year by Sir Henry Tizard, Rector of Imperial College. Hanbury explained to Tizard that he was following up some original work by Van der Pol on oscillator circuits without inductance and hoped ultimately to combine an interest in radio with flying. In fact, Tizard had already challenged him about the amount of time he spent flying with the University of London Air Squadron.

Tizard told Hanbury to see him again in a year's time and that he might then have a job for him. In fact, within three months Tizard accosted Hanbury and said he had an interesting research project in the Air Ministry for him. After an interview by R. A. Watson-Watt, Hanbury was offered a post at the

Radio Research Board in Slough. His visit to Slough was brief; he was soon told to report to Bawdsey Manor in Suffolk, which he did on 15 August 1936. Thereby, unaware of what Tizard had in mind for him, Hanbury's career as one of the pioneers of radar began.

2 Orfordness

On 26 February 1935 Watson-Watt had demonstrated that reflections from a Heyford bomber flying through the beam of the BBC transmitter at Daventry could be detected as he had suggested in his memoranda to the Tizard Committee in January and February of that year. On 13 May five members of the Radio Research Station at Slough were sent to Orfordness to begin the development of a system for the detection of enemy aircraft. It was to this research group that Hanbury was despatched to work on the secret project then known as R.D.F. (Radio location and Direction Finding) and later as Radar. He arrived at Orfordness in August 1936 and joined the small group then working on the development of receivers and antennae.

Tests on a wavelength of 13 metres were in progress with a transmitter generating 20-microsecond pulses at a peak power of 100 kilowatts. An array of dipoles produced a broad beam and Hanbury worked on the receiver and antennae using crossed dipoles and a goniometer to determine the angle of arrival of the reflected echo. Two dipoles at different heights and a goniometer were used to estimate the height of the approaching aircraft.

The tribulations and early development of this system at Orfordness have been described by E. G. Bowen (1987). It was this basic 13-metre wavelength system that rapidly evolved into the CH (Chain Home) stations along the East and South Coasts that proved so vital in the 1940 Battle of Britain. The main work at Orfordness ended in 1937 and for a short time Hanbury was involved in the first operational CH installation at Dunkirk in Kent.

Tizard was confident that the CH radar chain would give the RAF sufficient warning for day-time defence from the Luftwaffe and that the Germans would then turn to night bombing. It was at his insistence that the development of an airborne interception system was initiated. E.G. Bowen was placed in charge of this development and Hanbury was transferred to his group in the autumn of 1937.

3 The first airborne radars

By the time Hanbury joined this group Bowen was facing the problem of installing a complete radar in an aircraft. This required a transmitter of sufficient power at a short wavelength and was made possible by the recent arrival of the Western Electric 316A (the 'door knob') valve. This generated 100 watts at a wavelength of 1.5 metres and the initial flight with a complete radar in the aircraft had been made in August 1937. On 14 September under conditions of poor visibility ships of the Fleet were detected in the North Sea, with the associated Swordfish aircraft operating from the deck of an aircraft carrier. This historic success led eventually to the development of AI (Air Interception) and ASV (Air to Surface Vessel) operational systems; there were, however, immense problems still to be overcome.

The development of this first airborne radar was carried out in a small building in the grounds of Bawdsey Manor and the flight testing took place from the nearby aerodrome at Martlesham Heath. Towards the end of 1938 Hanbury moved there to take charge of the installation and testing of the experimental equipment in aircraft. The details and hazards of this work have been described by Bowen (1987) and by Hanbury (119). Hanbury spent many hours testing and demonstrating the equipment in flight. During one test flight with Bowen, when flying over the Solent, echoes from a submarine were observed. This further stimulated the development of the ASV version of this airborne radar, which, in its various operational forms became an essential equipment of Coastal Command aircraft in the eventual battle against enemy shipping and U-boats.

By May 1939 the first flight trials were made of a possible operational AI system to enable the pilot to home on to a target aircraft. This installation was in a single-engine Fairey Battle aircraft. The transmitter used two thermionic valves as a squegging oscillator to produce 1-microsecond pulses with a peak power of 2 kilowatts. A single dipole produced a broad beam forward of the aircraft. Four dipoles mounted on the wings were connected to the receiver and cathode ray tube display in rapid sequence to produce split beams in elevation and azimuth. The pilot would home on to the target aircraft by changing azimuth and elevation to equalize the amplitude of the echoes. By June 1939, this system was used successfully to home on to a target flying at 15,000 ft at a range of 12,000 ft.

With the approach of war, intense pressure developed for the installation of the system in operational night fighters. Bowen's group faced demands for equipping thirty Blenheim fighter-bomber aircraft and encountered severe difficulties in transferring the aerial systems from the single-engine aircraft to the twin-engine Blenheims.

4 The Second World War

In August 1939, only days before the outbreak of the war, Hanbury left Bawdsey Manor and Martlesham Heath to follow the first of the operational Blenheims to 25 Squadron at Northolt. His aim was to help the Squadron evolve their techniques for night-fighting with AI equipment. The Bawdsey Manor research team moved to Dundee and Bowen's group to a small aerodrome at Scone near Perth and then to St Athan in South Wales, meeting disastrously poor working conditions that have been graphically described by Bowen (1987) and by Lovell (1991).

Hanbury spent most of his time at Northolt until the Fighter Interception Unit (FIU) was established at Tangmere early in 1940. Both at Tangmere and later at Ford, Hanbury was the senior of the small group of scientists helping with the training and introduction of the AI-equipped Blenheims for operational use as night fighters. During this period he also spent much time at various Coastal Command squadrons helping with the installation of ASV equipment and the training of RAF operators.

By March 1940 some twenty Blenheims with improvements in the airborne radar (AI Mk III) had been fitted at St Athan and despatched to the FIU. In night operation the AI in the Blenheims was an almost total failure. The consequent inability of the RAF to detect the Luftwaffe during the night blitz on London in the autumn of 1940 was a primary cause of Churchill's removal from office of Sir Hugh Dowding, the C-in-C of Fighter Command (Zimmerman, 2001). Meanwhile the research on the AI system was extended and with the decision to enlist the experience of major industrial firms a revised AI system known as AI Mk IV was evolved. This used a modulator to produce square-shaped pulses and with improved transmitter power and receiver sensitivity was fitted in the faster and more powerfully armed Beaufighters.

Hanbury had long argued that success in a night battle would be achieved only when the fighter could be placed in the vicinity of the target under ground control, although he was not involved in the eventual success of such a system.[1]

Early in 1941, during a training flight at FIU, Hanbury suffered a serious incident when his oxygen supply failed at high altitude. He was unconscious when the aircraft landed and spent three months in hospital being treated for severe damage to his hearing. He was left with inferior hearing for the remainder of his life. He had previously burst an eardrum when testing AI equipment in May 1939.

