JOHN BOLTON AND THE DISCOVERY OF DISCRETE RADIO SOURCES

Peter Robertson
School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia; and School of Agriculture, Computational and Environmental Science, University of Southern Queensland, Toowoomba,Queensland 4350, Australia.
Email: prob@unimelb.edu.au

Wayne Orchiston
National Astronomical Research Institute of Thailand, Heay Keaw Road, Chiang Mai, Thailand; and School of Agriculture, Computational and Environmental Science, University of Southern Queensland, Toowoomba, Queensland 4350, Australia.
Email: wayne.orchiston@narit.or.th

and

Bruce Slee
CSIRO Astronomy and Space Sciences, PO Box 76, Epping, NSW 2121, Australia.
Email: Bruce.Slee@csiro.au

Abstract: John Bolton was born in Sheffield in 1922 and educated at Cambridge University. After wartime service in the Royal Navy, in 1946 he joined the CSIRO's Radiophysics Laboratory in Sydney and began work in the fledgling field of radio astronomy. Radio emission from our Galaxy had been discovered and studied during the 1930s by the Americans Karl Jansky and Grote Reber. It was thought that the emission emanated from interstellar space, but the mechanism was unknown.

In June 1947, observing from Dover Heights near the entrance to Sydney Harbour, Bolton discovered that strong emission from the constellation of Cygnus came from a discrete point-like source. By the end of the year, with colleagues Gordon Stanley and Bruce Slee (a co-author of this paper), Bolton had discovered a further five of these discrete sources. However, the positions measured for them were not accurate enough to allow them to be identified optically with any known celestial objects.

In 1948 Bolton organised a three-month expedition to New Zealand where there were observing sites superior to the one at Dover Heights. The new observations gave more accurate positions and allowed Bolton to identify three of the sources: one was a supernova remnant in our Galaxy and two were unusual extragalactic objects. This paper will document this remarkable chapter in the development of twentieth century astronomy.

Keywords: John Bolton, Australian radio astronomy, discrete radio sources, optical identifications, sea interferometry, Dover Heights field station, Gordon Stanley, Bruce Slee

1 INTRODUCTION

The detection of radio waves from space in 1931 by the American physicist Karl Jansky was one of the most important discoveries of twentieth century astronomy. It opened a new 'window' in the electromagnetic spectrum through which astronomers could study the Universe. Jansky's discovery was followed up by a fellow American, the radio engineer Grote Reber, who produced maps of the intensity of radio emission across the sky. The third major breakthrough was made in 1947 by John Bolton and colleagues Gordon Stanley and Bruce Slee at the Dover Heights field station in Sydney. They were able to resolve some of the radio emission observed by Jansky and Reber into individual discrete sources. In 1949 they successfully identified three of these sources with unusual optical objects already known to astronomers. The identifications built a bridge between traditional optical astronomy and the fledgling new field of radio astronomy.

Before we examine this story in more detail, it will be useful to learn something of Bolton's background.[1] He was born in June 1922 in Sheffield, Yorkshire. Both his parents were school teachers, although his mother stopped teaching after John's birth. His parents made two unsuccessful attempts to start John at school, caused apparently by his unwillingness to accept the authority of the teacher. Fortunately there was a law in Yorkshire at this time that ruled it was not compulsory for a child to attend primary school if either parent was a teacher. John's mother taught him the basics, but otherwise Bolton was largely self-taught, reading whatever took his interest. He developed an independence of mind that seems to have

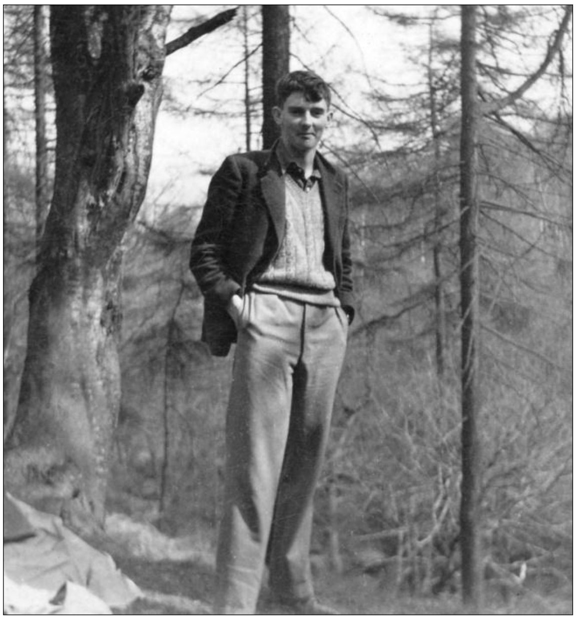


Figure 1: John Bolton at the time he entered Trinity College, Cambridge in 1940 (courtesy: Bolton family).

served him well during his career as a radio astronomer.

Bolton eventually entered primary school in grade 6 and then went on to Sheffield's leading secondary school. It was not until his final two years that he developed a special interest in physics and mathematics. He was fortunate to have his father, who was the senior mathematics teacher at another secondary school, as his tutor. In 1940 Bolton won two scholarships to study science at Trinity College, Cambridge (see Figure 1). Because of wartime conditions the normal three-year bachelor's degree was compressed into two.

Figure 2: Sydney localities mentioned in the text. Key: 1 = Collaroy, 2 = Dover Heights, 3 = Long Reef, 4 = Parramatta Observatory, 5 = Potts Hill, 6 = Radiophysics Laboratory, 7 = Georges Heights, 8 = West Head.

On graduating, Bolton joined the Royal Navy Voluntary Reserve. He spent two years carrying out research on airborne radar systems, first in Scotland and then at the Telecommunications Research Establishment in Worcester. In 1944 he was appointed radio officer on the British aircraft carrier *The Unicorn*, which saw out the remainder of the war on service in the Pacific. Bolton once remarked that his four years in the navy were far better preparation for his future career in radio astronomy than any Ph.D. program at a university (Robertson, 1984a).

At the end of the war Bolton decided not to return to England. After his discharge from the navy he applied successfully for a Research Officer position with the Radiophysics Laboratory in Sydney, a division of Australia's Council for Scientific and Industrial Research. The Radiophysics Laboratory, located in the grounds of the University of Sydney (for Sydney locations mentioned in the text see Figure 2), had been formed in 1940 to carry out secret research on radar for the Australian armed services. At the end of the war the Laboratory turned from wartime research to peacetime applications of radar and radio technology. As we see below, research in radio astronomy flourished in the Laboratory in the post-war years, largely through the activities of small groups of radio astronomers located at various field stations in or near Sydney. Observations also were carried out from the roof of the Radiophysics Laboratory, in central Sydney (see Orchiston and Slee, 2005; Robertson, 1992).

2 THE DISCOVERY OF EXTRATERRESTIAL RADIO EMISSION

To understand how Bolton's career developed during the post-war years, we need to go back to the beginning of radio astronomy some 15 years earlier (see Sullivan, 2009 for a comprehensive study on the origins of radio astronomy).[2] Many new fields of science have started as a result of serendipity, rather than design. Radio astronomy is a shining example. After graduating in physics, Karl Guthe Jansky (1905–1950; Sullivan, 1983; 1984a; 1984b) joined the Bell Telephone Laboratories in 1928 and was assigned the task of investigating sources of atmospheric static which might interfere with a new trans-Atlantic radio communication system. In 1931, at Bell's field station near Holmdel, New Jersey, Jansky constructed an aerial array mounted on four wheels with a small motor and chain drive which could rotate the array, a contraption which earned the name the 'merry-go-round' (Figure 3).

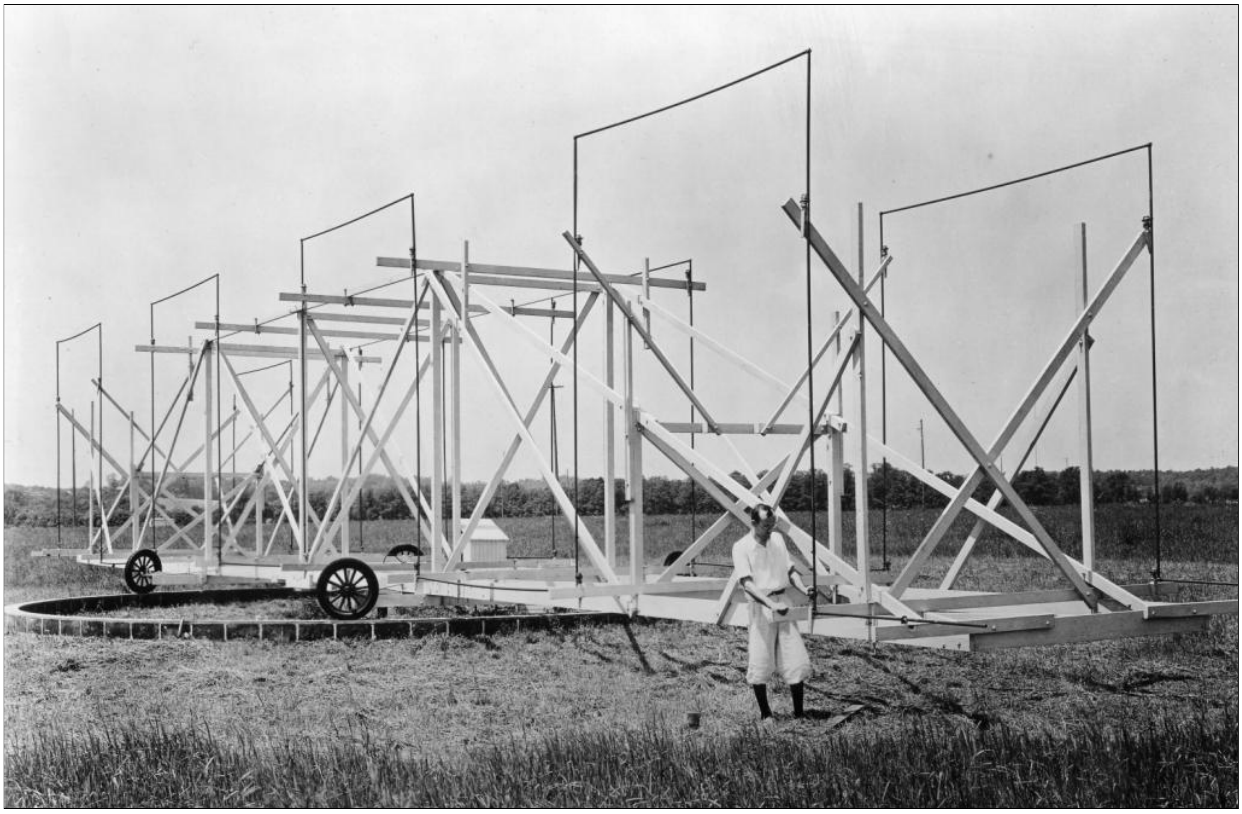


Figure 3: Karl Jansky and the 'merry-go-round' aerial used to discover extraterrestrial radio waves in 1931 (courtesy: AIP Emilio Segré Visual Archive).

Jansky was able to distinguish three distinct types of radio static. The first arose from local thunderstorms and the second was a weaker, steadier static due to the combined effect of many distant storms. The third type was composed of a very weak and steady hiss of unknown origin. Initially Jansky thought that the hiss was caused by some source of industrial interference, but then he noticed that the maximum strength of the signal came from a direction which moved around the sky each day and seemed to correspond roughly with the position of the Sun. The observations continued throughout 1932 and Jansky found that, contrary to what he first believed, the direction of the static began to drift further away from the position of the Sun. The daily period of variation of the noise was 23 hours and 56 minutes, known as the sidereal day, so Jansky concluded that the source of the noise must lie beyond the Sun, and beyond the Solar System as well. In his first two papers Jansky (1932; 1933) would cautiously state that the source of the 'cosmic static' comes from regions that are fixed with respect to the stars. Jansky continued observations for another year before publishing his final paper on the subject (Jansky, 1935). The distribution of the cosmic static across the sky was shown to approximately coincide with the distribution of stars, dust and gas visible along the plane of our Milky Way galaxy.

In 1936 Jansky's discovery was confirmed by Gennady Vasilyevich Potapenko (1894–1979) at the California Institute of Technology (Caltech) in Pasadena. Potapenko and his graduate student Donald Freeze Folland (1910–1998) built a receiver and antenna and they began observing on the roof of one of Caltech's buildings. However, Pasadena proved too radio noisy so they moved their equipment to the Mojave Desert where they succeeded in confirming Jansky's results, though their work was never published. They designed a new and much larger antenna, but were unable to find funding and the project did not go ahead (see Cohen, 1994 for details).

