

## THE CONTRIBUTION OF THE GEORGES HEIGHTS EXPERIMENTAL RADAR ANTENNA TO AUSTRALIAN RADIO ASTRONOMY

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**Abstract:** During the late 1940s and throughout the 1950s Australia was one of the world's foremost astronomical nations owing primarily to the dynamic Radio Astronomy Group within the Commonwealth Scientific and Industrial Organisation's Division of Radiophysics based in Sydney. The earliest celestial observations were made with former WWII radar antennas and simple Yagi aerials attached to recycled radar receivers, before more sophisticated purpose-built radio telescopes of various types were designed and developed.

One of the recycled WWII antennas that was used extensively for pioneering radio astronomical research was an experimental radar antenna that initially was located at the Division's short-lived Georges Heights Field Station but in 1948 was relocated to the new Potts Hill Field Station in suburban Sydney. In this paper we describe this unique antenna, and discuss the wide-ranging solar, galactic and extragalactic research programs that it was used for.

**Keywords:** Australia, radio astronomy, experimental radar antenna, solar monitoring, H-line survey, 1200 MHz all-sky survey, Sagittarius A, 'Chris' Christiansen, Jim Hindman, Fred Lehany, Bernie Mills, Harry Minnett, Jack Piddington, Don Yabsley

### 1 INTRODUCTION

In 2003 the IAU Working Group on Historic Radio Astronomy was formed, and one of its challenges was to identify and research radio telescopes that made important contributions to radio astronomy prior to 1961. One such Australian radio telescope was based on an experimental radar antenna (Figure 1) that originally was located at Georges Heights Radar Station, overlooking the entrance to Sydney Harbour.

During WWII the Council for Scientific and Industrial Research's<sup>1</sup> Division of Radiophysics (henceforth RP) was involved in the development of radar (Bowen, 1984), and following the war one of its main areas of research was radio astronomy.

At the end of WWII Dr Joe Pawsey (1908–1962; Figure 2; Lovell, 1964), the dynamic Head of Radio Astronomy at RP, decided to set up a number of field stations in or near suburban Sydney. By the early 1960s these field stations and associated remote sites had mushroomed in number, eventually totalling twenty-one. Their geographical distribution is shown in Figure 3, which also includes the Radiophysics Laboratory, located in the grounds of the University of Sydney (where high frequency solar and lunar observations were made in the late 1940s). These field stations were a special feature of RP radio astronomy, and one of the reasons for Australian pre-eminence in radio astronomy during the two decades following WWII (see Orchiston and Slee, 2017). For those of us who worked at RP in the early 1960s, the field stations bring back fond memories,<sup>2</sup> and with the close down of the field stations and remote sites following the commissioning of the 64-m Parkes Radio Telescope in

November 1961 (Robertson, 1992) the nature of Australian radio astronomy changed forever (see Sullivan, 2017).

The experimental radar antenna that is the subject of this paper started its radio astronomical 'career' at Georges Heights Field Station (site

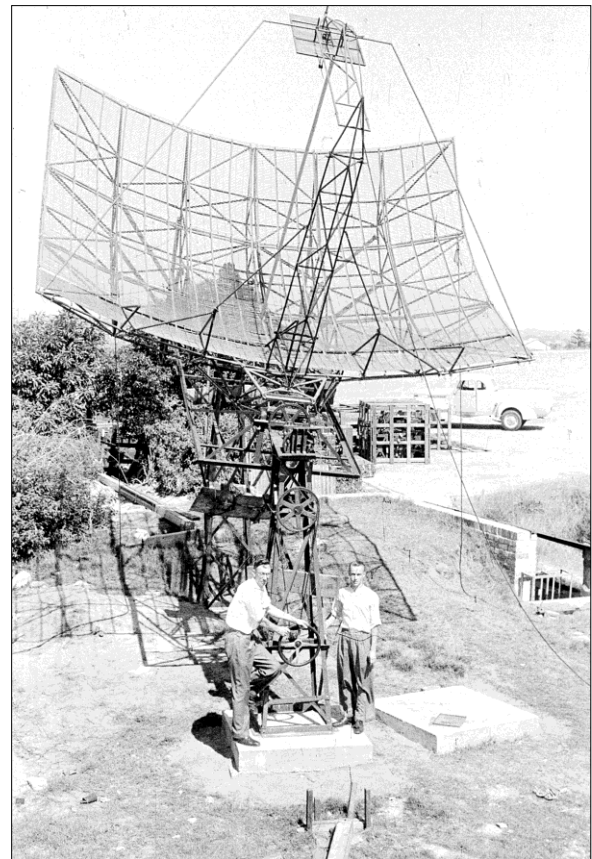


Figure 1: The Georges Heights experimental radar antenna. Posing in the photograph (left to right) are Joe Pawsey and Don Yabsley (courtesy: CSIRO Radio Astronomy Image Archive—henceforth CRAIA, B1031-9).



Figure 2: Dr Joseph Lade Pawsey (courtesy: CRAIA).

8 in Figure 3), when this military facility was taken over by RP at the end of the War, but less than three years later it was transferred to the Potts Hill Field Station (site 16 in Figure 3). Let us now examine the role that this historic radio telescope played in international radio astronomy.