Hanbury returned to TRE (now in Dorset) in June. By that time the primary interest in AI was the development of a system on centimetre wavelengths using the cavity magnetron (see Lovell, 1991) and since he could no longer fly at high altitude he decided to leave the air interception research group. He joined J.W.S. Pringle, a former member of Bowen's team at St Athan, who had started work on the Rebecca-Eureka beacons (119, Chapter 6).

5 Transponder beacons

Pringle was interested in airborne collaboration with the Army and he and Hanbury soon demonstrated the possibilities of such collaboration by placing a transponder at an agreed spot and arranging for an AI-equipped aircraft to release a smoke signal within a few yards of the hidden beacon. The system, known as Rebecca/Eureka, was developed for use by the Special Operation Executive (SOE) and became of critical value during the D-day operations for the invasion of Europe. The transponders were dropped through cloud by aircraft using a precise navigational beacon and they guided the airborne forces to the dropping zones.

At the end of 1942 Hanbury went to America to collaborate with the US forces in the production and use of the Rebecca and Eureka beacons. It was his intention to return to England in 1943 but he was instructed to remain in the USA and join the Combined Research Group (CRG) at the Naval Research Laboratory in Washington. The British section of this group was directed by Vivian Bowden. The main task of the CRG was to design a secondary radar to identify friend from foe (UNBIFF – United Nationals Beacons and Identification of Friend and Foe). A British system of IFF (Identification of Friends from Foe) had already been developed – mainly for airborne use so that the radar in the fighter could obtain a response if the suspected target was a 'friend'. The new system (UNBIFF) was to be applied at all operational wavelengths, used for land, sea and air and to give all Allies a universal system of transponder beacons.

The combined group developed equipment in a new frequency band – 900-1000 MHz – and devised a coding system for all military requirements. Although Hanbury contributed to the development of this technologically difficult system, it is evident from his own account (119) that he was unhappy to be so remote from the operations in Europe.

Before the UNBIFF could be tested under operational conditions the war ended and the British team was disbanded. Much of the work of the combined group on UNBIFF was later applied to civil aviation but Hanbury left Washington feeling that he had little to show for the two years there except for a number of technical reports. He returned to England in October 1945, two years after he had planned to return to the operational era of Rebecca and Eureka.

6 Post War 1945-49

When Hanbury returned to England he was still a scientific officer in MAP (Ministry of Aircraft Production). On the advice of Watson-Watt he returned to TRE and took charge of a group developing aircraft navigational aids. This phase of his career was short-lived. With the cessation of urgent operational demands the inspiration, and many of the staff, had left TRE. For a year he divided his time between the application of the wartime navigation aids to civil aviation and helping the Air Historical Branch of the Air Ministry to write an account of the early development of airborne radar.

In the summer of 1947 Watson-Watt persuaded Hanbury to leave the scientific civil service and join him as one of three junior partners in his newly formed firm of research consultants. Vivian Bowden who had been the head of the CRG in Washington and Edward Truefitt, formerly with the Baird Television Company, were the other junior partners. Their main task was to act as consultants to the boards and managers of companies on topics such as radar aids to navigation, and to television and film companies. Hanbury's main occupation was with radio and radar aids to navigation in Europe and the USA. In 1949 Watson-Watt announced that he was moving the firm to Canada. Although Hanbury and the other partners objected, Watson-Watt insisted and Hanbury and the other partners resigned.

7 Jodrell Bank 1949-62

When Watson-Watt moved his consulting firm to Canada Hanbury, at the age of 33, had no occupation. He decided to resume his academic research career and after an unsuccessful approach to the California Institute of Technology he wrote to F. C. Williams who had returned to the University of Manchester at the end of the war. Williams was then Professor of Electrical Engineering in the University and when he received Hanbury's letter he generously suggested that he might be particularly interested in the developments at Jodrell Bank (Lovell, 1968). The telephone call from Williams to Lovell early in May 1949 led on the 19th of that month to Hanbury's visit to Jodrell and the beginning of a brilliant phase of his career.

At that time Hanbury's idea was to return temporarily to a university to carry out research for a PhD. Notwithstanding his outstanding qualifications, he was without academic experience and the option of a university post did not exist. The problem was solved by P.M.S. Blackett, then Langworthy Professor of Physics at Manchester, who offered to support Hanbury for an ICI research fellowship. The Fellowship Committee were apprehensive about the appointment of a non-academic of Hanbury's age to a research fellowship, but backed by Blackett, Williams and the comments of external referees these scruples were overcome.

In October 1949 Hanbury joined Lovell's group at Jodrell as a candidate for the degree of PhD and his impact was instantaneous. At that time Lovell had only a small group of relatively inexperienced young men using ex-Army trailers as a laboratory and into that group Hanbury brought his years of international experience as an outstanding electrical engineer.

8 The Andromeda nebula

When Hanbury arrived at Jodrell a number of researches were in progress, mainly on meteors and on radio astronomy. J. A. Clegg had joined Lovell from TRE in the search for greater sensitivity for the detection of radar echoes from large cosmic ray showers (Blackett amp; Lovell, 1941; Lovell, 1993). They had built a large parabolic radio telescope from scaffolding poles and hawsers on which they had wound 16 miles of wire to form a 218-ft diameter reflector (see Lovell, 1968). The focus was carried on a 126-ft steel mast. This transit telescope had been used by a student to record the cosmic radio waves from the zenithal strips of sky. Hanbury's attention was directed to this instrument and with a research student, Cyril Hazard, he soon achieved an outstanding result.

At that time the subject of radio astronomy was in an early stage. The local galaxy was known to emit radio waves and in Australia J.G. Bolton and G.J. Stanley (1948; Bolton, 1948) had discovered a number of localised, small-diameter radio sources in the general background of the radio emission, while in Cambridge M. Ryle and F.G. Smith (1948) had discovered further localised radio sources in the northern hemisphere. One of these sources was identified with the Crab nebula and at that time the general belief was that the small-diameter sources were an unknown type of radio star in the Milky Way. Very few astronomers then believed that radio waves from outside the local galaxy formed a significant part of the cosmic radio waves received on Earth.