Although Jansky's work created some interest among astronomers, none of the US observatories followed up his discovery—primarily because no astronomer knew enough about radio engineering. The new science of radio astronomy might have fallen into limbo had it not been for the initiative of the young American engineer Grote Reber (1911–2002; Reber, 1983; 1984; cf. Kellermann, 2004; 2005). Reber read Jansky's research papers and understood their significance (Robertson, 1986). Jansky had exploited his discovery to the technical limits of his merry-go-round aerial, so Reber realised further progress would require the construction of new equipment specifically designed to observe the cosmic static. The best solution seemed to be a large parabolic reflector or 'dish' which could be accurately pointed to selected positions in the sky. Different radio frequencies could be investigated by changing the receiver placed at the focus of the dish (see Figure 4).

Reber's first attempts to detect radio emission from prominent objects such as the Sun, Moon, planets and several bright stars produced no response. He persevered and built a new receiver working at a frequency of 150 MHz. Early in 1939 he was rewarded by detecting the cosmic static along the plane of the Milky Way, thereby confirming Jansky's discovery (Reber, 1940). Reber then carried out detailed measurements of the variation in radio strength across the sky. In addition to the peak radio strength near the Galactic Centre, other subsidiary peaks were prominent in the constellations of Cygnus and Cassiopeia. While Jansky's discovery laid the

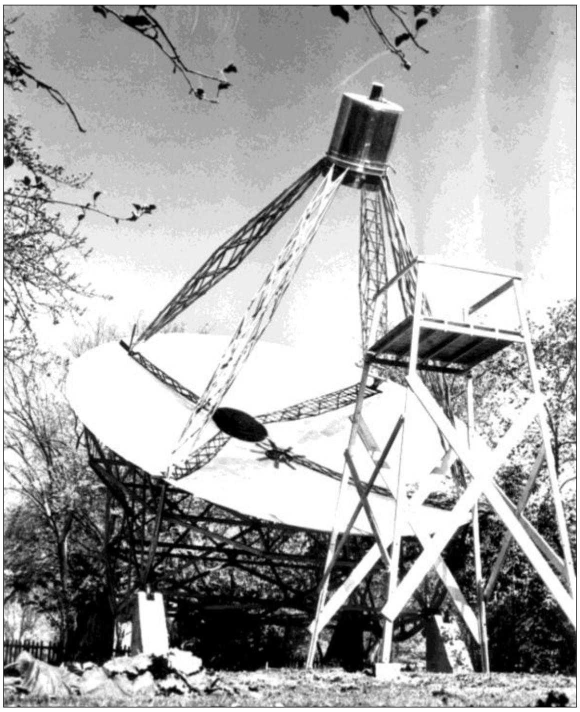


Figure 4: The radio telescope built by Grote Reber in his parents' yard in Wheaton, Illinois (courtesy: NRAO).

the first foundations for the new science of radio astronomy, Grote Reber became its first practitioner. His radio maps of the sky were not improved upon until the work of John Bolton and his group in the late 1940s.

3 THE DOVER HEIGHTS FIELD STATION

Radio astronomy was not completely dormant during the war years. In fact, the next major development came, again through serendipity, as a direct result of wartime radar research. Late in February 1942 radar stations throughout England reported severe bursts of radio noise which had made normal operation impossible for several days. The War Office knew that the Germans had been developing methods of jamming radar and assigned James Stanley Hey (1909–2000) of the Army Operational Research Group the top priority task of investigating the problem. After an analysis of the records, Hey (1946) realised that the mysterious interference was not the result of enemy jamming, but came from a direction in the sky which seemed to coincide with the Sun. Hey checked with the Royal Greenwich Observatory and learnt that during the days of maximum interference an exceptionally active sunspot had been in transit across the solar disc. In his secret report Hey concluded that despite previous German successes in jamming British radar, this time the real culprit had been the Sun.[3] Across the Atlantic, at about the same time, George Clark Southworth (1890–1972; 1945) and a group at the Bell Telephone Laboratories—colleagues of Karl Jansky—made the same discovery, but they were working at a much higher frequency so only detected continuum emission, not solar bursts.

The existence of solar radio emission had been known in the Sydney Radiophysics Laboratory well before the end of the war, through the "... almost simultaneous arrival of three reports in the laboratory ..." (Payne-Scott, 1945) in mid-1945. One was Reber's (1944) paper in the *Astrophysical Journal*, and the other two were 'secret' wartime reports of independent radar detections by Hey in England and Elizabeth Alexander (1908–1958) in New Zealand (see Army Operational Research Group (1945) and Alexander (1945), respectively). In addition, both the Chief of the Radiophysics Laboratory, Edward George ('Taffy') Bowen (1912–1991), and senior scientist Joseph Lade Pawsey (1908–1962), had visited the Bell Telephone Laboratories and learnt of Southworth's (1945) work. Inspired largely by Alexander's New Zealand work with 200 MHz Royal New Zealand Air Force COL[4] radar antennas (see Orchiston, 2005a), in October 1945 (just two months after the end of the war) Pawsey and colleagues began their own solar observations using a Royal Australian Air Force 200 MHz COL radar antenna at Station 54 overlooking the sea at Collaroy, a northern Sydney suburb (see Orchiston et al., 2006). Success came immediately. Their observations not only confirmed the overseas reports, but then an analysis of certain features in the signals yielded a very surprising result. Even with sunspot activity at a minimum, the strength of the radio emission indicated that the Sun's corona was at temperatures as high as 10^6 degrees. Their results, anticipated on theoretical grounds by their Commonwealth Observatory colleague at Mt Stromlo, David Forbes Martyn (1906–1970; Martyn, 1946b), were summarised in the papers by Pawsey (1946) and Pawsey et al. (1946), both of which were published in *Nature*.

In their study of radio emission from sunspots Pawsey and his group introduced a technique known as sea interferometry (for an explanation of the technique see Figure 5, and Bolton and Slee, 1953). The technique is the radio analogue of Lloyd's mirror in classical optics, named after the Irish physicist Humphrey Lloyd (1800–1881). In 1834 Lloyd demonstrated that a monochromatic beam of light reflected from a glass surface, at a low angle of incidence, combines with the direct beam to produce an interference pattern, strong evidence at the time for the wave-like nature of light. The radio analogue was well known to wartime radar operators, including Bolton (Bickel, 1975). The direct radar beam received from distant aircraft combined with the beam reflected from the sea surface to produce an interference pattern. The pattern could be used to calculate the elevation of the aircraft above the sea surface, which often indicated whether the aircraft was friend or foe.[5]

John Bolton commenced work at the Radiophysics Laboratory in September 1946 and was assigned to Pawsey's solar group (Bolton, 1982). He was given the task of investigating the polarisation properties of sunspot radiation, a subject of particular interest to Martyn (1946a).[6] Bolton spent the first month designing and building an antenna in the Radiophysics workshop. The antenna consisted of two Yagi aerials, basically the same as the first television aerials. The antenna was mounted on a movable platform, so that it could track the Sun, and connected to a modified radar receiver operating at 60 MHz. Bolton installed the antenna at the Dover Heights field station near the entrance to Sydney Harbour (see Figures 6 and 7).

Bolton was assisted by another new recruit to Radiophysics, Bruce Slee (see Figure 8), who would become Bolton's first scientific collaborator. Owen Bruce Slee (b. 1924) had an interesting background leading up to his appointment. During the war he had worked as a radar mechanic at an RAAF station at Lee Point near Darwin. On several occasions late in 1945 he noticed that when the radar antenna faced west out to sea at sunset there was a sudden increase in radio noise, which he soon showed came from the Sun. Slee became yet another wartime radar operator to independently discover solar radio emission (Orchiston and Slee, 2002; Orchiston et al., 2006). After reading a newspaper article on the solar work at Radiophysics, Slee wrote to the Radiophysics Laboratory reporting his own discovery and enquiring whether there might be an opportunity to join the staff. Pawsey, now Head of the Radio Astronomy Group, was impressed and, following a meeting in Slee's home town of Adelaide, offered him a job on the spot. It was the beginning of a remarkable career. Slee started as a lowly technical assistant; studied evenings, eventually acquiring B.Sc. Honours and D.Sc. degrees; and worked his way up the ranks to become one of Australia's most distinguished radio astronomers (Orchiston, 2004; 2005b).

The attempt by Bolton and Slee to detect polarisation in the sunspot radiation was a failure. The Sun had entered a dormant period with no sunspots visible on its surface. However, Bolton had another idea. He had learnt of Jansky's discovery of cosmic noise while a student at Cambridge. He was also aware from his time as a radio officer on *The Unicorn* that pointing a radar aerial along the plane of the Milky Way would lead to a significant increase in the amount

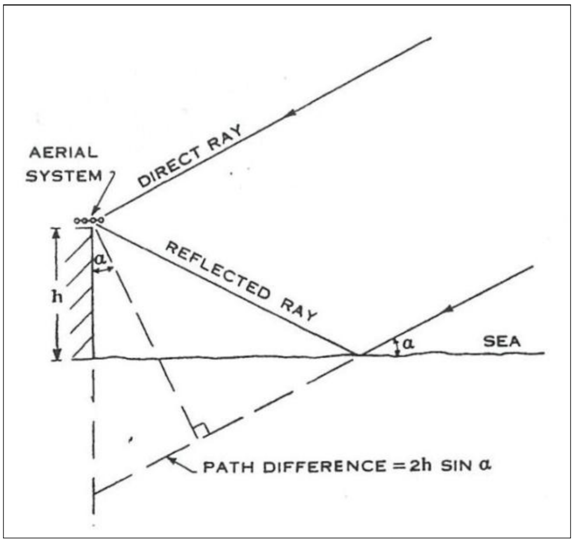


Figure 5: Radio astronomy began in Australia with the sea interferometer. The cliff-top aerial combines the direct signal with the signal reflected from the sea to create an interference pattern. These two signals produce maximum intensities when their path lengths differ by an even number of half-wavelengths and minimum intensities when path lengths differ by an odd number of half-wavelengths. The reflected signal simulates an imaginary aerial, spaced from the real aerial at a distance equal to twice the height of the aerial above sea level. The difference in path length between the direct and reflected signals is given by $2h \sin\alpha$, where h is the height of the aerial above sea level and α is the angle of incidence of the reflected signal to the sea surface, corrected for the curvature of the Earth and atmospheric refraction of the signal (after Stanley and Slee, 1950: Fig. 1).

of radio interference. For most radar operators, Jansky's 'noise' was considered an operational nuisance rather than an important astronomical discovery. However, Bolton speculated that if the Sun can emit strong radiation, could there be other astronomical objects that contribute to Jansky's noise? Bolton and Slee pointed two of their Yagi aerials towards the eastern horizon to work as a sea interferometer, the same technique used earlier by Pawsey and his group to study sunspot radiation. They consulted an astronomy textbook and star atlas to guess which type of object might be a strong radio emitter. After a couple of weeks attempting to detect a number of objects as they rose above

Figure 6: The Dover Heights field station in 1943, located 5 km south of the entrance to Sydney Harbour and overlooking the Tasman Sea to the east. The radar unit on top of the blockhouse was used for air warning during WW II. The 5 ha site, at an elevation of 79 m above sea level, was later to become one of the main CSIRO Radiophysics radio astronomy field stations. Despite its suburban location and the presence of a nearby road, the site proved suitably radio-quiet over the frequency range 40–400 MHz used for radio astronomy (courtesy: ATNF Radio Astronomy Image Archive (RAIA) B81-1).