## 2 THE ABORTIVE 1947 SOLAR ECLIPSE EXPEDITION

One of the key challenges for the early researchers was the low resolution of the existing radio telescopes, which prevented the determination

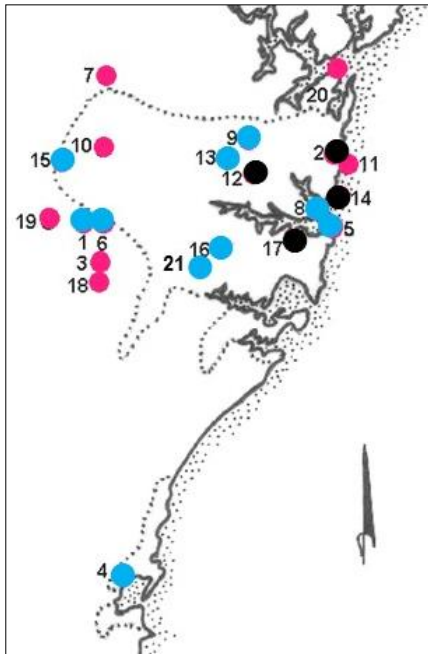


Figure 3: Radio astronomy localities in the Sydney-Wollongong region; the dotted outlines show the current approximate boundaries of Greater Sydney and Greater Wollongong. Key. Field stations: blue; remote sites: red; other sites: black. 1 = Badgerys Creek, 2 = Collaroy, 3 = Cumberland Park, 4 = Dapto, 5 = Dover Heights, 6 = Fleurs, 7 = Freeman's Reach, 8 = Georges Heights, 9 = Hornsby Valley, 10 = Llandilo, 11 = Long Reef, 12 = Marsfield (ATNF Headquarters), 13 = Murraybank, 14 = North Head, 15 = Penrith, 16 = Potts Hill, 17 = Radiophysics Laboratory (Sydney University grounds), 18 = Rossmore, 19 = Wallacia, 20 = West Head, 21 = Bankstown Aerodrome. For scale: from Dapto (site 4) to Dover Heights (site 5), as the crow flies, is 88 km (map: Wayne Orchiston).

of precise positions of the sources of solar radio emission. Some early progress was made by McCready et al. (1947) using a sea interferometer, but it was soon realised that solar eclipses offered a more sophisticated method of establishing the locations of different radio-emitting regions in the solar corona (see Hey, 1955). In 1946, the Canadian radio astronomer, Arthur Covington, used the partial solar eclipse of 23 November to accurately measure the time—hence position projected onto the solar disk—when radio emission at 2,800 MHz was masked by the passage of the Moon's disk (Covington, 1947). Sander (1947) also used this same eclipse to examine the distribution of radiation across the Sun's disk at 9,428 MHz. Although Dicke and Beringer (1946) were the first to observe a solar eclipse at radio frequencies, it was Covington who first showed that strong emission was associated with a sunspot group that was occulted during an eclipse.

These promising results inspired Joe Pawsey to plan RP's first eclipse expedition: to observe a total solar eclipse from Brazil on 20 May 1947. In a proposal from the Chief of the Radiophysics Division, Dr E.G. ('Taffy') Bowen (1946) to the Chief Executive of the C.S.I.R., Dr F.W.G. White, the rationale for this expedition was outlined: a solar eclipse offered an ideal opportunity to measure the apparent diameter of the solar disk at different frequencies. Pawsey (1946c) explained why this was important:

A quantitative theory concerning the steady component of radiation has now been advanced by D.F. Martyn. This assigns a distribution of intensity over the disc of the sun which changes radically with the frequency of observation. An interesting prediction is that, in the region of 600 Mc/s, the radiation should be intense near the edge of the sun and weak in the centre, so that the sun should appear as a bright ring and not a disc. Such a distribution gives an intensity variation during the eclipse markedly different from that from a disc. The part of the theory dealing with intensity distribution over the surface is as yet unsupported by experiment and it appears that eclipse observations provide a sound method of verification. This quantitative verification is an extension of Bowen's suggested measurement of the apparent diameter of the sun's disc.

This was Radiophysics' first international venture, and was a major undertaking. Despite the cost being around £6,000, the proposal received Government approval on 13 November 1946, and Joe Pawsey, Lindsay McCready (1910–1976) and Don Yabsley were selected as the proposed members of the expedition.

What was needed on short notice was a versatile radio telescope that functioned simultaneously at 200, 600 and 1,200 MHz. The COL radar antennas used at the radar stations around

Sydney were totally unsuited, because they were 'permanent' fixtures, were not capable of tracking the Sun throughout the day, and could not be used effectively over the required frequency range.

Pawsey and others from RP then visited the Georges Heights Radar Station, which occupied an attractive strategic position on Middle Head (Figure 4) overlooking the entrance to Sydney Harbour and during WWII was home to a number of different radar antennas (see Figure 5). After carefully evaluating these, they settled on the experimental radar antenna shown in Figure 1, a 16 × 18-ft (4.9 × 5.5-m) section of a parabola that was on a crude mounting. This could track the Sun—after a fashion—throughout the

day, but more importantly, it could operate successfully over the frequency range 200–1,200 MHz.

The idea was to construct 200, 600 and 1,200 MHz receivers for it, and then ship this antenna to Brazil, along with two separate single crossed Yagi antennas that also could make total power measurements, and at the same time measure polarization at 100 and 200 MHz (Pawsey, 1946a).