The shortest wavelength on which the transit telescope could be used was about 2 metres with a beamwidth of 2 degrees. Hanbury built a stable and sensitive receiver and with this on the transit telescope he and Hazard recorded the radio waves from space as the rotation of the Earth swept the vertical beam of the telescope through the 2-degree zenithal strip of the sky. The Andromeda nebula M31 was a small angular distance from the zenith and if the beam of the telescope could be moved from the vertical strip it seemed that a decisive answer could be obtained as to whether M31 was a source of radio waves similar to the Milky Way. The central mast of the transit telescope was held vertically by eighteen guy wires and the only way of shifting the beam from the zenith was to tilt this mast by adjusting these guy wires. To avoid kinking the slender mast only very small adjustments to the guy wires could be made but eventually Hanbury and Hazard succeeded in tilting the mast and hence the beam of the telescope 15 degrees either side of the zenith.

During ninety nights in the autumn of 1950 they succeeded in surveying the zenithal region of the sky containing the M31 nebula and obtained the first decisive proof that M31 emitted radio waves and that the phenomenon of radio emission was not unique to the local galaxy (2,3).

The detailed survey of the zenithal area continued with the 218-ft diameter transit telescope for nearly eight years until the 250-ft steerable telescope became operational. In this survey they discovered radio emission from the remnants of Tycho Brahe's 1572 supernova (6) and published papers dealing with the radio emission from the region of the intense sources in Cygnus and Cassiopeia (4,8), on 23 localised sources in the northern hemisphere (9), and on the general radio emission from the galaxy (10). Other papers dealt specifically with the radio emission from the galaxy M81 (11) and with the contribution of extragalactic radio emission (5,12). At a time when the nature of the localised radio sources was unexplained and many astronomers believed them to be a new type of radio star in the galaxy, Hanbury made a radio survey of the great loop in Cygnus with D. Walsh (18) and investigated the possibility that remnants of supernovae in the galaxy were the main contributors (16).

9 The intensity interferometer

These observations were made in the era when many localised sources of radio emission were discovered without positive identification with known objects. It was uncertain whether the radio sources were unknown types of stars in the galaxy or extragalactic objects. The positive identification of supernovae remnants in the galaxy and of a few extragalactic spiral nebulae as radio sources could be used to support either the galactic or extragalactic theories.[2] The lower limits placed on the positions of the localised sources covered an area of sky in which the conventional astronomical atlases revealed large numbers of objects and so attempts to identify a radio source were not successful. An important step was taken by Graham Smith in Cambridge when he succeeded in measuring the positions of the strong radio sources in Cassiopeia and Cygnus to within a minute of arc (Smith, 1951). In 1951 W. Baade amp; R. Minkowski photographed these areas of sky with the 200 inch Palomar telescope and discovered the optical counterpart of these two radio sources. The Cassiopeia radio source was identified as a faint filament of a supernova remnant in the Milky Way and the Cygnus source as a distant extragalactic object then believed to be two interacting extragalactic nebulae (W. Baade amp; R. Minkowski, 1954). This discovery increased the dilemma 8211; were the majority of localised radio sources galactic or extragalactic? Much lower limits had to be placed on the angular diameter of the unidentified radio sources if progress was to be made into their real nature.

One problem was that existing radio interferometers using spaced aerials were connected to the common receiver by cable and the necessity to preserve phase stability limited the separation of the aerials to a few kilometres. Thus the angular diameters of the radio sources were known only to be less than several minutes of arc, that is, some ten thousand times the angular diameter of visible stars.

During 1950 Hanbury joined in the discussions at Jodrell Bank about this problem. Techniques for using wavelengths below the metre wavebands did not then exist and the limits to angular size measurements were set by the difficulty of preserving phase stability along cable-connected aerials. If the radio sources were similar to the visible stars aerial separations of thousands of kilometres would be necessary to measure their angular size. There seemed no possibility of preserving the phase and amplitude over such distances.

Hanbury envisaged two separated individuals observing the noise-like signal from a source. If they saw similar signals a correlation would exist, but if they moved far enough apart the correlation would cease. Hanbury realised that the signal corresponded to the low-frequency fluctuations in the intensity of the source. Thus, the concept of the intensity interferometer emerged in which it was only necessary to compare the fluctuations in the intensity of a source as the separation of the receivers was increased until the correlation disappeared. This placed no limit on the separation of the receivers, since the comparison of the intensity of the fluctuations at the separate receivers could be made through cable, land line or radio link.

Hanbury stimulated two research students, R.C. Jennison and M.K. das Gupta, to develop an interferometer based on this idea. They constructed two independent receivers on a frequency of 125 Mc/s, each connected to its own antenna of aperture 500 sq. metres. The bandwidth of the receivers was 200 kc/s and after rectification in a square-law detector the signals were fed to a low-frequency filter with a passband of 1-2 kc/s.[3] The two outputs were multiplied together in a correlator and their cross correlation coefficient measured as a function of the baseline between the two antennas.

It had been envisaged that a large separation of the aerials would be necessary and the signals were to be combined by radio link. In fact, when the system was tested on the strong radio sources in Cygnus and Cassiopeia the correlation decreased within a baseline of a few kilometres. These preliminary results were published in December 1952 (7) and in more detail by Jennison amp; das Gupta (1953). The most important result was that the Cygnus radio source showed two lobes separated by 1'28" and that Cassiopeia was resolved over a similar baseline. Surprisingly, the angular diameters were only a little less than the lower limits of several minutes of arc established by the phase-correlation interferometer. A similar result using an extended baseline with the phase-correlation interferometer was established simultaneously in Cambridge by F.G. Smith (1952) and in Australia by B.Y. Mills (1952).

The intensity interferometer used a square-law detector and was relatively insensitive compared with the phase-correlation system. With rapid improvements in the technology of the phase-correlation interferometer, Hanbury's intensity interferometer did not survive as a technique for the measurement of the angular sizes of radio sources. As Hanbury later remarked, he had spent two years 'building a steamroller to crack a nut' (119, p.108). However, there were soon to be developments of this concept that again changed his career.

10 The development of the phase-correlation interferometer

There were soon more straightforward developments of the phase-correlation system both at Jodrell Bank and elsewhere. An interferometer using the transit telescope with a smaller transportable array was used to determine the angular diameters of the 23 localised sources already delineated by Hanbury and Hazard (9). Hanbury, H.P. Palmer and A.R. Thompson (15) soon obtained important results with this system. Of the 23 sources, those in Cassiopeia and Cygnus had already been measured and identified. For six others the amplitude of the interferometer fringes fell to zero at a baseline of about 50 wavelengths, implying that they were radio sources of large diameter 8211; 1 to 3 degrees. This added a fifth filamentary nebula (in Auriga) to those already known in the Milky Way. Five of the sources in the survey showed no sign of resolution when the baseline was increased to 500 wavelengths (about 1000 metres), and this raised the first of the new technical problems since it was not possible to maintain phase stability with further increases in the cable length and the shortest operational wavelength at which the transit telescope was efficient was 1.89 m. The alternative was to use a radio link from the remote array to the common receiver. A link was constructed on a frequency of 206 MHz with a separate link on 175 MHz to lock the local oscillators at the two antennae.