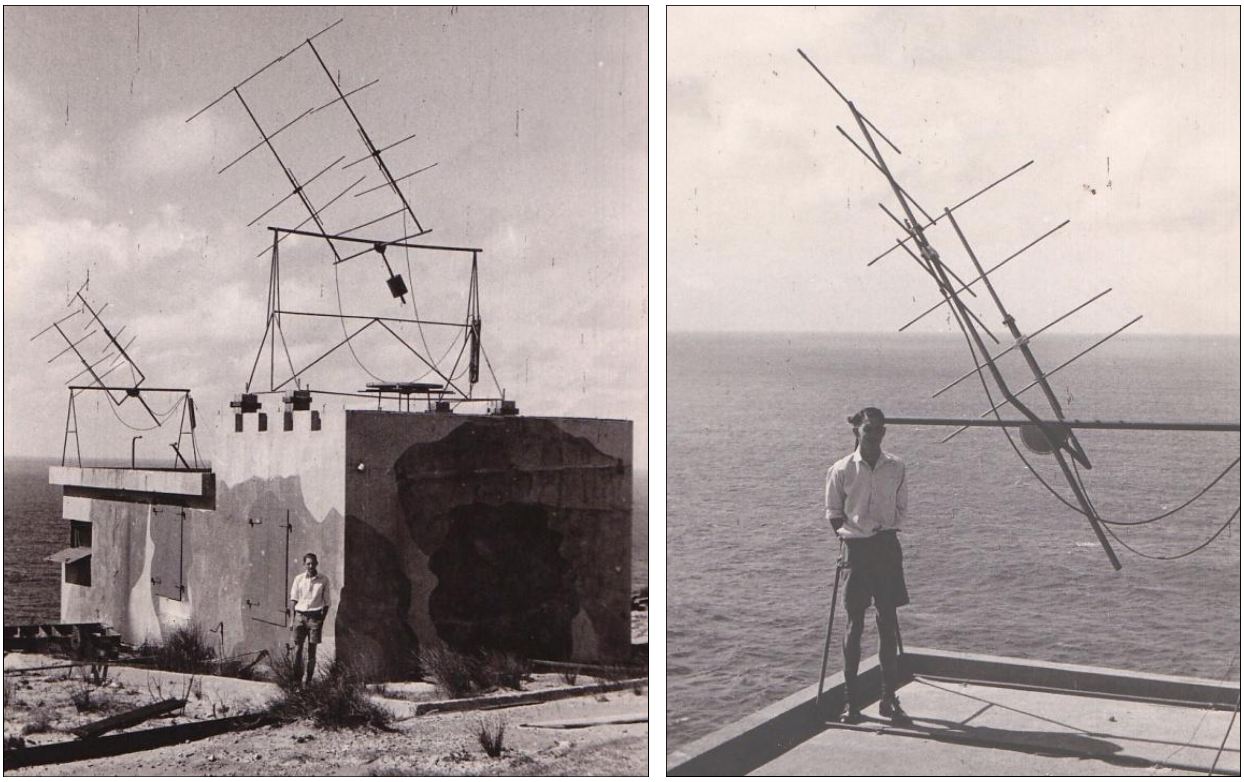


Figure 7: Bolton at the Dover Heights blockhouse in May 1947, a month before the detection of the Cygnus source. Left: Two of the twin Yagi antennas used for solar observations at 100 MHz (left) and 60 MHz. The Yagi pairs are perpendicular to each other to study the polarisation of the solar radiation. The 200 MHz antenna was on the far corner and is not visible. Right: The two elements of the 100 MHz Yagi could be positioned horizontally, pointing to the eastern horizon, to form a sea interferometer. This aerial was used for the discovery of the first eight discrete sources (courtesy: Stanley family).

the sea, the project was cut short by an unexpected visit from their boss Joe Pawsey who saw immediately that the aerials were not pointing at the Sun. Pawsey was not impressed by their insubordination and ordered the pair back to the Radiophysics Laboratory (Slee, 1994).

At the time Pawsey was planning an expedition to Brazil to observe a total eclipse of the Sun. The passage of the Moon across the solar disk would allow the location of the sunspot radiation to be measured with far greater precision than Pawsey could achieve with a sea interferometer. Pawsey reassigned Bolton to work with Gordon Stanley (1921–2001; see Figure 9) who was building equipment for the expedition. It was the start not only of a lifelong friendship, but also of a collaboration that would be the most important of both their careers. Gordon James Stanley was born in the small town of Cambridge, south-east of Auckland, New Zealand, in 1921. His father suffered from tuberculosis and so the family decided to move to the warmer and dryer climate of Sydney when Gordon was six. He left school early and joined a company that manufactured a wide range of electrical products, where he began to show an exceptional talent for understanding the operation of anything electrical. Dividing his time between work and study he earned his high school diploma and then a Diploma of Engineering from the Sydney Technical College (now the University of New South Wales). When the Pacific war broke out Stanley enlisted in the army for a period and then in 1944 he was transferred to the Radiophysics Laboratory where the authorities thought he would be of more value to the country's war effort (Kellermann et al., 2005).

As it turned out, the expense and the logistical difficulties of getting personnel and equipment halfway round the world to Brazil proved too great and the eclipse expedition was cancelled.[7] Bolton (1982: 350) later recalled:

> Towards the end of February 1947 Pawsey came into the room where Gordon and I were working and told us that the expedition to Brazil was not to take place. He then said, "If you can think of anything to do with all this equipment – you can have it." As he reached the door he turned around and, almost as an afterthought, and in typical Pawsey fashion, said, "If you can think of anything to do with Gordon – you can have him too!"

It was an opportunity too good to miss. Bolton and Stanley spent an afternoon loading up a truck with the eclipse equipment, together with tools, spares and test equipment, and next morning headed out to the blockhouse at Dover Heights. They managed to install two of the solar receivers, operating at 100 and 60 MHz (see Figure 7), when one of the largest sunspots seen for several years appeared on the Sun's

Figure 8: Bruce Slee was John Bolton's first collaborator at Dover Heights. He trained as a radar technician and after serving at a number of radar stations in WWII, he joined the Radiophysics Laboratory in 1946 as a Technical Assistant (courtesy: Bruce Slee).

limb and began its transit across the solar surface. The sunspot was inactive for almost a week until one afternoon when Bolton was about to start an observing shift. He heard the chart re-

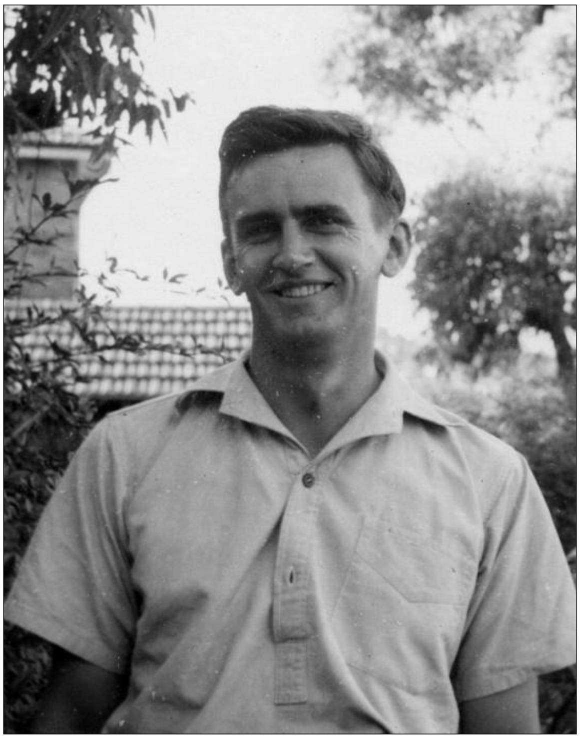


Figure 9: Gordon Stanley was John Bolton's other collaborator at Dover Heights, and they and Bruce Slee formed the team that discovered the first discrete radio sources. Stanley trained as an engineer and joined the Radiophysics Laboratory in 1944, where he specialised in receivers and electronics (courtesy: Stanley family).

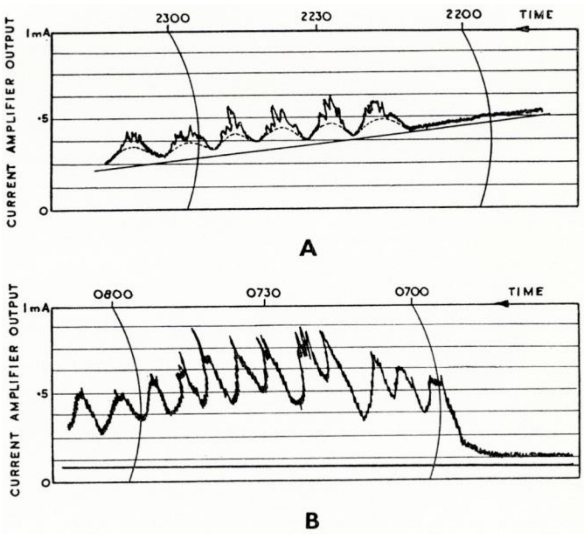


Figure 10: (A) The interference pattern for Cygnus A recorded at 100 MHz after 10 pm on the evening of 19 June 1947 at Dover Heights. The strength of the signal decreases (towards the left) as the source rises higher above the horizon. (B) For comparison, the interference pattern recorded from the quiet Sun at dawn on 24 June 1947 (after Bolton and Stanley, 1948b: 60).

corder for the 100 MHz antenna jump off scale and he moved quickly to turn the gain setting down as low as possible. After several minutes the strength of the signal began to decrease when suddenly the 60 MHz recorder also went off scale. After about 15 minutes the signal from both antennas had dropped back to normal.

Further work confirmed that the outburst was caused by a huge solar flare which generated intense radio emission first at the higher frequency of 200 MHz,[8] followed by intervals of several minutes to the lower 100 and 60 MHz frequencies. The explosive force of the flare ejected a column of ionised material out through the solar atmosphere at speeds of up to 1500 km per second. The arrival of the ionised material in Earth's atmosphere a day or so later caused auroral displays and strong magnetic storms. The following day a bright aurora could be seen in the Sydney sky, a rare event at this latitude (nearly 34° S) and demonstrating just

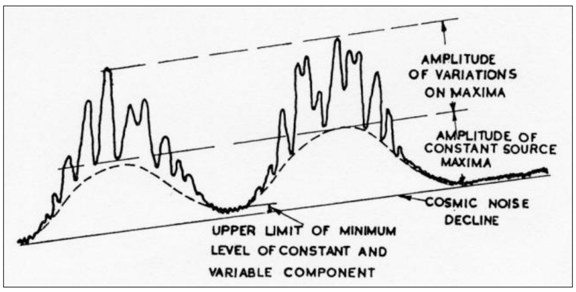


Figure 11: An enlarged section of the Cygnus record in Figure 10 showing how the maxima and minima of the constant and variable components are identified. The dashed curve results from the sinusoidal variation in path difference given by $2h \sin\alpha$ (see Figure 5). The relative heights of the maxima and minima in the dashed curve provide an upper limit on the angular size of the source (after Bolton and Stanley, 1948b: 63).

how powerful the solar flare had been. The report on the flare event in *Nature* was Bolton's first research paper (Payne-Scott, Yabsley and Bolton, 1947).

4 THE CYGNUS A 'RADIO STAR'

After the war Hey and a group at the Army Operational Research Group near London carried out a sky survey of radio emission at 100 MHz, producing isophote maps similar to those published earlier by Grote Reber (Hey, Phillips and Parsons, 1946). Hey and his group noticed that whereas radio signals from any given direction were relatively constant in strength, emission from the constellation of Cygnus exhibited peculiar fluctuations, changing in intensity during time intervals as short as one minute. In a paper reporting this discovery, Hey, Parsons and Phillips (1946) argued on physical grounds that this variable emission must come from a relatively small region of space, possibly from some unknown astronomical object. As we shall see in Section 6, this assumption turned out to be correct, but for the wrong reason.

In August 1946 the Chief of the Radiophysics Laboratory, 'Taffy' Bowen, was visiting England, and he sent Pawsey a reprint of the *Nature* letter by Hey's group and encouraged him to try to confirm the discovery. Within a few days Pawsey was able to report the detection of a variable source at both 60 and 75 MHz, with the fluctuations similar in appearance to the bursts observed in solar noise. Pawsey continued the observations hoping to find the cause of this surprising phenomenon. The initial success, however, seems to have been followed by a period of conflicting observations, during which the reality of the Cygnus fluctuations came into question. In the end Pawsey gave up observing Cygnus, not knowing what to make of Hey's claim (Sullivan, 2009: 139).

Later, in May 1947, Bolton and Stanley were at Dover Heights when the Sun again entered a phase of low activity. They decided to return to the topic which Pawsey had brought to an abrupt halt six months earlier. Pawsey had said they could use the Brazil equipment for any purpose they liked, so they would take him at his word. By day they would continue routine monitoring of the Sun, but at night they would renew the search for other radio objects in the sky. To begin with, they decided to see whether they could find Hey's anomalous source in Cygnus.

Early in June 1947 Bolton and Stanley succeeded in detecting this source on their first attempt, using the 100 MHz antenna shown in Figure 7. The signal was not as strong as the solar bursts they had been observing, but the source did produce the distinctive fringe pattern on their chart recorder (see Figures 10 and 11). They continued the observations as the source rose each night and, by the end of June, they had enough data for Bolton to give a brief talk at the Radiophysics Laboratory, with the title "Variations in cosmic noise from the constellation Cygnus". He could report that the source had been detected at 100 and 60 MHz, but not yet at 200 MHz, and he gave an approximate position for the source which differed by about 3° from the one listed by Hey. There was also a hint of a much weaker source further south.[9]

Two weeks later Bolton (1947) reported to David Martyn:

> Work on Cygnus has progressed quite well. The exact locality of the source is not known with sufficient accuracy yet. The approximate position is RA 20 hours, declination 40 deg, but errors are still of the order of 3 minutes in RA and 20 minutes in declination. A further attempt at localisation is going to be made this week. As you know, the source is rather variable and I am at present studying these factors. I hope to be able to have the general features a bit clearer before the joint colloquium at the end of July. The size of the source is certainly less than 8 minutes; again further investigations are proposed for a more accurate determination.