The radio astronomers at Cambridge University group also planned to send an expedition to Brazil, but upon learning about RP's expedition they decided to cancel theirs (Ratcliffe, 1946). It was only after this occurred that Pawsey's group

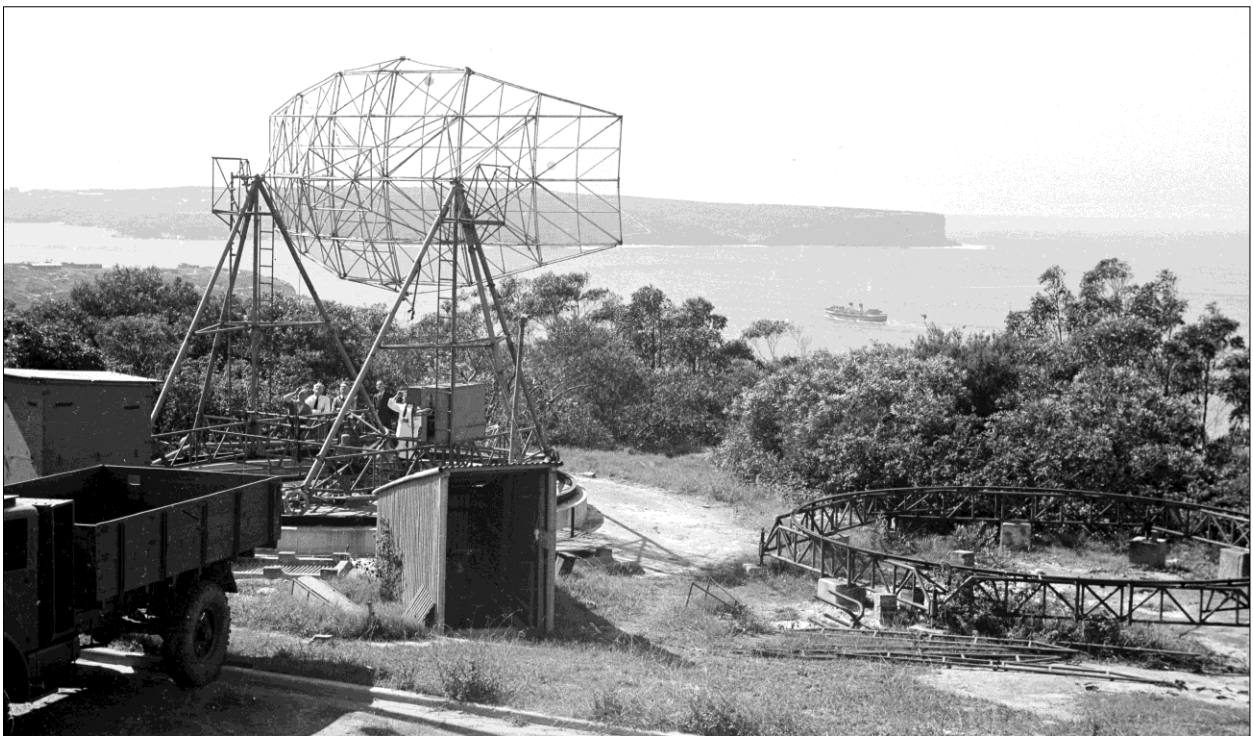


Figure 4: A photograph showing the commanding view of the entrance to Sydney Harbour from the Georges Heights Radar Station. North Head is shown, and below it a Manly ferry. The suburb of Manly is at the head of the inlet on the left, just off of the photograph (courtesy: CRAIA, B2736-3).

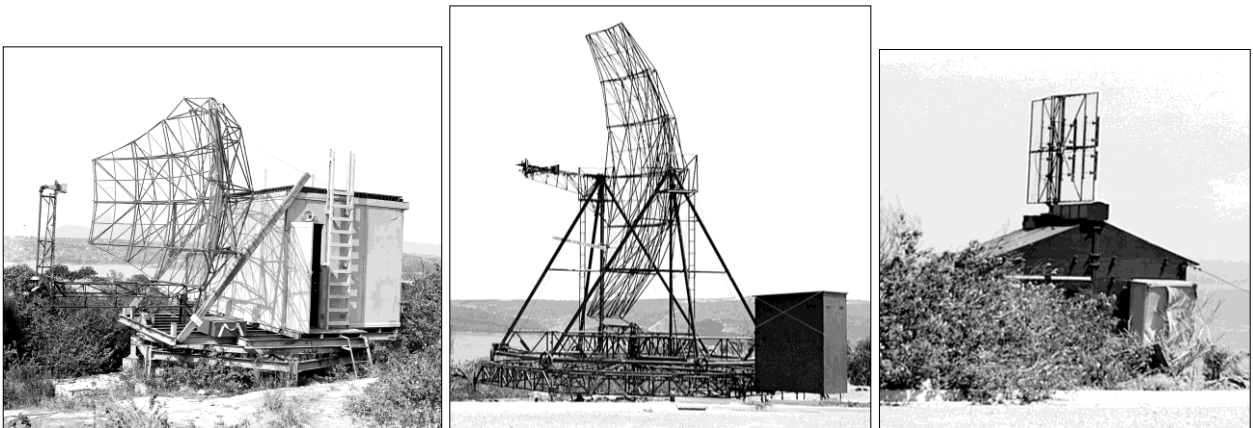


Figure 5: Three of the five different WWII radar antennas at Georges Heights when this radar station was taken over by RP as a radio astronomy field station. The other two antennas are shown in Figures 1 and 4. After a careful evaluation of each antenna—e.g. see the RP staff assessing the antenna in Figure 4—they chose to use the antenna in Figure 1 for radio astronomy (courtesy: CRAIA, B1507-4, B1362).