A further problem arose; since the two arrays were used as a transit instrument the fringe frequency of the interferometer pattern increased beyond the limits of reliable observation. To overcome this Hanbury, Palmer and Thompson developed a rotating-lobe interferometer, employing a rotating magslip phase-shifter driven at an adjustable speed by a velodyne motor (19). Measurements with this system began in June 1954 with a baseline of 480 wavelengths (0.91 km). The baseline was successively doubled until the sources were resolved. In September 1955 at a spacing of 6,700 wavelengths (12.8 km) two of the sources had been resolved but three showed no sign of resolution implying that their angular size must be less than 24 seconds of arc. Eventually in 1956 the remote array was moved to a high point in the Peak District at a spacing of 10,600 wavelengths (20 km). The three sources remained unresolved implying an angular diameter of less than 12 seconds of arc (Morris, Palmer amp; Thompson 1957). The implication was that these sources must be of the same type as the remote extragalactic sources in Cygnus.

The 250-ft Mk I radio telescope came into use in the autumn of 1957 and using this instrument instead of the transit telescope the angular diameter measurements were extended to several hundred radio sources. Several were found to have angular diameters of less than 3 seconds of arc and the important part this played in the discovery of quasars has been described by Hanbury (119) and by Lovell (1973). Hanbury used the MK I telescope to extend the survey of the 23 sources he had made with Hazard using the 218-ft transit telescope (9). These measurements are described in two papers on the radio emission from normal spiral galaxies (44) and from irregular and early type galaxies (45). He also joined in the early surveys with the MK I telescope of the angular sizes of radio sources (48).

During these years of intense interest in the optical identification of radio sources, in 1961 Hanbury decided to gain some practical experience. With R.D. Davies and J.E. Meaburn he used the telescope on the Pic du Midi in the Pyrenees to photograph a curious and unexplained feature of the radio sky (42) 8211; a huge arc of radio emission that they suggested might be a supernova remnant. They found no trace of any visible remnant that could be associated with the radio spur (49).

11 The optical interferometer

When the idea of the intensity interferometer arose, Hanbury's main concern was that the system would be too insensitive to measure the angular diameters of radio sources and he thought that a detailed mathematical treatment would be desirable before an observational system was developed. He was advised by Vivian Bowden to seek the assistance of Richard Twiss, formerly a mathematical scholar of Trinity Hall, Cambridge who had been in TRE during the war. Twiss was then at the Services Electronic Research Laboratory at Baldock. The association of Hanbury and Twiss led to consequences not then foreseen.

In their full mathematical treatment of the concept (14) Hanbury and Twiss concluded that although the idea could be used for measurements in the radio spectrum it could not be developed for the measurement of the angular diameter of stars in the optical spectrum because 'it breaks down due to the limitations imposed by photon noise'.

At that time it had been possible to measure the angular diameters of only a few of the giant stars, using a Michelson-type interferometer. Stellar diameters had been inferred from spectroscopic measurements of effective temperatures, from eclipsing binaries and in a few cases by lunar occultations. Much uncertainty existed about the diameters of the hotter stars of types O and B and of the nuclei of the Wolf-Rayet stars. To measure these it was believed that a mirror separation of the order of a mile might be necessary and this was beyond the possibility of the Michelson-type interferometer because of atmospheric turbulence.

It was against this background that discussion ensued about extending the radio intensity type of interferometer to the optical spectrum, notwithstanding the doubts already expressed by Hanbury and Twiss. Telescopic mirrors would replace the radio antennae and photoelectric cells the radio receivers. The system would work only if the times of arrival of photons at the two photocathodes were correlated when the light beams incident on the two mirrors were coherent 8211; and if the correlation was preserved in the photoelectric system. Such correlation of photons from a light source had never been observed and the possibility was denied by many theorists.

In order to test this contentious issue, Hanbury and Twiss designed a laboratory experiment in 1955. A light source was formed by a small rectangular aperture, on which the image of a high-pressure mercury arc was focused. The 4358 line was isolated by filters, and the beam was divided by a half-silvered mirror to illuminate the cathodes of two photomultipliers. The two cathodes were at a distance of 2.65 m from the source and their areas were limited by identical rectangular apertures. In order that the degree of coherence of the two light beams might be varied, one photomultiplier was mounted on a horizontal slide that could traverse normal to the incident light. The two cathode apertures, as viewed from the source, could thus be superimposed or separated by any amount up to about three times their own width. The fluctuations in the output currents from the photomultipliers were amplified over the band 3-27 Mc/s and multiplied together in a linear mixer. The average value of the product, which was recorded on the revolution counter of an integrating motor, gave a measure of the correlation in the fluctuations. The results of this laboratory experiment, published early in 1956 (23), showed beyond question that the photons in two coherent beams of light are correlated, and that this correlation is preserved in the process of photoelectric emission. Furthermore, the quantitative results were in fair agreement with those predicted by classical electromagnetic wave theory and the correspondence principle.

The publication of these results led to much dispute in the scientific community (see for example 119, p.120). In particular, two independent groups attempted to repeat the experiment and concluded that Hanbury and Twiss had misinterpreted their data and that if such a correlation existed, a major revision of fundamental concepts in quantum mechanics would be required (dm, Jnossy amp; Varga, 1955; Brannen amp; Ferguson, 1956). In their response (25) Hanbury and Twiss pointed out that although the experimental procedure in both cases was beyond reproach, their critics had missed the essential point that correlation could not be observed in a coincidence counter unless one had an extremely intense source of light of narrow bandwidth. Hanbury and Twiss had used a linear multiplier that was counting a million times more photons than the coincidence system used in their critics' experiments. In fact, they calculated that Brannen and Ferguson would need to count for 1,000 years before observing the effect and dm ¡em¿et al.¡/em¿ for 10¡sup¿11¡/sup¿ years. They also responded (27) to a criticism of their theoretical treatment by Fellgett (1957) and subsequently, in order to settle all remaining arguments, the laboratory experiment was repeated using the coincidence counting system of Brannen and Ferguson but with an intense narrow-band isotope light source with which they observed the expected correlation in a series of twenty-minute runs. With the isotope light source replaced by a tungsten filament lamp, no correlation could be found (29).