The most important value in the letter is the upper limit to the angular size of the source, which Bolton derived from the interference fringes, using the following formula:

$$W = (\lambda / \pi h)\,(3R)^{1/2} \qquad (1)$$

where W is the equivalent radiating strip, λ is the wavelength, h is the height of the cliff where the sea interferometer is located, and R is the ratio of the heights of the interference fringe maxima and minima above an extrapolated cosmic drift background level. Bolton's value of <8′ was an improvement by a factor of 15 on the value arrived at by Hey's group. The beamwidth of Hey's aerial was 2°, meaning that the aerial could not resolve any detail smaller than a patch of sky equal to about four times the angular width of the Moon. Hey had argued that the Cygnus source was most likely compact because of the rapid variation in its signal strength. Whereas Hey had *inferred* a small size, the Dover Heights data provided the first *proof* that Cygnus was indeed a compact star-like object. The existence of the first 'radio star', the first discrete radio source, had now been established. Years later, Bolton explained how the ratio of fringe maxima to minima provided an upper limit for the angular size of the source (Bickel, 1975):

> I can give a crude analogy. If you have a picket fence and you roll a marble up and down over the pickets, the marble will describe almost exactly the form of the top of the picket fence. If you take a tennis ball, then it doesn't go up and down as far. If you take a basketball, you might as well be running it over a flat plane. There's an analogy in the sea interferometer. If the source is larger than the separation between the maxima or minima, then it won't give you a pattern. If it's intermediate, it will give you a minimum which is not a perfect minimum, a maximum which is not a perfect maximum. So we were immediately able to say, "We've got an upper limit on its diameter".

The main priority now was to measure a more precise right ascension and declination for the source, as the approximate position reported by Bolton in his talk was far too imprecise to be able to identify the source with a visible object. Both coordinates could only be measured with any accuracy by observing the source setting in the north-west and combining the data with Cygnus rising in the north-east at Dover Heights.

Early in July 1947 Bolton and Stanley towed a trailer fitted out with their 100 MHz antenna to two headlands north of Sydney. The first of the sites, known as Long Reef near the suburb of Collaroy (see Figure 2), had an elevation of only 30 metres above sea level, but it had the advantage of covering the whole hour angle range from rising to setting. Observations made over a week enabled them to measure an approximate right ascension accurate to ±1 minutes. It was difficult work and there was no option but to camp out mid-winter to guard against their equipment being stolen or vandalized.

The second site further north was an isolated promontory called West Head (see Figure 2), accessed by a dirt track in the rugged Ku-Ring-Gai Chase National Park. The site was at an elevation of 120 m above sea level (50% higher than Dover Heights) and overlooked the wide estuary of the Hawkesbury River. A nearby island and opposing cliffs blocked most of the hour angle track, but Cygnus could be observed for a couple of hours both before and after culmination. The approximate right ascension from the Long Reef site could then be used to identify the corresponding fringe minima at the second site. The elevation path of Cygnus was then reconstructed by plotting the elevations of fringe minima (corrected for refraction and Earth curvature) against sidereal time. The declination was then computed from the latitude of West Head and the duration of the semi-diurnal arc. This process was repeated on a number of nights and the derived positions were averaged to give the final position.

By September 1947, after three months of observations, Bolton and Stanley had enough data to publish. Taffy Bowen thought that the Cygnus discovery was important enough to be published in the *Proceedings of the Royal Society of London*, the most prestigious science jour-

Commonwealth of Australia
COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH
(*Reprinted from* NATURE, *Vol.* 161, *page* 312, *February* 28, 1948.)

Variable Source of Radio Frequency Radiation in the Constellation of Cygnus

COSMIC or galactic noise was discovered by Jansky[1] in 1931; but its exact origin has remained uncertain. It is generally supposed to originate from collisions in interstellar matter[2]; but there are divergencies between existing theory and experimental results, particularly at lower radio frequencies[3]. Hey, Parsons and Phillips[4] discovered variations in the intensity of galactic noise from the direction of the constellation of Cygnus, with a period of about one minute—suggesting that this particular radiation has its origin in a discrete source.

During the past three months, we have made a study of this region, mainly on 100 Mc./s., but also occasionally on 60, 85 and 200 Mc./s. The technique employed was to observe the region rising over the sea with aerials situated on a high cliff, as described by Pawsey, Payne-Scott and McCready[5]. Due to interference between the direct ray and the ray reflected from the sea, a lobe pattern is obtained which gives rise to a succession of maxima and minima. An estimate of the size of the source can be made from the relative heights of maxima and minima, and an accurate position found from the times of occurrence of minima.

Small aerial arrays were used—one or two Yagis—and considerable care was taken with receiver stabili-

Figure 12: Part of the first page of the letter by Bolton and Stanley announcing the discovery of the discrete source in Cygnus. The letter to *Nature* was submitted on 4 December 1947 and published on 28 February 1948 (after Bolton and Stanley. 1948a).

nal in the British Commonwealth. However the ‘Royal’, as it was known, was experiencing publication delays of over a year and there was a danger that the Cygnus discovery might be ‘scooped’ by another group. After some debate it was decided to make a brief announcement in *Nature* (see Figure 12), followed by a detailed paper in the new *Australian Journal of Scientific Research* (see Bolton and Stanley, 1948a; 1948b). The *AJSR* was about to be launched by CSIR Head Office in Melbourne and would be the first nationwide science journal published in Australia. The Cygnus paper appeared in the first issue of volume 1, early in 1948. A brief announcement letter in *Nature*, followed by a detailed *AJSR* paper, became the standard publishing practice for the Dover Heights group over the following years.

The *AJSR* paper reported the detection of the source at 60, 85, 100 and 200 MHz, providing the first spectrum of the source. The position given for the Cygnus source was

> Right ascension: 19 hr 58 min 47 sec ± 10 sec Declination: +41° 47′ ± 7′,

a vast improvement on Hey’s position which was known to no better than 5° accuracy. Bolton and Stanley (1948b: 68) announced that the angular width of the source was less than 8′ of arc and that its radio emission had two components, one believed constant, and the other showing considerable variations with time. In the discussion of their results they noted:

> Reference to star catalogues, in particular the Henry Draper Catalogue, shows that the source is in a region of the galaxy distinguished by the absence of bright stars and objects such as nebulae, double and variable stars, *ie. the radio noise received from this region is out of all proportion to the optical radiation*. Although the experimental technique allows only an upper limit to be placed on the size of the source, this is believed to be effectively a point

> and therefore a single object. The determined position lies in a less crowded area of the Milky Way and the only obvious stellar objects close to the stated limits of accuracy are two seventh magnitude stars. *There is certainly no comparable optical radiation from this region.* (our italics).

Astronomers at the Commonwealth Observatory near the nation's capital, Canberra, carried out a close examination of this region and produced a photographic plate that confirmed the Draper Catalogue. There were two unremarkable stars of seventh magnitude close to the position, but no object that appeared in anyway unusual. The identity of the Cygnus source would remain a mystery for some time to come.

To conclude their paper, Bolton and Stanley (1948b: 69) speculated on a possible emission mechanism for the source. They noted that if its size was <8′, the effective temperature at 100 MHz would be greater than 4×10^6 K, making a thermal origin of the radiation improbable. Instead, they noted that a mechanism similar to the one proposed "... to account for the steady enhanced noise from a large active sunspot – perhaps the association of moving ionised matter and strong magnetic fields – is quite possible." This was a prescient prediction of the synchrotron emission mechanism, which was verified by theoretical work in the early 1950s (see Ginzburg and Syrovatskii, 1965).

The Cygnus results caught the attention of a number of prominent astronomers overseas. In September 1947 Joe Pawsey embarked on a year-long trip to the United States and Europe. Pawsey's first stop was to the Mt Wilson Observatory near Pasadena, home to the 100-in Hooker Telescope, the largest in the world (but soon to be overtaken by the 200-in Hale Telescope on Palomar Mountain). Pawsey (1947a) reported to Bolton and Bowen:

> I discussed the Cygnus work in some detail with the Mt Wilson people and found them intensely interested. They immediately searched out the region given in Bolton and Stanley's paper but found nothing. Further, they promised to take further relevant photographs. I consider this collaboration is very worth while and told them we would be very happy to work in with them. At present, I think this collaboration will simply involve exchange of information.

This source became of special interest to Rudolph Minkowski (1895–1976), who would later play a significant role in Bolton's career.

In November, Pawsey visited the Yerkes Observatory near Chicago and held discussions with its Director, Gerard Kuiper (1905–1973), and two visiting astronomers, Jan Oort (1900–1992) from Leiden Observatory and Bengt Strömgren (1908–1987) from Copenhagen Observatory. As Pawsey (1947b) reported to Bolton:

> These people were exceedingly interested in your work on Cygnus. In fact, we had a session which lasted nearly three hours, so you see, your work is appreciated. Out of that discussion came one suggestion which I think you should consider. One of them suggested that it is possible that the fluctuations in the source are due to the refractive effects in the ionosphere, causing fluctuations analogous to the twinkling of stars … I don't think that this explanation is correct, but I do not have enough evidence to exclude it, and I should advise you to think it over rather carefully. If you do not have observations which can be used to check this possibility, I suggest that it might be worthwhile doing a spaced receiver experiment because this seems to be a fairly direct method of testing the suggestion.

Later correspondence reveals that it was Kuiper who had argued that the ionosphere might be the cause of the fluctuations (see Pawsey, 1948b).

Early in 1948 Bolton and Stanley took up Pawsey's suggestion and carried out further observations at 100 MHz at the West Head site, about 25 km north of Dover Heights. A comparison between the signals recorded at both sites showed a good correlation between the rapid fluctuations, confirming Bolton's own view that the fluctuations were intrinsic to the source and not caused by the ionosphere. As it turned out Bolton was wrong (see below). With the West Head site almost due north of Dover and, with Cygnus relatively low on the northern horizon, the signals at each site essentially passed through the same column of the ionosphere. If the observations had been done instead with 25 km separation in an east–west direction, there probably would have been a poor correlation between the source fluctuations at each site.

5 A NEW CLASS OF ASTRONOMICAL OBJECTS

Bruce Slee rejoined the Dover Heights team in September 1947 to assist Bolton and Stanley with improvements to the receivers and antennas. The operation of equipment needed to be monitored at all times and there were routine tasks to perform such as maintaining the flow of paper to the chart recorder. Another task for the observer was to monitor the total power deflection on the recorder chart, which varied according to the galactic latitude, so that frequent adjustment of the recorder pen was often necessary. Security was another issue. Earlier when the solar flare observations were in progress the blockhouse had been left unattended at night. Even though the site was fenced off and a caretaker lived on site, on several occasions vandals had climbed onto the blockhouse roof and damaged the antennas. To guard against further damage a fringe of barbed wire was installed around the roof, and the external ladder was removed and replaced by an internal one with a steel hatch. A new steel door and steel shutters on the windows completed the vandal-proofing.

In parallel with the Cygnus observations the search continued for other possible radio sources by scanning the sky at different declinations and looking for the tell-tale interference pattern. Early in June 1947, even before the initial detection of Cygnus, Bolton and Stanley thought they had found a source in Centaurus. However, repeated attempts to confirm the detection proved a frustrating failure. It soon became apparent that —if indeed other sources did exist—the sensitivity of the antenna systems was not good enough to pick out sources from the background noise. Short time variations in the receiver noise were drowning out any signals fainter than the strong Cygnus source. Stanley made the crucial breakthrough in October when he developed a high-tension power supply that eliminated most of the noise variations in the receivers. The receiver output was stable to about one part in several thousand, so much fainter signals could now be detected. Early in November a second source was detected, in Taurus, followed early in December by a third in Coma Berenices and then a fourth in Centaurus. Taffy Bowen (1947a) wrote excitedly to Pawsey, who was in Washington, DC:

> Bolton has now discovered *three* more discrete sources of cosmic noise, two in Taurus and one near the north galactic pole. The intensities of the former are about one-fifth that of Cygnus, the latter one-fiftieth. He is quite certain of the results but not too sure of their position as yet. We are naturally very excited about this and Bolton is pushing it as hard as he can … I think, too, it would be wise not to be too specific about them in the US and UK until Bolton has had a chance of finalising his observations and getting them published. I will be sure to keep you informed of progress. (his italics).