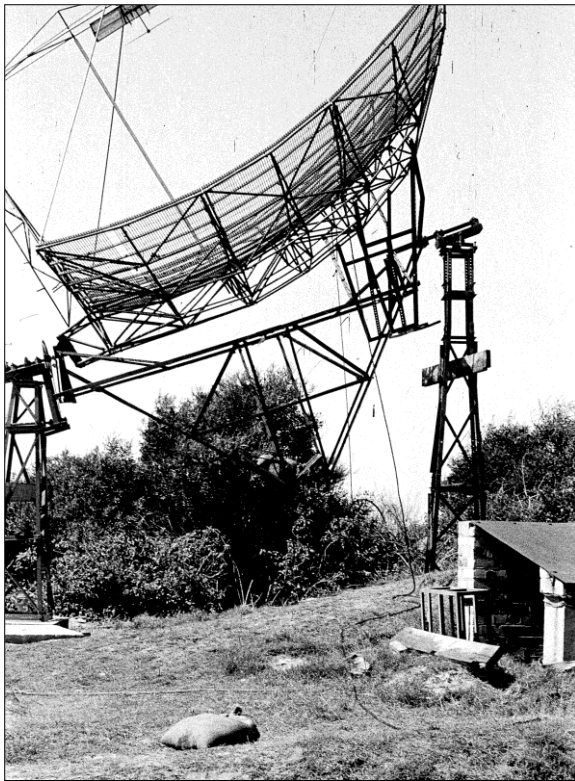


Figure 6: A side elevation view showing the antenna's simplistic mounting (courtesy: CRAIA, B1031-12).

realised that they had seriously underestimated the amount of time required to make the Georges Height antenna operational at three frequencies and get it and the other equipment to Brazil in time. Unfortunately, the 3-ton consignment had to be shipped via London, and the transit time plus delays in customs would see it arrive in Brazil after the eclipse! So in December Pawsey (1946b) reluctantly wrote to Ratcliffe, informing him that the RP expedition had been abandoned, and apologizing for having disrupted Cambridge's initial plans.

For further details of RP's planned Brazil eclipse expedition see Wendt et al. (2008a).

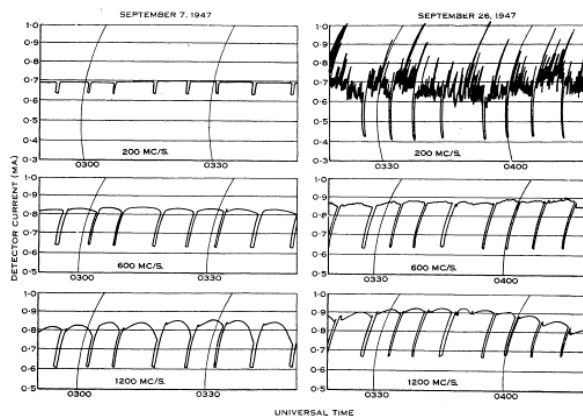


Figure 7: Chart records for 200, 600 and 1,200 MHz obtained at Georges Heights on 7 and 26 September 1947. Note the extensive 200 MHz burst emission on 26 September. The distinctive 'picket fence' nature of the chart record is clearly illustrated in the 600 and 1,200 MHz plots (after Lehany and Yabsley, 1949: 55).

### 3 SOLAR MONITORING AT GEORGES HEIGHTS FIELD STATION

The regretted cancellation of the Brazil expedition opened the way for RP to convert the Georges Heights facility into a field station—although it would turn out to be short-lived (see Orchiston, 2004b). More importantly, it allowed the experimental radar antenna to be developed as a radio telescope for regular solar monitoring at 200, 600 and 1,200 MHz, thus significantly expanding the frequency-coverage of RP's solar program, which at the time focussed on work carried out at 60, 100 and 200 MHz by Ruby Payne-Scott (Goss, 2013; Goss and McGee, 2009) and Don Yabsley at Dover Heights Field Station.

One major impediment, however, was the primitive mounting (see Figure 6). Because the antenna was not driven, the only way it could be used for solar observations was to place it ahead of the Sun, let the Sun drift through the beam, hand-crank the antenna ahead of the Sun again, and repeat the process throughout the day. This tiresome procedure produced a distinctive 'picket fence' chart record (Figure 7), and although it was far from ideal it would produce useful results. So Pawsey's team decided to live with the existing mounting for the time being, instead of making time-consuming and costly modifications. These would come later—as we shall see.

Joe Pawsey assigned two young RP researchers to carry out solar observations with the Georges Heights radio telescope. They were Fred Lehany and Don Yabsley, and like others in Pawsey's fledgling Radio Astronomy Group they were radio engineers, and had little—if any—knowledge of astronomy (see Sullivan, 2017). Consequently, Pawsey's group studied 'cosmic noise' and 'solar noise', and initially found it challenging to try and reconcile their observations with accepted astronomical theory and practice. They were engineers, not astronomers, and even the term 'radio astronomy' would only be coined in 1948 (Sullivan, 2009). It would then take nearly a decade before optical astronomers began to openly accept their radio colleagues as 'astronomers' (see Jarrell, 2005).

Fred Lehany (1915–1994) was born in New Zealand, and had an M.Sc. degree from the University of Otago, in Dunedin. During WWII he was employed by Amalgamated Wireless (Australasia) Ltd. (AWA), and between 1945 and 1948 he worked at RP as a Senior Research Officer, before transferring to the National Standards Lab—where he eventually assumed the post of Director. Thus, his involvement in radio astronomy research was short-lived, and his Georges Heights involvement

... came about in a typical 'Pawseyian way', before I knew what was happening ... there was an observing program and ... Yabsley and I were a suitable pair to share not only the week days but also the weekend duty ... (Lehany, 1978).

Yabsley (1986) later pointed out that Lehany's special contribution was

... the provision of a cavity filter at the input of both the 600 MHz and 1200 MHz mixer receivers, thereby suppressing the unwanted image frequency and higher frequency bands using harmonics of the local oscillator for frequency conversion. Thus each of these receivers was essentially monochromatic and this feature facilitated the achievement of accurate calibration of flux densities. He was also responsible for providing the matched hot loads used to perform the calibration.