12 Measurement of the angular diameter of Sirius

In the meantime Hanbury had assembled equipment to measure the angular diameter of the star Sirius. For the two mirrors he borrowed two Army searchlights of diameter 156 cm and with a focal length of 65 cm. These focused the light from Sirius on to the cathodes of photomultipliers. The intensity fluctuations in the anode currents were amplified over a band 5-45 Mc/s. The outputs were multiplied in a linear mixer and the product recorded on the revolution counter of an integrating motor that gave a direct measure of the correlation between the intensity fluctuations in the light received from Sirius in the two mirrors.

The two searchlights were placed 6.1 m apart on a north-south line near the incomplete structure of the 250-ft radio telescope at Jodrell Bank and the receiver system was mounted in the then empty control room. Sirius was observed within 2 hr of transit (elevation between 15 and 20). Observations were attempted on every night in the first and last quarters of the moon during November and December 1955. A second series with the searchlight mirrors on an east-west baseline of 5.6, 7.3 and 9.2 m was made in January-March 1956.

The difficulties and hazards of this experiment carried out almost unaided by Hanbury have been described by him (119, p.123) and the observational details and results were published by Hanbury and Twiss in 1956 (24). The best fit to the observations was given by a disk of angular diameter 0.0068¡sup¿2¡/sup¿ with a probable error of 0.0005¡sup¿2¡/sup¿. The angular diameter of Sirius predicted from astrophysical theory is 0.0063¡sup¿2¡/sup¿. This first direct measurement of the angular diameter of a star for thirty years was published in November 1956 when arguments over the interpretation of the laboratory experiment on the correlation of photons were taking place. After this brilliant practical vindication the phenomenon became known as the Hanbury Brown-Twiss effect.

In 1957 and 1958 Hanbury and Twiss published four major papers on their work. In Part I (30) they developed the basic theory of the correlation between photons in coherent beams of radiation. They concluded that the phenomenon exemplified the wave rather than the particle aspect of light, and was most easily interpreted as a correlation between the intensity fluctuations at different points of the wave front that arose because of interference between different frequency components of the light. On the corpuscular picture they showed that the correlation was related to the bunching of photons arising because quanta are mutually indistinguishable and obey Bose-Einstein statistics.

In Part II (31) they described an experimental test of the theory for partially coherent light. Two photomultipliers were illuminated with partially coherent light and the correlation measured as a function of the degree of coherence. In Part III (34) they discussed the application of the principle to astronomy. They concluded that the relative insensitivity of the intensity interferometer probably limits angular diameter measurements to stars visible to the naked eye but that the measurements would be substantially unaffected by atmospheric scintillation. In Part IV (35) they described in detail the test of the intensity interferometer on Sirius A. In this paper a detailed theoretical analysis was presented of the measurement, and the value for the angular diameter of Sirius given in the preliminary description of the work (24) was revised to 0.0069 0.0004”.

13 The Narrabri stellar intensity interferometer

The success of this measurement encouraged Hanbury and Twiss to envisage a stellar interferometer for measuring the diameters of 200 stars. Hanbury has described the successive attempts to finance such an instrument (119). Originally they proposed to site the interferometer under the clear skies of Haute Provence. However, Twiss had moved to Australia and the difficulty of securing a sufficient grant from the Department of Scientific and Industrial Research (DSIR), to which Hanbury had applied, led Twiss to approach H. Messel, head of the School of Physics of the University of Sydney. Eventually this resulted in a joint project between the DSIR and the Universities of Sydney and Manchester for the stellar interferometer to be built in Australia.

The interferometer had two reflectors of approximately 7 m diameter, the reflecting surfaces of which each consisted of 252 small spherically-curved hexagonal-shaped mirrors mounted on a paraboloidal framework. The reflectors were mounted on carriages that moved on a 188 m diameter circular railway track so that a line joining them always remained perpendicular to the star being observed, thus equalizing the paths from the star to each reflector. The reflectors, control system, and correlator electronics were developed and constructed in England but were not fully assembled or tested before being shipped to Australia in 1962. Messel and Twiss had chosen a site for the instrument in northern New South Wales, near the small town of Narrabri, some 550 km by road from Sydney. The site was located on a 3,000-acre sheep property and, being west of the Great Dividing Range, promised clear nights for 60-70Hanbury was given leave of absence by the University of Manchester to erect and test the interferometer with the expectation that Twiss would remain there to supervise the measurement of stellar diameters. However, Twiss returned to Europe and in 1964 Hanbury resigned from his Chair in the University of Manchester and resided in Australia for the remainder of his scientific career.

14 Installation and commissioning

When Hanbury arrived in Narrabri in early 1962, the circular railway track, central control building and garage for housing the reflectors were complete and the components for the reflectors were arriving from Sydney after their sea voyage from England. The assembly and testing of the Narrabri Stellar Intensity Interferometer (NSII) was a daunting task in the heat of an outback Australian summer with relentless swarms of flies and the need to be aware of poisonous snakes and spiders. The interferometer was located on a tongue of red soil running out from the Nandewar range of mountains 40 km to the east and lay some 10 km north of the town of Narrabri. The site was almost surrounded by black soil that was unsuitable for the instrument's foundations but that was less prone to dust storms than red soil. Unfortunately, after rain, black soil can only be traversed in a four-wheel drive vehicle and at worst it becomes impassable. Hanbury moved his family to Narrabri and, after five days of rain initially prevented him from getting to the site, he plunged into the challenge of assembling the interferometer in spite of the many difficulties facing him. Twiss was now in England supervising the completion and testing of the correlator electronics being developed by Mullards. Cyril Hazard and John Davis, both from Jodrell Bank, had preceded Hanbury from England to work in the interferometer programme and had been appointed to the staff of the School of Physics at the University of Sydney. The story of the assembly and testing of the Interferometer has been described by Hanbury in ¡em¿The Intensity Interferometer¡/em¿ (77) and in ¡em¿Boffin¡/em¿ (119).

Many problems were encountered during the commissioning phase and were solved through Hanbury's single-mindedness and determination. Difficulties in getting the reflector carriages to move smoothly on the track were overcome by having new wheels machined to Hanbury's specification but, as with any other significant machine-shop tasks, the nearest place equipped to do it was over 150 km away 8211; mostly over dirt and gravel roads. Colourful parrots swung from the catenary cables between the carriages and a central mast and chewed through the signal-carrying coaxial cables so that they had to be provided with a parrot-proof wrapping. Venomous black snakes coiled themselves amongst coils of black coaxial cables of comparable thickness! These and other problems have been described by Hanbury in his books, but he accepted the challenges with his usual cheerful and very much hands-on approach. Throughout the commissioning and observational programme of the NSII the group was small in number and, including Hanbury, never exceeded four scientists. As Hanbury wrote in ¡em¿The Intensity Interferometer¡/em¿ (77, p.19), based on his experience in the early days of radar and of radio astronomy, he knew 'how much easier it is to maintain interest in a project if everybody has a large personal share in the responsibility of the venture as well as in the routine' and that this necessarily meant a small group. He led a harmonious group by example and never asked anyone to do anything he was not prepared to do himself if he could.