Pawsey (1947b) assured Bolton that he was being non-committal when questioned about the existence of further sources:

> I hope your work is progressing very satisfactorily at Dover. I have heard from Bowen of the new sources which you think you have discovered, and this sounds very interesting indeed. With regard to discussions over here, I am simply saying that you suspect there are other sources, but are not sure yet of the results. It might be worthwhile at a fairly early stage, discussing the location of these new sources with the Mt Wilson people. I think they are the best crowd to collaborate with in this work, but I shall leave this for you people in the laboratory to decide.

By Christmas 1947 a fifth and a sixth source had been added to the list. It had been a vintage year for the Dover Heights group. It began in March with the lucky observation of a giant solar flare and was followed by the discovery in June that Cygnus is a point-like source. Evidence was now emerging for the existence of a whole new class of objects previously unknown to astronomers.

In March 1948 Bolton took a break from searching for new radio sources. He married Letty Leslie at Sydney's Registry Office and they spent their honeymoon on an island resort in the Whitsundays in Queensland. The couple had met in 1946 before Bolton's discharge from the navy and no doubt Letty was an important reason why John had decided not to return to England. Letty had first married Ernest Leslie in 1940 and they had two sons (who later John would formally adopt). Ernest went to England where he trained to be a navigator in the Royal Air Force. During a raid on a German submarine base his aircraft was shot down over France, killing all but one of the crew members.

In early April 1948 Bolton wrote up a further *Nature* paper on the new sources (Bolton, 1948a). Aside from Cygnus, six new sources were now known at 100 MHz and approximate positions had been found for three of them (see Table 1). All six were weaker than Cygnus, with radio intensities ranging from 0.25 down to 0.03 that of Cygnus. Initially Bolton named each source in the order it was found, followed by the year it was found; thus, source 1.46 corresponded to Cygnus, 2.47 to Taurus, etc. Later, this convention was dropped in favour of naming each source

Table 1: Radio sources detected at Dover Heights up to 1 February 1948 (adapted from Bolton, 1948a: 141).

Temporary Designation[A]	Position		Flux at 100 MHz (Jy)[B]	Angular Width	Type
	R.A.	Dec.			
Cygnus A (1.46)	19h 59m	+41° 47′	6000	< 8′	Variable
Taurus A (2.47)	05h 13m	+28°	1000	< 30°	Variable?
Coma Berenices A	12h 04m	+20° 30′	1500	< 15′	Constant
Hercules A (7.48)	16h 21m	+15°	200	< 1°	–
8.48	–	–	200	–	Constant
5.47	–	–	300	< 1°	Constant
Centaurus A (6.47)	–	–	1000	< 15′	Variable?

[A] A second source in Taurus (3.47) was later shown to be fictitious. Coma Berenices A (4.47) was later renamed Virgo A (see next section).

[B] The source intensities were originally given in SI units where 1 Jy ≡ 1×10^{-26} W m^{-2} Hz^{-1}.

after the constellation where it was found, followed by a letter A, B, … to indicate that it was the strongest, second strongest source, etc., in that constellation. This naming convention was quickly adopted by radio astronomers around the world and it is still partly in use today.

When writing up the *Nature* paper Bolton was advised by David Martyn at Mt Stromlo to simply present the data on the new sources and not to engage in speculation on their possible nature (Bolton, 1948b). However, Bolton felt that because the Dover group had discovered the sources he had as much right as anyone else to put forward ideas. With Bowen's blessing, half the paper was a discussion of the possible origin and distribution of galactic radiation. As Bowen (1948) informed Pawsey:

> After a few delays here and at Head Office we have finally sent off Bolton's letter to *Nature* about his new sources of cosmic noise … You will see that in addition to the experimental data he has had a fling at interpretation. We debated this a little and finally decided it couldn't do much harm in a letter to *Nature* and might do some good.

Bolton proposed that the radiation had three components, the first being the free-free transitions of charged particles in interstellar space, the mechanism favoured earlier by Reber and others [see Sullivan (2009), Section 15.2.1]. The second component was the aggregate of emissions from individual stars in regions of high star density. For the third component:

> A contribution from individual discrete sources, which may be distinct 'radio-types' and for which a place might have to be found in the sequence of stellar evolution. Purely electromagnetic disturbances as an origin of these have been discussed by several writers, and the following additional possibilities are envisaged: (*a*) A pre-main sequence model consisting of a large cool gas sphere, gravitational energy of contraction being radiated in the radio frequency spectrum. (*b*) A post-main sequence model – possibly a development of the planetary nebula consisting of an intensely hot central star, with its radiation in the far ultraviolet, surrounded by a shell of predominantly stripped atoms.

Both pre- and post-main sequence models may have seemed plausible at the time, but neither turned out to be correct.

6 THE EXPEDITION TO NEW ZEALAND

The overriding priority was now to measure precise positions for the new sources in the hope of identifying some of them with known optical objects. A relatively accurate position for Cygnus A had been found by observing the source at Dover Heights and West Head. However, the six new sources were all at declinations well south of Cygnus A. At West Head some of these sources would rise and set over land, rather than the Hawkesbury estuary, and so a suitable fringe pattern could not be obtained. Bolton began scouting around for a new and better site. An island near Coffs Harbour, north of Sydney, was briefly in contention, but it soon became apparent that there was nothing suitable on the eastern seaboard of Australia. Lord Howe Island and Norfolk Island in the Tasman Sea were also investigated, but the best candidate appeared to be the region close to Auckland in New Zealand where there were exceptionally high cliffs on both the east and west coasts (Orchiston, 1993; 1994; Stanley, 1994). Bowen (1947b) officially launched the expedition by writing to the Surveyor-General of New Zealand in the capital city of Wellington:

Figure 13: The ex-Army radar trailer in the grounds of the Radiophysics Laboratory. This mobile radio telescope featured four Yagi aerials, a new 100 MHz receiver, recorders, chronometers, weather recording instruments and all the tools and backup equipment needed to operate reliably at a remote location. We were not able to establish the identity of the lady in the photograph (courtesy: RAIA B1259).

> We are planning to make a special series of observations of cosmic noise from the constellation of Cygnus and find that there is no site readily available in Australia for this purpose. It appears that we are much more likely to find a suitable spot in New Zealand, possibly in the North Auckland area, and we would be very much obliged if your Department could supply maps and some information relating to this area … Such a position should be accessible by a three-ton military trailer, ie. road unnecessary if country between road and site is flat or slightly undulating with firm ground.

Bolton decided the expedition would start in June 1948 primarily because Cygnus A, the main target of the trip, would rise in the evening about 10 pm and set about 4 am, the optimum times for making accurate observations. Most of the other sources would have at least one rise or set time at night. Stanley spent April and May converting an ex-Army radar trailer into a mobile observatory (see Figure 13). Five sites on the North Island were investigated with Cape Reinga on the northern-most tip considered to be

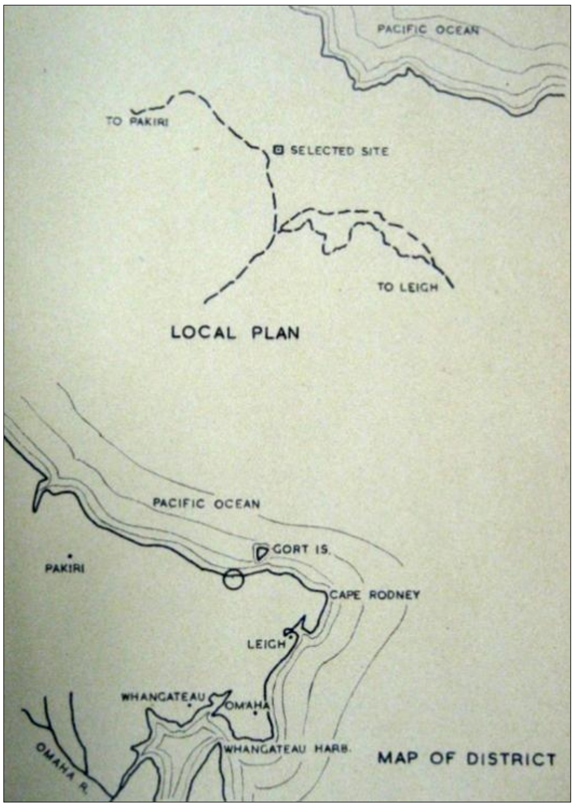


Figure 14: The observing site at Pakiri Hill north of the Leigh township showing the local plan (*above*) and a map of the district. The coastline at the site runs approximately east-west and allowed Cygnus to be observed rising in the north-east and setting in the north-west (courtesy: National Archives of Australia).

the best, but then ruled out because of poor road access and, with the nearest town 100 km away, just too isolated. Instead, two sites were chosen near the city of Auckland, one on the east coast and the other on the west coast.

For the east-coast observations a sheep farm in an area known as Pakiri Hill was chosen, just north of the small coastal town of Leigh and about 70 km north of Auckland (see Figure 14). At an elevation of 280 metres, the site was over three times the height of the Dover cliffs, which meant that the angular resolution of the sea interferometer would be over three times better. This section of the coastline ran roughly east–west which would give a view of Cygnus A rising in the north-east and setting in the north-west. The North Auckland Land and Survey Board surveyed the exact spot where the trailer would be parked. The longitude and latitude were known to an accuracy of 10 metres, while the elevation above mean sea level was measured to an accuracy of 25 cm. The site was excellent, but not perfect. An island group to the north-west cut off some of the setting, but otherwise Cygnus A could be observed throughout its six-hour transit across the northern sky.

The trailer was shipped to Auckland at the end of May, with Stanley flying over to arrange for its transport to the Pakiri Hill farm (Figure 15). Bolton arrived a week later and introduced himself to the Greenwood family who had owned the farm since the first European settlement of the district in the 1860s. Bolton (1948c) was able to report to Bowen:

> When I arrived at Leigh a week last Sunday I found the trailer on site but with no power, Stanley with a very bad cold, myself with an incipient one and a public holiday the following day. Since then I am pleased to say things have gone better … Cooperation both official and unofficial has been magnificent. The farmer on whose land we are sited has raised no objection to us using his timber, digging holes in his paddocks etc. – in fact has done everything to assist. They even brought us tea and sandwiches at five o'clock in the morning on the last two nights – for which we are very grateful. Nine hours at a stretch without Dover's comforts is just a little tough.

Figure 15: The mobile radio telescope on the Greenwood farm at Pakiri Hill in June 1948. The cabin mounted on the trailer could swivel in azimuth to observe sources rising at different declinations along the horizon (courtesy: Stanley family).