Lehany's youthful companion, Donald Yabsley (ca 1922–2003), joined RP as an Assistant Research Officer in 1944 after completing a combined B.Sc./B.Eng. at the University of Sydney, and he worked on the radio-navigation LORAN project (Yabsley, 1978). Immediately after the War he carried out solar observations in collaboration with Ruby Payne-Scott at Dover Heights, and in 1947 he transferred to Georges Heights. There he was responsible for designing and building the triple-feed system (see Figure 8) that allowed the ex-radar antenna to operate simultaneously at 200, 600 and 1200 MHz.

Meanwhile, assisting Lehany and Yabsley between June and August 1947, mainly during the development of the receivers and feed systems and operational testing of the antenna, was a young Technical Assistant named Bruce Slee (1924–2016; Figure 9). Later Slee would establish an international reputation through his work at Dover Heights, Fleurs, Parkes and Culgoora (see Orchiston, 2004; 2005a).

A frequent visitor to Georges Heights during the developmental phase was Lindsay McCready, one of RP's receiver experts, who monitored the development of the three new receivers. Slee (pers. comm., 2002) also recalled that Ruby Payne-Scott and Joe Pawsey were occasional visitors.

By August 1947, the equipment was fully operational (see Figure 10), and in the first instance solar monitoring was carried out for about two hours daily, from 18 August until 30 November. Although a considerable number of short-duration bursts were detected at 200 MHz, these were usually absent at 600 and 1200 MHz. The only notable exception to this general pattern occurred on 4 October 1947, when a conspicuous outburst was recorded at 600 and 1200 MHz and

... the intensity levels at both frequencies increased to thirty times their normal value and remained high for approximately ten minutes ...

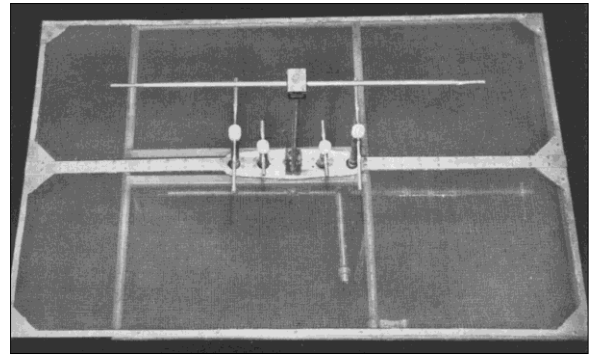


Figure 8: The prime focus assembly showing the different dipoles for 200, 600 and 1200 MHz (courtesy: CRAIA).

(Lehany and Yabsley, 1949: 58; cf. Lehany and Yabsley, 1948).

Despite the rudimentary state of their astronomical knowledge, Lehany and Yabsley (1949: 60) postulated that the emission at 600 and 1200 MHz was

... compatible with the thermal radiation expected from the solar atmosphere at these frequencies. It is considered that the variations in intensity ... are at least partly due to the magnetic fields of the sunspots raising parts of the effective radiating shells into the corona ...

Clearly Lehany and Yabsley were well on the way to becoming astronomers—even though Lehany (1978) later was quick to admit that he had little intrinsic interest in the discipline!

Accompanying the 4 October 1947 outburst was corresponding burst activity at 200 MHz and (on the basis of Dover Heights records) at 60 and 100 MHz (see Figure 11). About twenty-five minutes after the end of the outburst at 600 MHz there was a further period of activity, characterized by a succession of intense bursts of short-duration. As Figure 11 shows, some correspond-



Figure 9: Bruce Slee in 1947, one year after he joined RP as a Technical Assistant. During WWII Slee was a radar technician, and he independently discovered solar radio emission while based near Darwin (courtesy: Bruce Slee).