The arrival of the electronic correlator from England in January 1963 brought its own problems but once they were solved, a bright early-type star, ¡font face="symbol"¿b¡/font¿ Centauri, was chosen for the first stellar observational tests. It was an ideal choice based on the knowledge of the star at the time but initially it gave absolutely no correlation. Hanbury reviewed the theory and every aspect of the instrument with Twiss before realizing that, although the time delays in the cables and correlator had been carefully matched, it was not known how well the delays in the photomultipliers were matched. It was soon shown that they were not matched but as soon as they were, correlation was observed 8211; but only about half that expected. The concern raised by this observation was finally dispelled when the instrument was turned to observe Vega (¡font face="symbol"¿a¡/font¿ Lyrae); the expected correlation was obtained and the first angular diameter was determined with the new instrument (51). Subsequent observations led to the conclusion that ¡font face=”symbol”¿b¡/font¿ Centauri was not a single star but an unexpected binary star with components of approximately equal brightness.

15 The stellar programme

Following the successful observations of Vega the observational programme settled down to determine the angular diameters of early-type stars 8211; the NSII was limited to stars hotter than the Sun. Hanbury had resigned from his Manchester chair in 1964 and had been appointed to a Chair of Physics (Astronomy) at the University of Sydney and to head the new Chatterton Astronomy Department, a research department established by Messel for the NSII programme. This was a key factor in ensuring the success of the programme and a number of original and important observations were made including the interferometric investigation of the Wolf-Rayet binary system ¡font face=”symbol”¿g¡/font¿¡sup¿2¡/sup¿ Velorum (65), the measurement of the angular diameter of the early O star ¡font face=”symbol”¿z¡/font¿ Puppis (66), the first detailed study of a double-lined spectroscopic binary (¡font face=”symbol”¿a¡/font¿ Virginis) combining interferometric and spectroscopic measurements to determine stellar masses and distance as well as the effective temperature, radius, and luminosity of the primary component (68). At the end of the stellar observational programme in January 1972, the angular diameters of 32 stars had been measured (73). In a collaboration with astronomers at the University of Wisconsin the effective temperature scale and bolometric corrections for early-type stars were established (82). In 1997, an International Astronomical Union Symposium on 'Fundamental Stellar Properties: the Interaction between Observation and Theory' (Bedding, Booth amp; Davis, eds, 1997) was held in Sydney in honour of Hanbury's 80th birthday. Remarkably, the results obtained with the NSII had stood the test of time and had not been superseded, some 25 years after the NSII stellar observational programme was completed.

Throughout the programme Hanbury strove to improve the sensitivity, stability and performance of the NSII. New photomultipliers were introduced when gains in quantum efficiency or radio frequency bandwidth became available and a progressive switch from vacuum-tube to solid-state electronics was made. In particular, a transistorized version of the linear multiplier, a key component of the correlator, was developed by L.R. Allen and R.H. Frater (1970). The resulting improvement in the stability of the correlator was vital for the observations of fainter stars towards the end of the stellar programme.

In addition to the observational results outlined above, a number of exploratory experiments were carried out at Hanbury's instigation. These included attempts to reveal the effects of distortion of a rapidly rotating star (¡font face=”symbol”¿a¡/font¿ Aquilae), the effects of limb darkening on the instrumental response with baseline (Sirius) (74), and electron scattering in the atmosphere of an early-type star (¡font face=”symbol”¿b¡/font¿ Orionis) (75). Unfortunately the NSII lacked the sensitivity to produce significant results in these experiments but the work showed the potential of interferometry for studies in stellar astrophysics. Only now, some thirty years later, have instruments been developed that are capable of extending the NSII's pioneering work. The potential effect of Cerenkov light in producing spurious correlation was also explored with a null result (62) and a number of previously unsuspected binaries were also identified in the course of the observational programme. Although it would have been possible to continue a stellar programme it was clear that it would only add data of much lower precision on fainter stars of similar types to those already measured. Hanbury decided that this would not add anything of scientific significance to the results of the programme.

16 Gamma rays

At the completion of the stellar observational programme in January 1972, Hanbury received a proposal from the Center for Astrophysics (CfA) in Cambridge, Massachusetts, to use the NSII to look for extra-terrestrial gamma rays by detection of the Cerenkov radiation produced when they enter the Earth's atmosphere. Scientists from the CfA brought detectors and electronics to Narrabri and, in a collaborative programme, observations were made in 1972-4. The results were disappointing in that only one source of gamma rays, the radio galaxy Centaurus A, was discovered. Evidence was also obtained to suggest that the pulsar in Vela (PSR 0833-45) is a source of gamma rays. The characteristic double peak signal, symmetrical about the direction to a high-energy gamma ray source, was recorded for the Crab nebula on one night but, as follow-up observations failed to confirm the result, it was not published. The Crab nebula has since been shown to be a variable source of gamma rays and, in hindsight, the NSII almost certainly made the first gamma ray detection from this source. The results of this collaborative programme were published in a series of papers (71, 78, 79).

17 Closure of the Narrabri stellar intensity interferometer

At the completion of the gamma-ray programme, Hanbury kept the NSII intact for a further four years in case a worthwhile proposal for its use was forthcoming. In 1978, in view of the continuing costs of maintaining the site, he decided that it was appropriate to dismantle the instrument and restore the site to the property owners. He was reluctant to do this himself and left John Davis (JD) to complete the task. The NSII was an outstanding example of an instrument optimally designed for a particular task. Hanbury was proud of the fact that he had built an instrument to carry out a specific programme, that it had done so successfully, and that he had closed it on that note rather than prolong its life for work of low significance.

18 A successor to the Narrabri stellar intensity interferometer

In 1970, as it became clear that the end of the observational programme was approaching, Hanbury started to look for a new project. His initial idea, supported by Messel, was to build a medium-sized conventional telescope with an aperture in the 2-2.5 m range and to couple this with electronic detectors that were becoming available 8211; the photographic plate then being still the primary recording medium. Hanbury felt that optical astronomers needed to be shown the way! Although the Anglo-Australian Telescope project had been under discussion between the British and Australian Governments for some years, the Anglo-Australian Telescope Agreement had not been ratified at this stage and the Act and supporting regulations did not come into effect until February 1971 (Gascoigne, Proust amp; Robins 1990). Hanbury embarked on a tour of telescope manufacturers in the UK, Europe and the USA with JD and the wisdom of demonstrating what could be done using a 2 m telescope, constructed primarily for that purpose, was discussed. Once the value of electronic detection had been demonstrated, it would be quickly adopted on larger telescopes and a 2 m telescope would no longer be at the pioneering frontiers of astronomical research.