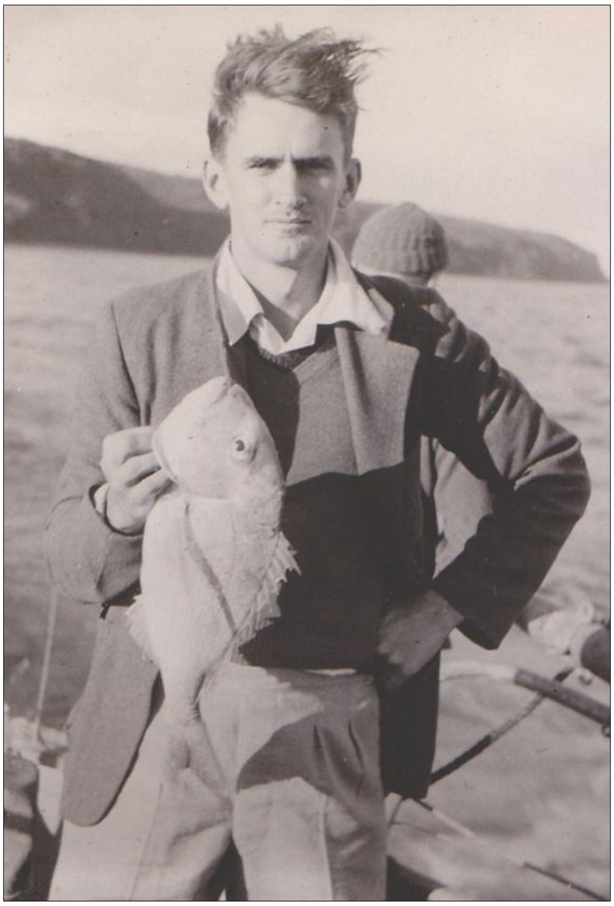
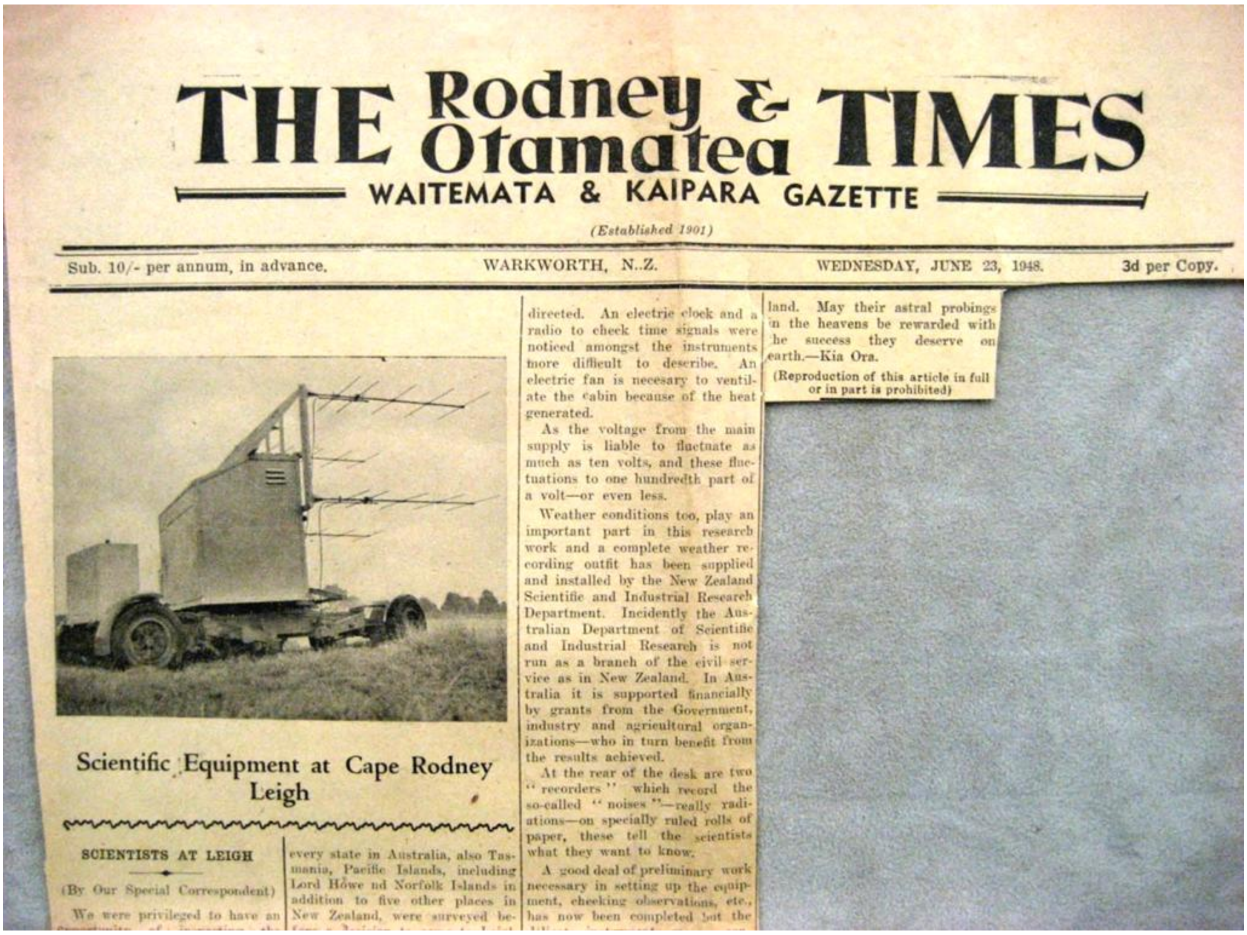



Figure 16: John Bolton (left) and Gordon Stanley stayed in the Cumberland Hotel in Leigh during their two-month observing run at Pakiri Hill. Gordon not only went fishing, but also visited relatives he had not seen since leaving New Zealand at the age of six (courtesy: Stanley family).

Although initially there were problems getting the power connected, Bolton and Stanley settled into a routine of ten observing days, followed by four days of rest and recreation (see Figure 16). Typically each observing day consisted of about 16 hours broken into two shifts. Most of each shift was spent seated at a small desk inside the trailer cabin checking that the receivers and the various instruments were operating correctly. A control panel was used to rotate the cabin mounted on the trailer and point the antenna to a different declination along the eastern horizon. The main problem was the variable power output from the 3 kW transformer installed on site which made the chart recorders run at speeds varying by up to 10%. The heat generated by the bank of instruments had to be ventilated from the cabin by an electric fan, but at least the cabin could be kept warm during the freezing winter nights. The weather at times was appalling and operations were often shutdown with the cabin lashed by storms rolling in from the Pacific Ocean.

During their sojourn at Pakiri Hill, word of the exploits of these two young scientists from Australia reached the media, and as a result they featured in the local and Auckland newspapers (e.g. see Orchiston 1994 for an account of a long and detailed article that appeared in the *New Zealand Herald* on 25 June). Much closer to home, their research made the front page of the local newspaper (Figure 17). Bolton and Stanley also were visited at Pakiri Hill by staff members, and a captivated graduate student, from the Physics Department at Auckland University College (Orchiston, 1994). After completing his M.Sc. on solar radio astronomy later that year, that graduate student, Alan Maxwell, would go to the University of Manchester for his Ph.D., and then move to the USA and build an international reputation in solar radio astronomy while at Harvard College Observatory and their Radio Astronomy Station at Fort Davis, Texas (Orchiston, 1994; Thompson, 2010).

By the end of July, Bolton and Stanley had obtained good records for Cygnus A on thirty nights and for Taurus A on five nights (see e.g. Figure 18), and a handful of records for some of the other weaker northern sources. With the work at Pakiri Hill finished, the trailer was then towed over to the west coast to start observations of the sources setting. The site chosen was a former WWII radar station a few kilometres south of Piha, a popular resort town about 30 km due west of Auckland. The site had a number of advantages, including a very stable power supply which avoided the problem



THE Rodney & Otamatea TIMES
WAITEMATA & KAIPARA GAZETTE
(Established 1901)

Sub. 10/- per annum, in advance. WARKWORTH, N..Z. WEDNESDAY, JUNE 23, 1948. 3d per Copy.

Scientific Equipment at Cape Rodney Leigh

SCIENTISTS AT LEIGH

(By Our Special Correspondent)

We were privileged to have an

every state in Australia, also Tasmania, Pacific Islands, including Lord Hówe nd Norfolk Islands in addition to five other places in New Zealand, were surveyed be-

directed. An electric clock and a radio to check time signals were noticed amongst the instruments more difficult to describe. An electric fan is necesary to ventilate the cabin because of the heat generated.

As the voltage from the main supply is liable to fluctnate as much as ten volts, and these fluctuations to one hundredth part of a volt—or even less.

Weather conditions too, play an important part in this research work and a complete weather recording outfit has been supplied and installed by the New Zealand Scientific and Industrial Research Department. Incidently the Australian Department of Scientific and Industrial Research is not run as a branch of the civil service as in New Zealand. In Australia it is supported financially by grants from the Government, industry and agricultural organizations—who in turn benefit from the results achieved.

At the rear of the desk are two " recorders " which record the so-called " noises "—really radiations—on specially ruled rolls of paper, these tell the scientists what they want to know.

A good deal of preliminary work necessary in setting up the equipment, checking observations, etc., has now been completed but the

land. May their astral probings in the heavens be rewarded with the success they deserve on earth.—Kia Ora.

(Reproduction of this article in full or in part is prohibited)

Figure 17: The expedition featured on the front page of the local newspaper. The article appeared under the pen name 'Kia Ora', the Maori term for 'good luck' (courtesy: Bolton papers, National Library of Australia).

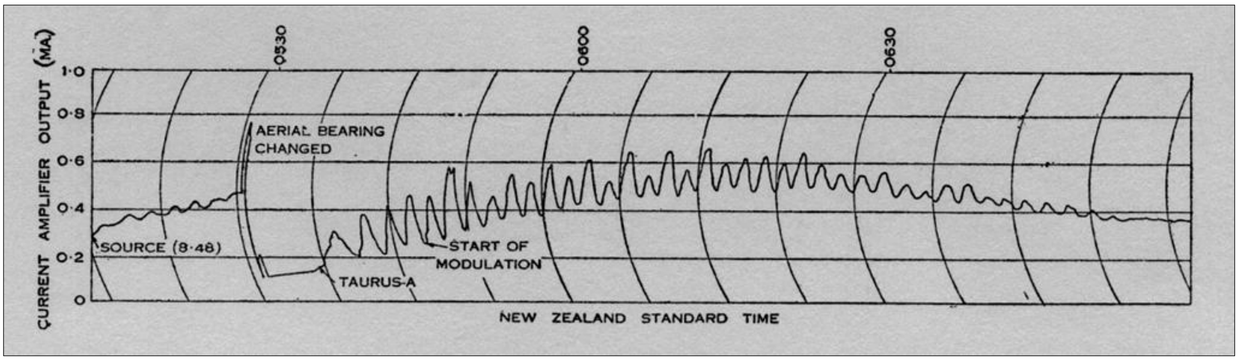


Figure 18: Record of sources (8.48) and Taurus A obtained at Pakiri Hill on 13 July 1948 at a frequency of 100 MHz. Note the modulation of the Taurus A interference pattern caused by a third source in this region. Note also the absence of the spiky structure observed for Cygnus A (see Figure 10), the result of Taurus A being an extended source (see Section 7) with angular dimensions of 4′ × 6′ (after Bolton and Stanley, 1949: 141).

faced with the chart recorders at Pakiri Hill. The level of man-made interference compared to Sydney was so low that good quality records could be obtained for some sources that set during the daytime. The weather was excellent and records were obtained over a two-week period for the four sources: Cygnus A, Taurus A, Centaurus A and Virgo A. The Virgo A source had previously been labelled Coma Berenices A (see Table 1), but the Dover Heights position turned out to be inaccurate by a massive 8°. The Piha observations meant that the source had to be moved from one constellation to another!

7 OPTICAL IDENTIFICATIONS FOR THE FIRST THREE SOURCES

Bolton returned to Sydney in mid-August 1948, while Stanley stayed on for a few days to arrange shipment of their mobile radio telescope. The expedition had been a major success on a number of levels. A further six discrete sources had been discovered, bringing the known number to 13, and there was strong evidence that there might be up to fifty more. The sources were far too faint to examine in any detail during the expedition, but could be followed up later at Dover Heights.

The fluctuations of Cygnus A also provided a further major discovery. During the expedition Bruce Slee had continued observations of Cygnus A at Dover Heights. A comparison of the Dover and New Zealand records, taken at a distance apart of 2000 km, showed no correlation between the two. As a control experiment, observations at both Dover and Piha had been made of a group of sunspots that had appeared on the Sun over a three-day period early in August. As expected, there was a strong correlation between the two sets of records. Thus, there was no longer any doubt that the Cygnus A fluctuations were not intrinsic to the source itself, but were caused by the radio signal passing through the Earth's atmosphere. Bolton's earlier belief that the fluctuations originated in the source was wrong. The suggestion by Gerard Kuiper at the Yerkes Observatory, made over a year earlier, that the Cygnus A fluctuations might be analogous to the twinkling of starlight turned out to be correct (see Section 4).

Bolton then began the long and laborious task of analysing the previous three months of observations. He decided to concentrate on calculating the celestial coordinates of the four strongest sources. Records for Cygnus A and Taurus A had been obtained at both Pakiri and Piha, but there were no records for Centaurus A and Virgo A from Pakiri as both sources rose over the land rather than the sea. For these two sources it would be necessary to rely on the Piha observations of setting in the west and of further observations at Dover Heights of rising in the east. With the two sites 2000 km apart, the records would need to be 'normalised' before the data from each site could be combined. The calculation of declination had to take into account the different latitude at each site. Similarly, the calculation of Right Ascension had to take into account the longitude of each site and also the two-hour time difference between New Zealand and Australian Eastern Standard times. Bolton also had to take note that the observations took place at different times of the year and convert solar times to sidereal times.