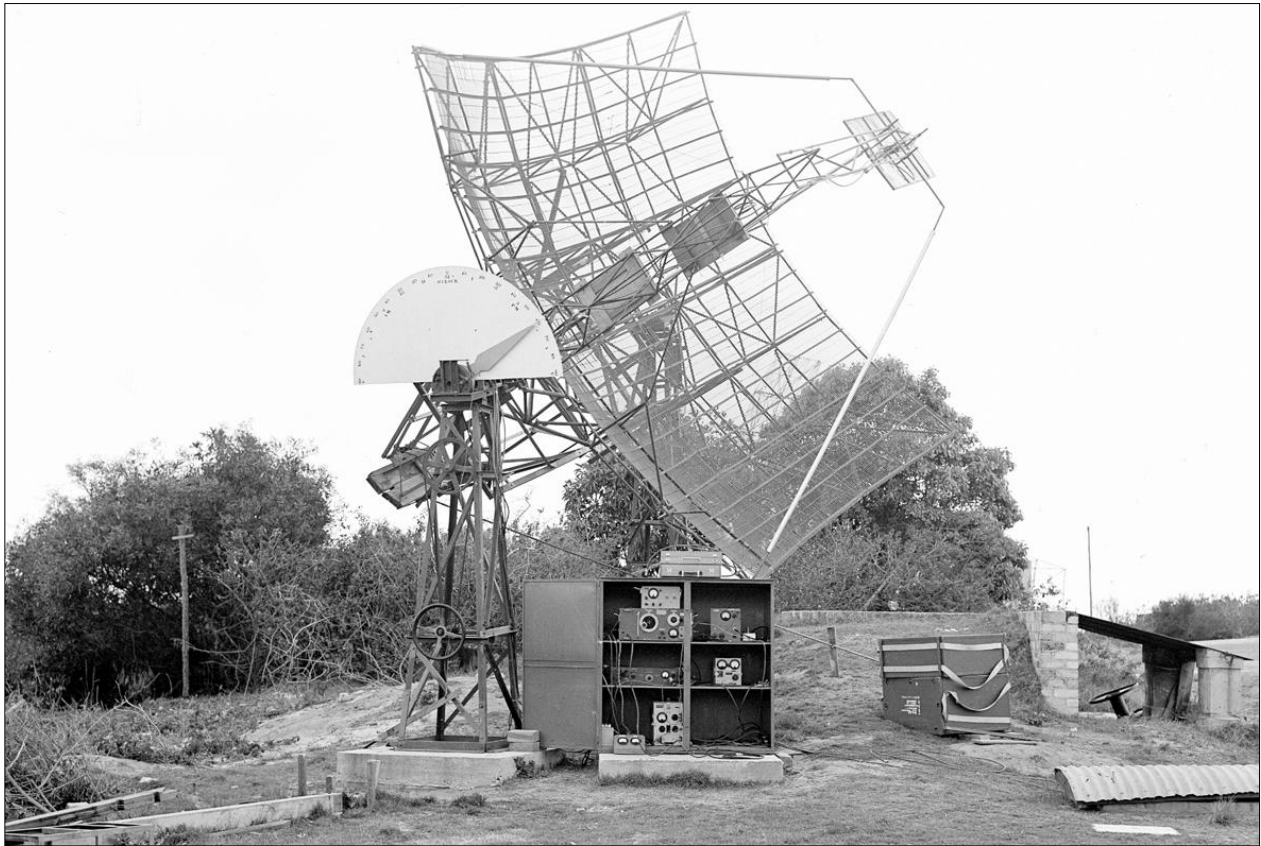


Figure 10: A view of the Georges Heights radio telescope, set up for solar monitoring at three frequencies. Note the large white semi-circular indicator used for tracking the position of the antenna and the newly-installed receiver box adjacent to the antenna. Also obvious is the wheel that was used to crank the antenna ahead of the Sun during observations (courtesy: CRAIA, B1164).

ing burst activity was also recorded at 60 MHz and 200 MHz, but these bursts were conspicuously absent at 1200 MHz. At the time of the initial outburst, the ionospheric recording station at Mt Stromlo recorded a short-wave radio fade-out.

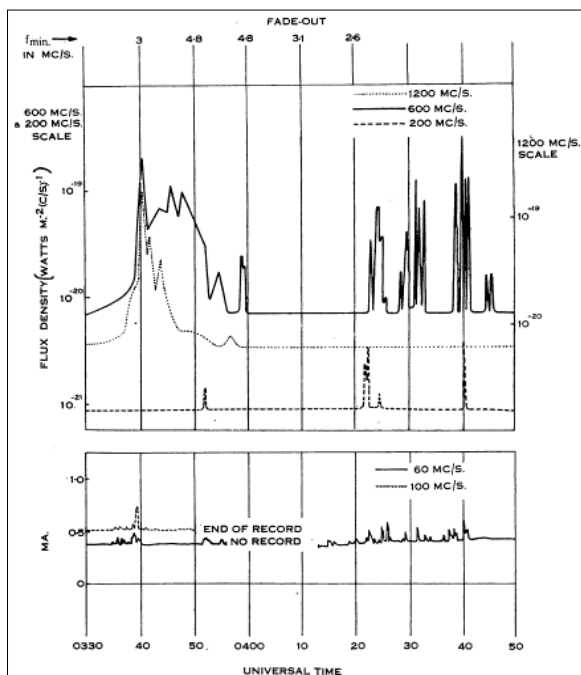


Figure 11: The 4 October 1947 outburst and subsequent bursts at 60, 100, 200, 600 and 1200 MHz. (after Lehany and Yabsley, 1949: 58).

The 4 October 1947 event (now classed as a comparatively rare spectral Type II outburst) was anomalous, and for much of the monitoring period, Lehany and Yabsley (1949: 48) found that

At 600 Mc/s. and 1200 Mc/s., the received intensity was normally steady on any one day but underwent long-period variations over a range of about two to one. The radiation received when the sun was almost free of sunspots corresponded to an effective black-body temperature of 0.5 million °K [sic] at 600 Mc/s. and 0.1 million °K [sic] at 1200 Mc/s. As sunspots appeared, the temperature rose and showed marked correlation with sunspot area.

Thus, the general flux variations with time were correlated with sunspot area (see Figure 12).

During mid-1948, the Georges Heights Field Station also was used as a test-base for two portable 10-ft (3.05-m) dishes<sup>3</sup> that would be used to observe the 1 November 1948 partial solar eclipse from Rockbank in Victoria and Strahan in Tasmania. Sadly, this eclipse was the death-knell for Georges Heights as an RP Field Station, for a decision was made to transfer the ex-radar antenna to the Potts Hill Field Station where it would be used to observe the eclipse.

#### 4 THE NOVEMBER 1948 PARTIAL SOLAR ECLIPSE

The Potts Hill Field Station (Figure 13; Davies,

2008; Wendt et al., 2011b) was founded in 1948. It is shown as site 16 in Figure 3, and was located beside Sydney's main water reservoir in what, at that time, was an outer southwestern suburb of Sydney.

Apart from the relocated Georges Heights radio telescopes, by November 1948 the Potts Hill Field Station boasted a single Yagi antenna that was used by Alec Little to observe the Sun at 62 MHz, a 44-inch (1.1-m) solid metal dish with 9,000 and 24,000 MHz receivers relocated from the 'Eagle's Nest' observing precinct atop the Radiophysics Laboratory in the grounds of the University of Sydney, and a 10-ft (3.05-m) wire-mesh dish that later would be employed by for solar and galactic research at 1,210 MHz.