The NSII had demonstrated the potential of interferometry for stellar studies and the development of a more sensitive intensity interferometer was considered. Hanbury explored the astronomical potential of stellar interferometry with JD and they developed a proposal for a large stellar intensity interferometer. The performance of the proposed instrument could be confidently predicted based on the experience gained with the NSII, since the only instrumental parameters affecting the sensitivity were the area of the light-collecting apertures, the quantum efficiency and radio-frequency bandwidth of the detectors, and the number of optical passbands that could be correlated separately.

The proposed instrument was to have straight railway tracks running to the east and west of a central building that would house fixed paraboloidal reflectors with their optical axes directed along the tracks. Large flat reflectors on the railway tracks would reflect starlight into the fixed paraboloids. In order to keep the cost within reasonable limits low-quality optics were envisaged, similar to those used in the NSII, but with tighter tolerances on path variations commensurate with the anticipated increased radio-frequency bandwidth. High-quality optics were required if conventional dispersion techniques were to be used to provide multiple optical channels but this would have been prohibitively expensive. The design was therefore a compromise, with the optical channels being defined by dichroic multilayer mirrors and filters. Assuming two 12 m diameter apertures in each arm of the interferometer, a radio-frequency bandwidth of 1 GHz, and ten optical channels, the limiting magnitude was estimated to be +7.3 compared with +2.5 for the NSII.

A proposal for the new interferometer was submitted to the Australian Government in 1971 and in 1974 the Government announced that it would make an initial grant of $75,000 'to make a design study of a large interferometer' and that it 'would consider further grants for the construction of the interferometer following the design study, when a firm estimate of the construction cost would be available'.

During the period the Government was considering the proposal, a number of important developments were taking place. Antoine Labeyrie had developed the new technique of speckle interferometry (1970) and was working on a Michelson-type interferometer with two small telescopes (1975). Significant advances in active optics had been made, accompanied by a greatly improved understanding of the effects of atmospheric turbulence. These developments suggested that a modern form of Michelson's original stellar interferometer (Michelson amp; Pease 1921), an amplitude interferometer, could be built using modern technology that would overcome the atmospheric and mechanical problems that had prevented the development of Michelson's technique. The concern was that an amplitude interferometer, in principle inherently more sensitive than an intensity interferometer, might be built by others in parallel with the new intensity interferometer and that, if it had significantly greater sensitivity, it would leave the intensity interferometer akin to a white elephant. A particular concern was that the predicted limiting magnitude for the new intensity interferometer was regarded as marginal for several of the most interesting observational stellar programmes. While the gains from increased aperture area and the number of optical channels could be predicted with certainty, the gain based on extrapolation of the performance of photomultipliers was uncertain. The predictions of the manufacturers were judged to be optimistic 8211; and time has proved the judgment to be correct. After the award of the initial grant, Hanbury's first step was to undertake a fact-finding tour of potential suppliers of critical components for the new interferometer in the USA, accompanied by JD. JD continued to the UK and Europe to gather information on the prospects for the development of an amplitude interferometer and, in particular, he visited Twiss to see the prototype amplitude interferometer that he was developing at Monte Porzio near Rome. A detailed comparison of the relative merits of intensity and amplitude interferometers was made and it became clear that an amplitude interferometer appeared more attractive 8211; it would be cheaper to build and, at least on paper, it would be more sensitive. Further discussions were held with Twiss and Labeyrie, and with Welford [4] in London. It was a difficult decision for Hanbury but he concluded that 'in the long run, an amplitude interferometer was more promising and we accepted the challenge of developing it' (119, p.161). The outcome was a decision to build a prototype amplitude interferometer and Hanbury persuaded the Australian Government to allow the design study grant to be converted into a grant for exploring the potential of amplitude interferometry. William Tango, who had worked with Twiss in Italy, was recruited to assist in the design and development of the prototype. Hanbury was approaching retirement and, while retaining a close interest in the project and giving it his wholehearted support, he chose to pass responsibility for the project to JD. Hanbury officially retired from his Chair at the University of Sydney at the end of 1981.

Fringes were obtained with the prototype interferometer and the angular diameter of Sirius was measured in 1985 giving a result in excellent agreement with the NSII value (Davis amp; Tango 1986). JD wrote a proposal in collaboration with Tango and Hanbury the same year for a large amplitude interferometer. Although Hanbury had decided not to have an active involvement in the design and implementation of the project, he maintained his strong interest in it and, as he had promised, gave his wholehearted support and assistance to the raising of funds for the new interferometer, which has become known as the Sydney University Stellar Interferometer (SUSI) (Davis ¡em¿et al.¡/em¿ 1999). Although he lived in England for the last years of his life, Hanbury maintained his interest in SUSI and its scientific programme.

During the development of the prototype interferometer, having chosen not to have a direct involvement, Hanbury undertook a number of administrative tasks that he 'had so far managed to avoid'. Although, in his own words, he was not 'a willing committee-animal' (119, p.164) he felt it was his duty to serve on a number of committees for the Australian Government and for the Australian Academy of Science. One very important contribution he made was to the committee called to advise the Minister of Science on the running of the 150 inch Anglo-Australian Telescope. Hanbury fervently believed that it should be run as a national facility with an independent director, a view strongly opposed by the Australian National University and the Director of their Mt Stromlo Observatory. The latter maintained that, as the owner of all the major optical telescopes in Australia, they were best able to run the new telescope. It took a great deal to disturb Hanbury's equanimity but this was an issue that he felt very strongly about. A letter he wrote to the Australian Minister for Science on 11 April 1973 precipitated the final solution (Gascoigne, Proust amp; Robins, 1990, p.144). The subsequent establishment of the Anglo-Australian Observatory ensured that the principle of national facilities was accepted in Australia. Hanbury found his service with the Australian Research Grants Committee (1979-81), advising on the distribution of government research grants to universities and colleges, to be amongst the most rewarding of all the committee work he undertook.

19 Postscript on the choice on interferometric technique

Amplitude interferometry is the technique of choice for the many optical/infrared instruments that have been or are being developed. Only now are amplitude interferometers exceeding the sensitivity limit that would have been achieved with the very large intensity interferometer that Hanbury abandoned. While the conclusion that the amplitude interferometer was more promising in the long run was undoubtedly correct, it is also clear in hindsight that the large intensity interferometer would have achieved many significant results before an amplitude interferometer became competitive.