Bolton (1948d) prepared a series of brief internal Radiophysics reports setting out his calculations for each of the four sources. For Cygnus A, the angular size of the object was shown to be <1′, eight times smaller than the earlier measurement at Dover Heights and proving without doubt the point-like nature of the source. The new position for Cygnus A was >1° further south than the old one and showed that the previous estimate of atmospheric refraction had been significantly in error. Bolton studied the star charts with this new position, but to his great disappointment he could not see any object within the error box that seemed a likely candidate. The New Zealand expedition had been organised primarily to try to reveal the identity of the object—by choosing the time of the year when it would rise and set at night and the site at Pakiri with its view of the source low in the northern sky—but frustratingly Cygnus A continued to elude them. It would be almost three years before Cygnus A was finally identified. In 1951 F. Graham Smith at Cambridge measured a new and far more accurate position for the source (Smith, 1951). This prompted Rudolph Minkowski and Walter Baade at the Mt Wilson–Palomar Observatories to make extended observations of the position, revealing a very faint galaxy at the extraordinary distance of approximately 10^9 light-years.[10]

The disappointment of Cygnus A was soon swept away by the results for the other three sources. The position measured for Taurus A almost coincided with an ordinary star but, as Bolton (1948d) noted, also well within the error box was "... the most remarkable object in this region – NGC 1952 or the Crab nebula." Bolton's observation was a considerable understatement. The object is not only remarkable in this region of the sky, but it is one of the most remarkable in the *whole* sky. Aside from objects within the Solar System, there have probably been more research papers written about the Crab Nebula than any other astronomical object (Mitton, 1978: 175). The Crab Nebula (Figure 19) is a supernova remnant, the remains of a star that violently exploded in the year AD 1054. No account of this supernova can be found in European chronicles surviving from this time (see Stephenson and Green, 2003), but there are various Arabic, Chinese, Japanese and Korean records of it (Pankenier, 2006; Stephenson, 2004; Stephenson and Green, 2002). In particular, astrologers in the court of the Chinese emperor kept a detailed record of this spectacular event. The supernova appeared suddenly and was said to develop spikes leaving it in all directions. Its reddish-white colour remained clearly visible even in bright daylight for three weeks and for months afterwards it dominated the night sky (Mitton, 1978: 16). Bolton felt confident enough of the Taurus A identification to publish a detailed account in the Australian journal (Bolton and Stanley, 1949), which boasted the revealing title, "The position and probable identification of the galactic source Taurus A", and in it Bolton and Stanley gave a slightly revised position of RA 05h 31m 20 ± 30s and Dec. +22° 02′ ± 8′. They concluded:

> The limits in the position of the source enclose NGC 1952, otherwise known as the Crab nebula. According to Baade (7) this nebula is the remains of the supernova of AD 1054 observed by Chinese astronomers. The angular dimensions of the nebula are 4′ by 6′ and the angular rate of expansion is 0.13″ per year ... The measurements on 100 Mc/s. give an effec-

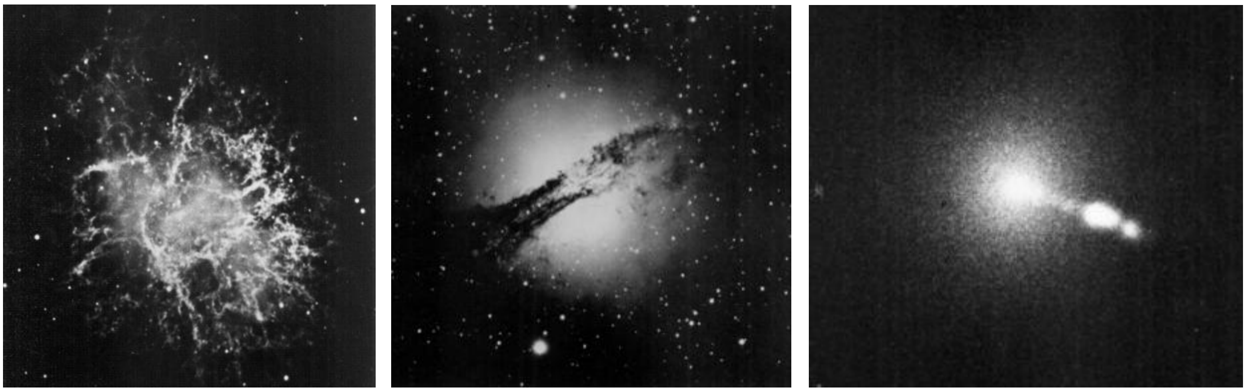


Figure 19: The first three radio sources to be identified with visible objects by the Dover Heights team. Left: Taurus A with the Crab Nebula (NGC 1952); centre: Centaurus A with NGC 5128; and right: Virgo A with M87 (NGC 4486) (courtesy: RAIA).

> tive temperature of two million degrees, assuming a source size of 5′ for Taurus A. From the present values of temperature and density in the Crab nebula it would be difficult to explain this result in terms of strictly thermal processes. However, it is not unlikely that non-thermal components would arise from differential expansion within the nebula and general expansion into interstellar matter. In view of this and the close agreement between the positions of the Crab nebula and the source Taurus A, *it is suggested that the Crab nebula is a strong source of radio-frequency radiation*. (Bolton and Stanley, 1949: 145–146; our italics).

This paper was praised by Grote Reber (1950):

> I have been greatly impressed by your series of publications upon discrete sources of galactic radio waves. The last one, in the June 1949 issue of the *Australian Journal of Scientific Research*, is a beautiful piece of work.

However, as Orchiston and Slee (2006: 46) have noted,

> It is important to stress that this initial identification was regarded by some astronomers (including radio astronomers) as tentative, and it was only when Britain's Graham Smith (1951) and RP colleague, Bernie Mills (1952a) published refined positions, and when Mills (1952b) measured the angular size of the source, that the identification was beyond doubt (see Bolton, 1955).

The two other radio sources, Virgo A and Centaurus A, provided an even bigger surprise, though initially Bolton did not realise the full significance of his identifications. Virgo A coincided with an object known as M87 (or NGC 4486). The object is distinguished by a bright blue jet of material extending from its centre, an extremely unusual feature. The other, Centaurus A (NGC 5128), turned out to be a bright and peculiar object with a dark dust band straddling its disk (see Figure 19). In his internal report Bolton (1948d) noted:

> The limits in position of the source RA 13 h 22 m 20 s ± 1 m, Declination –42° 37′ ± 8′ enclose NGC 5128. This object is classed as an extragalactic nebula. It is a seventh magnitude object with a peculiar spectrum. Baade calls it a freak and it is referred to by Shapley as a 'pathological specimen' though no details are known at present as to the exact nature of its peculiarity. It will be an interesting object to study with the Stromlo nebular spectrograph during the late summer months.

Of the four sources analysed by Bolton, Centaurus A was the only one located in the southern half of the sky. In an interesting historical twist, its optical counterpart NGC 5128 was first observed not far from Dover Heights, over 120 years earlier, by James Dunlop at the Parramatta Observatory, west of Sydney (see Robertson et al., 2010).

Bolton's identifications of the three radio sources with optical objects all turned out to be correct, though it would take several years before some astronomers were fully convinced. Each identification was to some degree a lucky guess. The error box around each radio source contained a fair number of possible candidates and there was no logical reason to rule them out. The Taurus A identification seemed the safest as a great deal was known about the Crab Nebula and it is seemed quite plausible that it could be an intense radio emitter. Bolton knew however that many of the possible candidates were relatively ordinary stars and that, if they were similar to the Sun, they could not be the source of such intense radio emission. He guessed that the optical object was more likely to be something new and unusual and here his intuition proved correct.

Although confident of the Taurus A identification, the other two sources presented a difficult dilemma. Bolton spent a week in February 1949 at Mt Stromlo talking to the Commonwealth Observatory astronomers and scouring the literature for information on NGC 5128 and M87. Although both objects were classified as extragalactic, the evidence was not strong. Individual stars had not been resolved in either object which would prove that both were indeed galaxies outside our own Galaxy. Since Centaurus A and Virgo A were among the strongest of the known

Table 2: Positions of three radio sources and their possible associated visible objects (adapted from Bolton, Stanley, and Slee, 1949: 101).

Source	Position (Epoch 1948)		Possible associated visible object	
	RA	Dec.	Object	Remarks
Taurus A	05h 31m 00s ± 30s	+22° 01′ ± 07′	NGC 1952 [A] (Messier 1)	Crab Nebula, expanding shell of an old supernova
Virgo A	12h 28m 06s ± 37s	+12° 41′ ± 10′	NGC 4486 (Messier 87)	Spherical nebula, unresolved
Centaurus A	13h 22m 20s ± 60s	–42° 37′ ± 08′	NGC 5128 [B]	Unresolved nebula crossed by a marked obscuring band

[A] Weak emission lines of H, He, forbidden lines of N, O and Si
[B] Weak emission lines, Hβ, Hγ, Hδ, and λ4686

sources, it seemed logical that both objects must be relatively close, within our Galaxy, and not at vast extragalactic distances. Bolton was concerned that an extragalactic claim for Centaurus A and Virgo A would be seen as sure evidence that he had guessed incorrectly for both and that other Galactic objects in the error boxes must be the actual sources of the strong radio emission. He also reasoned that the journal referees would probably come to the same conclusion, and in all probability the paper would be rejected for publication.

In March 1949 Bolton drafted a brief paper summarising the optical identifications of the three radio sources. The title made clear his decision: "Positions of Three Sources of Galactic Radio-frequency Radiation". Before submitting the paper he wrote to three leading experts on the Crab Nebula, Rudolph Minkowski (Mt Wilson-Palomar), Jan Oort (Leiden) and Bengt Strömgren (Copenhagen). All three were familiar with the work at Dover Heights following their discussions with Joe Pawsey during his overseas trip (see Section 4). Minkowski and his colleague Walter Baade (1893–1960) had in fact carried out the detective work that proved the Crab Nebula is the remnant of the supernova observed by the Chinese in AD 1054. In his letter to Minkowski, Bolton (1949a) gave the positions of the three sources and then noted:

> The most interesting of these is the source in Taurus whose position corresponds very closely to that of the Crab nebula. I referred to papers on this object by Baade and yourself in the *Astrophysical Journal*. The intensity of the radiation at 100 Mc/s gives an equivalent temperature of about a million degrees for an angular width of 5′. From your results on temperature and density in the Crab nebula it seems unlikely that this equivalent temperature could be due to strictly thermal processes in the nebula … I would be interested to hear your opinion on this.

Bolton received enthusiastic responses from all three astronomers. Oort wrote a five-page letter on the Crab Nebula supporting its association with Taurus A (Bolton, 1982: 352). However, he was sceptical of the identification of Virgo A with the galaxy M87 and added, diplomatically, that there are a great many objects in the Virgo cluster. Minkowski also wrote providing the latest information available on the three optical objects, including new evidence that strengthened the case that NGC 5128 and M87 were indeed external galaxies. Bolton was not persuaded, and continued to maintain that both were Galactic objects.

Early in May 1949 Bolton, with co-authors Stanley and Slee, dispatched the letter to *Nature* where it was published on 16 July (Bolton, Stanley and Slee, 1949). The heart of the paper was a brief table (see Table 2) giving the positions of the three sources and their possible associated visible objects (see Figure 19). NGC 5128 and M87 were described as 'unresolved nebula' and the case made for them to be Galactic objects:

> Neither of these objects has been resolved into stars, so there is little definite evidence to decide whether they are true extragalactic nebulae or diffuse nebulosities within our own galaxy. If the identification of these objects with the discrete sources of radio-frequency energy can be accepted, it would tend to favour the latter alternative, for the possibility of an unusual object in our own galaxy seems greater than a large accumulation of such objects at a great distance.

As indicated in the last sentence, Bolton believed that if the sources were extragalactic they must consist of a large number of unusual objects to account for such intense emission. It appears he did not consider the idea that the emission could come from a *single* extragalactic object. Bolton (1949b) expressed this view more colourfully in further correspondence with Minkowski: "In a letter to *Nature* (written before I consulted you) I have suggested that these objects may be within our own galaxy – on the basis that a close 'freak' is more probable than a large collection of 'freaks' at a great distance."

Bolton turned out to be spectacularly wrong. Baade and Minkowski made further observations of NGC 5128 and M87 and were able to resolve individual stars in both objects, proving almost certainly that they were external galaxies. Later, NGC 5128 was shown to be a peculiar galaxy at a distance of 15 × 10^6 light-years, while M87 turned out to be a giant elliptical galaxy at the even greater distance of 30 × 10^6 light-years (Robertson, 1992: 49). It was an extraordinary development. The discovery of the two extragalactic objects did not diminish the importance of the *Nature* letter—on the contrary it raised some profound questions. What was the mechanism responsible for this prodigious output of radio energy? If two of the strongest radio sources were distant galaxies could some of the fainter sources be even more distant? Might the fledgling field of radio astronomy be able to 'see' much further out into the Universe than traditional astronomy? Sullivan (2009: 324) has summed up the significance of this paper:

> The short paper by Bolton, Stanley and Slee (1949) was one of the most important in early radio astronomy, presenting a first plausible link between "galactic noise" and traditional astronomy. And what an exciting link it was, too, for this handful of intense radio stars was being associated with objects that were much fainter than any of the five thousand objects visible to the naked eye, yet still unusual enough to be included in manuals such as *Norton's Star Atlas*, the amateur astronomer's *vade mecum* that was frequently consulted by Bolton's group.