The principal incentive for the consolidation of solar astronomy at Potts Hill was the 1 November 1948 partial eclipse of the Sun. In the late 1940s the angular resolution of radio telescopes was poor, and observations of total and partial solar eclipses offered an elegant way of pinpointing the positions of localized regions responsible for solar radio emission and also of determining the distribution of radio brightness

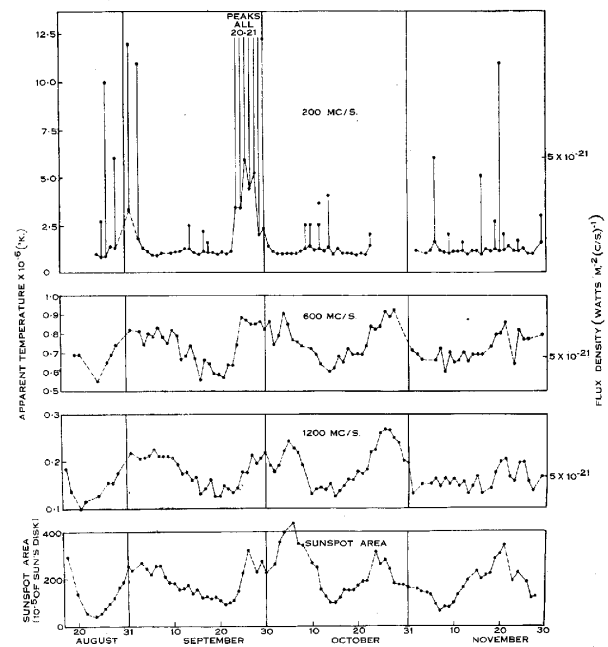


Figure 12: A diagram showing the correlation between solar radio emission at 600 and 1200 MHz (the two middle plots) and total sunspot area (the bottom plot). Burst emission at 200 MHz (the top plot), does not show this correlation (after Lehany and Yabsley, 1949: 56).



Figure 13: An aerial view of Potts Hill water reservoirs, looking south. The Potts Hill Field station was located around the Eastern Reservoir shown in full in this photograph. The ex-Georges Heights radio telescope was located in the flat land in the foreground, and can be seen as the small white square a little left of centre and directly in front of an isolated tree (courtesy: CRAIA, B3253-1).



Figure 14: The refurbished ex-Georges Heights antenna at Potts Hill (courtesy: CRAIA, B1803-5).



Figure 15: A map showing non-Sydney locations mentioned in the text (map: Wayne Orchiston).

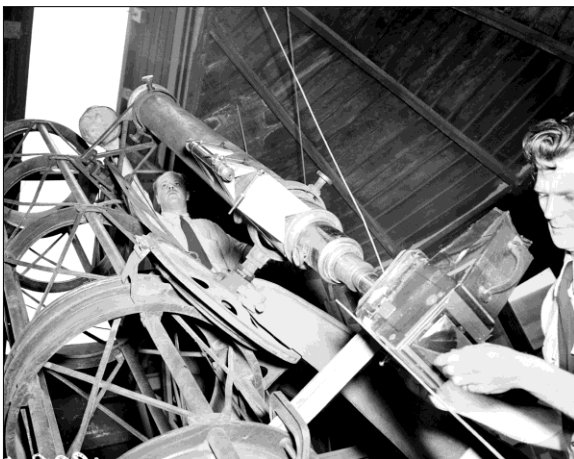


Figure 16: Photographs of the eclipse were taken through the 6-in (15.2-cm) refractor that served as a guide-scope for the 18-in (45.7-cm) reflector (courtesy: CRAIA, B1899-7).

across the disk of the Sun.

The reasoning was that as the Moon's limb moved across the Sun's disk and masked different radio-emitting regions there would be obvious dips in the chart record (Hey, 1955). Covington (1947) was the first to pioneer this technique, in 1946, and the RP radio astronomers were keen to take advantage of the 1948 eclipse, which was visible from Australia.

If there was only one observing site, then any dip in the chart record would simply indicate that the source region was located *somewhere* along the arc subtended by the lunar limb *at that particular moment*, but by using several widely-spaced observing sites the intersections of the different limb profiles allowed the precise positions of the radio-active regions to be determined.

For the 1948 eclipse, the ex-Georges Heights radar antenna—complete with a new equatorial mounting (Figure 14)—was used at Potts Hill, while 10-ft AN/TPS-3 U.S. radar dishes were installed at temporary observing stations at Rockbank, near Melbourne, and Strahan, on the west coast of Tasmania (see Figure 15 for non-Sydney locations). For the States of Victoria and Tasmania, this eclipse represented their very first forays into the exciting new world of radio astronomy (e.g. see Orchiston, 2004d). All three radio telescopes operated at 600 MHz, a frequency where the radio emission was known to be associated with sunspot activity. Meanwhile, photographs taken at the Sydney Technical College's observatory (Figure 16) provided optical coverage of the event (Millett and Nester, 1948).

The observations at the three sites were coordinated by Wilbur Norman ('Chris') Christiansen (1913–2007; Figure 17; Davies, 2009; Frater and Goss, 2011; Swarup, 2008; Wendt et al., 2011a), Bernard Yarnton ('Bernie') Mills (1920–2011; Figure 18; Frater et al., 2013; Orchiston, 2014a) and Don Yabsley. This was the first solar research project conducted by Christiansen, who would go on to establish an international reputation in this field with innovative new radio telescopes (Wendt et al., 2008b) and associated research programs at Potts Hill (Wendt et al., 2008c), and later at the Fleurs Field Station (location 6 in Figure 3). Bernie Mills would build an equally-impressive international reputation by inventing the 'Mills Cross' type of radio telescope, and through his non-solar research on discrete sources, first at Fleurs Field Station and later at Hoskinstown after he left RP and accepted a Chair at the University of Sydney (see Frater et al., 2013).