20 The Hanbury Brown-Twiss effect

The basis of the intensity interferometer, which may be viewed as a correlation between intensity fluctuations at different points on a wavefront or, with the particle picture, as due to 'photon bunching' arising because light quanta are mutually indistinguishable and obey Bose-Einstein statistics, has become known as the Hanbury Brown-Twiss effect. Hanbury's original insight and the seminal experiments he carried out with Twiss were a significant factor in the development of the field of quantum optics. Furthermore, in particle physics, it has become a standard technique in high-energy collisions, from heavy ions to meson-nucleon interactions, to electron-positron annihilation, and to anti-correlations of fermions in nuclear collisions (Baym, 1998). Anti-correlations in the arrival times of free electrons at two detectors illuminated coherently by an electron field emitter have been demonstrated by H. Kiesel, A. Renz amp; F. Hasselbach (2002) and represent the fermionic twin of the Hanbury Brown-Twiss effect for photons.

Hanbury's career as a research scientist was remarkable. When chance brought him to Jodrell Bank in 1949 at the age of 33 he was known as a pioneer of radar but not as an astronomer or scientist, and he registered for the degree of PhD with the aim of improving his academic qualifications. Within a few years he became a most distinguished figure in the international field of physics and astronomy. In 1960 the University of Manchester elected him to a personal chair of radio astronomy and awarded him the honorary degree of DSc, and he was elected a Fellow of the Royal Society of London in the same year.

Hanbury's immediate success in research came from the impact of his long experience in radar technology with the nascent science of radio astronomy. He was a scientist of the heroic age who could design and construct his own equipment and who seemed to thrive when faced with almost insuperable physical conditions 8211; witness his measurements of the radio emission from Andromeda nebula in 1950 and his single-handed measurements of the angular diameter of Sirius under the appalling conditions of winter nights at Jodrell

Bank in 1955. Then his determination led him to construct and use a complex astronomical instrument at Narrabri in the Australian bush, surrounded by natural and physical hazards that were antagonistic to reliable astronomical measurements.

Throughout, Hanbury retained his lively sense of humour and the wider vision of a cultured man. He was internationally respected and admired 8211; nowhere is this more evident than in the fact that within the space of a few years he addressed the World Council of Churches in 1979 on 'Faith, Science and the Future' and also presided over the International Astronomical Union meeting in Delhi during his term of office as President 1982-85. Hanbury became increasingly interested in the relation of science to society. His book ¡em¿The Wisdom of Science¡/em¿ (112) is concerned with the relevance of science to culture and religion. His last book, ¡em¿There are No Dinosaurs in the Bible¡/em¿, (127) written for his grandchildren and unpublished at the time of his death reflects his ultimate conclusion that there are fundamental issues in science that lie beyond human understanding.

1959 The Holweck Prize of The Physical Society 'in recognition of his work in radio astronomy'

1960 Elected Fellow of the Royal Society

1967 Elected Fellow of the Australian Academy of Science

1968 Eddington Medal of the RAS (jointly with R.Q. Twiss): 'For their invention and theoretical study of the intensity interferometer which has led to accurate measurements of the angular diameters of a number of stars'

1970 Lyle Medal of the Australian Academy of Science 8211; recognizing outstanding achievement by a scientist in Australia for research in mathematics or physics

1971 Britannica Australia Award 8211; Science: 'For outstanding achievements in Astronomy and Radio Astronomy'

1971 Hughes Medal of The Royal Society

1971 Commonwealth Visiting Professor, University College, London

1975 Raman Visiting Professor, Indian Academy of Sciences, Raman Research Institute, Bangalore

1975 Elected Honorary Fellow of the Indian Academy of Sciences

1976 Elected Foreign Fellow of the Indian National Science Academy

1977-9 Vice-President, Australian Academy of Science

1982 The Albert A. Michelson Medal of the Franklin Institute (jointly with R.Q. Twiss): 'For their prediction and experimental verification of the existence of enhanced intensity correlations with monochromatic thermal light, and for their successful construction of the stellar intensity interferometer for the measurement of the angular diameter of stars'

1982 Matthew Flinders Medal and Lecture of the Australian Academy of Science 8211; recognising scientific research of the highest standing in the physical sciences

1982-5 President of the International Astronomical Union

1986 Elected Associate of the Royal Astronomical Society

1986 Companion of the General Division of the Order of Australia

1987 ANZAAS Medal

¡a name=”19”¿¡/a¿¡strong¿Diplomas and Degrees¡/strong¿

1935 BSc (First Class Honours) Engineering, London

1938 Diploma of Membership of the Imperial College of Science and Technology (For course in Advanced Study in Electrical Communications, 1935-6)

1960 Doctor of Science, University of Manchester

1984 Doctor of Science (Honoris Causa), University of Sydney

1984 Doctor of Science (Honoris Causa), Monash University

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¡a name="23"¿¡/a¿¡strong¿Notes¡/strong¿ 1. With the development of the Plan Position Indicator (PPI) and with a rotating aerial array so that the echoe from both the fighter and the target could be displayed, success was achieved. The main research group moved from Dundee to Worth Matrevers in Dorset in April 1940 and in October of that year the first night operations with Ground Control Interception (GCI) took place. In November the first successful combat occurred and by May 1941 more than 10bombers were being destroyed. 2. At the Eleventh Solvay Conference in Brussels in 1958 on 'The structure and evolution of the Universe' it was reported (Lovell, 1958) that of the 2000 radio sources then listed in the Sydney and Cambridge Catalogues, only 16 normal and 7 abnormal extragalactic nebulae had been identified as radio sources, and in the local galaxy, 3 supernova remnants, 5 gaseous nebula and 15 emission nebulae of ionised hydrogen near hot stars had been similarly identified. 3. During the years covered in this memoir the notation used for the frequency of radio waves changed by international agreement from c/s (cycles per second), kc/s (kilocycles per second), and Mc/s (megacycles per second) to Hz (hertz), kHz (kilohertz), and MHz (megahertz). We have retained the nomenclature appropriate to the years and documents in question. 4. The late Professor W.T. Welford was an expert in optical design who had made significant contributions to the design of Twiss's prototype amplitude interferometer. ¡/p¿¡/span¿

¡/p¿¡hr¿ ¡em¿¡/em¿¡p¿ ¡em¿¡a name="by"¿¡/a¿John Davis, School of Physics, University of Sydney, Australia. ¡/em¿ ¡em¿Sir Bernard Lovell, FRS, Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire, UK. ¡/em¿