8 CONCLUSION

The short interval from June 1947, when the initial detection of Cygnus A took place, through to July 1949, when the identifications letter in *Nature* was published, was an extraordinarily productive period by the Dover Heights group. Bolton, Stanley and Slee had shown how some of the radio emission detected by Jansky, Reber and Hey was associated with discrete radio sources. The group had succeeded in measuring the positions of some of the sources with sufficient precision to identify a handful with known optical objects. And now came the most astonishing result of all—the discovery of a new class of astronomical objects with strange and intriguing properties. The youthful trio of Bolton, Stanley and Slee would all go on to carve out distinguished careers in radio astronomy, but none would produce another paper to rival the importance of their 1949 *Nature* letter. A new branch of astronomy had been founded—extragalactic radio astronomy (see Figure 20).

This new branch would revolutionise astronomy in the second half of the twentieth century. The detection of increasingly-distant radio galaxies and then the discovery of quasars in the 1960s led to an expansion in the size of the known Universe by almost two orders of magnitude. Extragalactic radio astronomy revealed a Universe populated by objects undergoing violent, energetic processes on a scale previously unimaginable to 'traditional' optical astronomers.

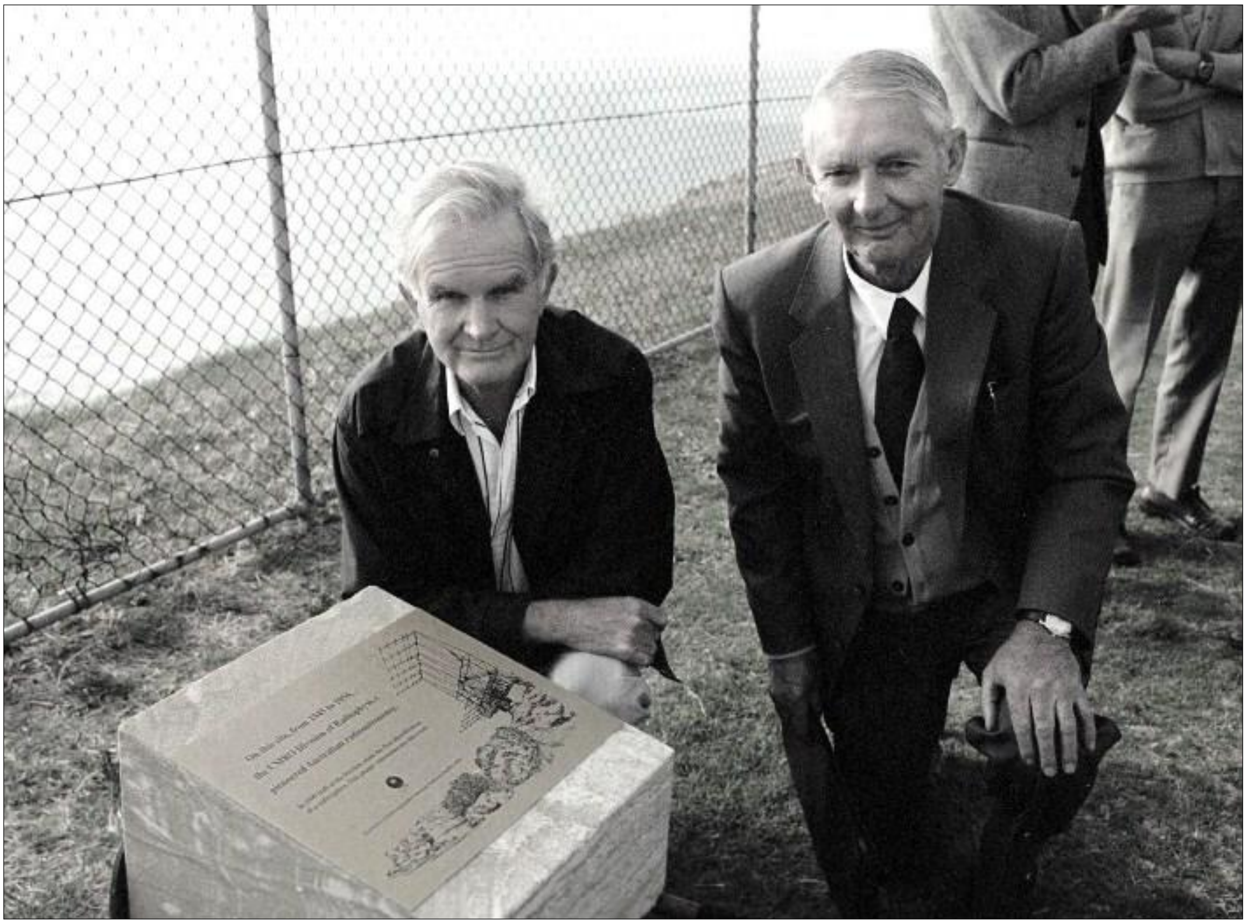


Figure 20: Bruce Slee (left) and John Bolton (right) at the unveiling of a plaque in 1989 at Rodney Reserve, the site of the Dover Heights field station. The plaque celebrated the birth of extragalactic radio astronomy forty years earlier. The field station has been converted into a rugby field with the plaque close to the sea cliff and near the halfway line (courtesy: RAIA N15506-4).

9 NOTES

1. For earlier biographical accounts of John Bolton see Goddard and Haynes (1994), Kellermann (1996), Orchiston and Kellermann (2008), Robertson (1984b) and Wild and Radhakrishnan (1995; 1996). For Bolton's own recollections of the early work on 'radio stars' see his paper "Radio astronomy at Dover Heights" (Bolton, 1982).
2. Note that we now refer to this science as 'radio astronomy' but during the 1930s, when Jansky and Reber were carrying out their pioneering work, they were investigating 'cosmic static' or 'cosmic noise'. The earliest known use of the term 'radio astronomy' was made in January 1948 in a letter by Pawsey (1948a). The new term was enthusiastically endorsed by Bowen (1948).
3. The Germans, for their part, also experienced similar problems to those encountered by Hey, and also assigned them, eventually, to solar radio emission (see Schott, 1947).
4. 'COL' stands for Chain Overseas Low-flying". These radar units were widely used during WWII and normally were coastally-located and looked out to sea in order to detect low-flying incoming aircraft.
5. The technique is also known as 'cliff interferometry' or 'sea-cliff interferometry'; however, we prefer the term 'sea interferometry', as used in the original Dover Heights publications.
6. Martyn was a former Chief of the Division of Radiophysics, and he and his Commonwealth Observatory colleague, Clabon Walter (Cla) Allen (1904–1987), were also keen to investigate solar radio emission at this time. Consequently, in early 1946 two Radiophysics staff members installed a 200 MHz radio telescope at the Observatory. This was virtually identical to the 2-element Yagi set-up that Bolton, Stanley and Slee later would use at Dover Heights (see Orchiston et al., 2006). Apart from Allen and Martyn, the Director of the Observatory, Richard van der Riet Woolley (1906–1986), was also interested in solar radio astronomy. It has been claimed, with some justification, that "The association between Mt Stromlo and Radiophysics was the first major collaboration between optical and radio astronomers anywhere in the world." (Robertson, 1992: 109). In general, it took much longer for optical astronomers in other parts of the world to accept radio astronomy as a valid area of astronomy and to collaborate with radio astronomers (see e.g. Jarrell, 2005).
7. Other nations experienced similar problems, and only the Russians ended up going to Brazil and successfully observing the 20 May 1947 eclipse (see Khaykin and Tchikhatchev, 1947).
8. The 200 MHz data were supplied by Mt Stromlo astronomers, as the 200 MHz Yagi array at Dover Heights was not operational at this time.
9. This source turned out to be Centaurus A. Bolton later made the point that if he and Stanley had detected this source first, instead of Cygnus A, they would not have cited Hey et al. in their discovery paper (Bickel, 1975). Thus, the later 'confusion' over whether Hey et al. or Bolton et al. discovered the first discrete radio source might have been avoided.
10. In fact, Bolton's Radiophysics Laboratory colleagues Bernard Yarnton Mills (1920–2011) and Adin B. Thomas, made this very optical identification two years earlier, in 1949. After observing Cygnus A from May to December 1949 with a 97 MHz swept-lobe interferometer at the Potts Hill field station (Wendt et al., 2011), Mills examined a photograph of the region that Minkowski had sent to Bolton and in the error box of their observations he noticed a faint extragalactic nebula. He felt that this could be the source of the emission and wrote to Minkowski suggesting this (Mills, 1949). However, Minkowski (1949) advised Mills against claiming the identification, so when their paper on Cygnus A finally appeared Mills and Thomas (1951) concluded that this faint galaxy was unlikely to be responsible for the emission. Smith's more precise position, obtained in 1951, confirmed that this galaxy was indeed responsible for the Cygnus A emission.

10 ACKNOWLEDGEMENTS

We are grateful to Professor Woody Sullivan for providing copies of the Bolton (1947; 1949a; 1949b) letters, and to Professor Ken Kellermann (NRAO) and Professor Richard Strom (ASTRON) for commenting on earlier drafts of this paper. One of us (PR) also is grateful to the Astrophysics Group, School of Physics, University of Melbourne for its support. The second author (WO) is grateful to the National Astronomical Observatory of Japan for providing the opportunity for him to complete the revision of this paper while at Mitaka on a Visiting Professorship.

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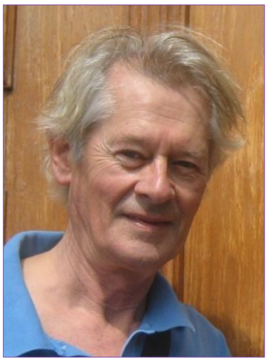
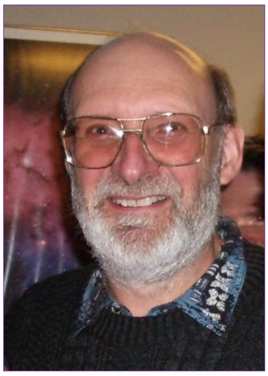


Peter Robertson is an honorary research associate in the School of Physics, University of Melbourne. He is a former managing editor of the *Australian Journal of Physics* (1980–2001) published by CSIRO Australia and the Australian Academy of Science. Peter is currently completing a full-length biography of John Bolton, the early pioneer of radio astronomy featured in this paper.



Professor Wayne Orchiston is a Senior Researcher at the National Astronomical Research Institute of Thailand, and the founder of the IAU Working Group on Historic Radio Astronomy. He has published extensively on Australian, French, Japanese and New Zealand radio astronomy and has supervised six Masters or Ph.D. theses on the history of Australian, British and U.S. radio astronomy. Currently, he, Professor Masato Ishiguro (NAOJ) and various Japanese colleagues are systematically documenting the early history of radio astronomy in Japan through a series of papers that are published in this journal.

Dr Bruce Slee is one of the pioneers of Australian radio astronomy. Since he independently detected solar radio emission during WWII he has carried out wide-ranging research, first as a member of the CSIRO's Division of Radiophysics, and then through its successor, the Australia Telescope National Facility. After working with Bolton and Stanley on the first discrete sources at Dover Heights, he moved to the Fleurs field station and researched discrete sources with Mills, using the Mills Cross. He also investigated radio emission from flare stars with the Mills and Shain Crosses, and used the Shain Cross and a number of antennas at remote sites to investigate Jovian decametirc emission. With the commissioning of the Parkes Radio Telescope he began a wide-ranging program, that focussed on discrete sources, and radio emission from various types of active stars. He also used the Culgoora Circular Array (*aka* Culgoora Radioheliograph) for non-solar research, with emphasis on pulsars, source surveys and clusters of galaxies, and continued some of these projects using the Australia Telescope Compact Array. He also has used a range of overseas radio telescopes for his research; has participated in VLBI experiments; and has collaborated on multi-wavelength observations of active stars. Over the past two decades, he also has been writing papers on the history of Australian radio astronomy, and he has supervised a number of graduate students who were researching history of radio astronomy theses. At 90 years of age he continues to conduct research as an honorary associate of CSIRO's Division of Astronomy and Space Sciences.