Successful observations were made at all three sites, and small, but obvious, variations in the levels of solar emission were noted during the eclipse (see Figure 19). Meanwhile, photo-



graphs taken in Sydney revealed the presence of six groups of sunspots, but their total area was small, amounting to only  $\sim 0.085\%$  of the total area of the visible disk of the Sun.

The radio observations made at Potts Hill, Rockbank and Strahan showed that radio emission from the Sun began to decrease  $\sim 10$  minutes before the commencement of the optical event (consistent with the idea that 600 MHz radio emission originated in the corona). As the eclipse progressed, the troughs in the declining emission curve indicated that several different localized regions of enhanced solar emission were present, and their precise positions—projected onto the solar disk—are shown in Figure 20.

Calculations indicated that the eight localized regions of enhanced emission shown in this figure contributed  $\sim 20\%$  of the total solar radiation received on 1 November 1948. These emitting regions were assumed to be approximately circular, and their areas varied by little more than a factor of two, with a mean of  $\sim 0.4\%$  of the total area of the visible disk of the Sun. Their effective temperatures varied by more than 10:1, and if we assume a quiet Sun temperature of  $\sim 0.5 \times 10^6$  K at 600 MHz, then the brightest localized regions in Figure 20 (numbers 4 and 6) would have had effective temperatures of  $\sim 10^7$  K.

Figure 20 shows that peak number 1 was located  $\sim 1.7 \times 10^5$  km beyond the solar limb, and above a magnetically-active region in the chromosphere marked by a conspicuous prominence. All other emission peaks were on the solar disk, and in the case of numbers 2, 7 and 8 coincided with sunspot groups. However, peaks 3–6 did not appear to be associated with any obvious photospheric features, although three of these were close to the positions occupied by sunspot groups exactly one solar rotation earlier. Meanwhile, two small sunspots groups and one large group (near the western limb) were not associated with measurable levels of solar radio emission.

In addition to determining the positions of radio-active regions, the RP radio astronomers also wanted to use the 1948 eclipse to determine whether limb-brightening existed at a frequency of 600 MHz (as postulated by D.R. Martyn in 1946) and see whether radio-emitting regions in the northern and southern hemispheres of the Sun exhibited opposite senses of circular polarization—as also predicted by Martyn.

Unfortunately, the limb brightening investigation produced inconclusive results:

... roughly half the (presumed) thermal component of the radiation originated close to, and predominantly outside, the edge of the visible disk of the sun. The details of the brightness distribution could not be derived from the re-

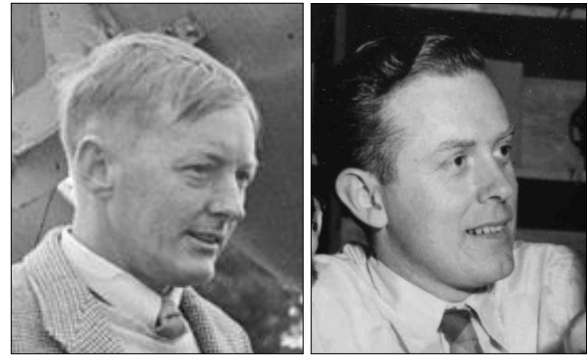


Figure 17 (left): 'Chris' Christiansen in 1952 (adapted from CRAIA B2842-66).

Figure 18 (right): Bernie Mills in 1956 (adapted from a CRAIA image).

ords. The latter were shown to be consistent with two tentative distributions, the first a theoretical one, involving limb brightening ... and the second a uniform one over a disk having 1.3 times the diameter of the optical disk of the

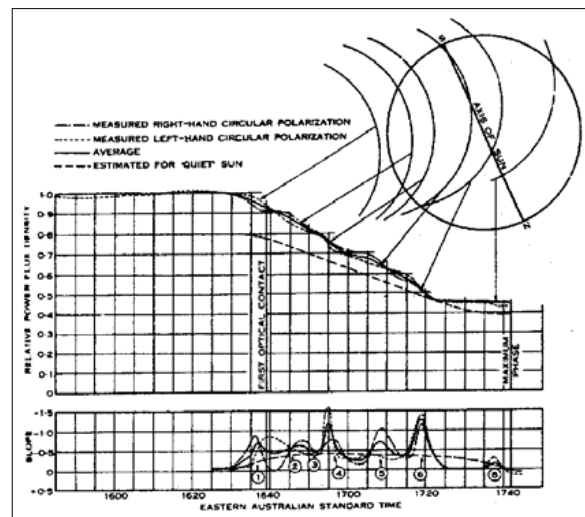


Figure 19: The solar eclipse chart record obtained at Rockbank (upper plot). In the lower plot this has been corrected for the slope and vertically-exaggerated, and the different emission peaks are numbered (after Christiansen et al., 1949a: 511).

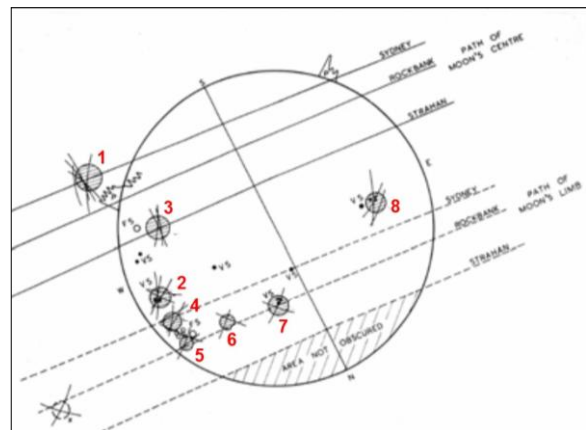


Figure 20: A map showing the distribution of 600 MHz active regions (hatched) during the 1 November 1948 eclipse. The small black dots indicate visible sunspots (VS), P indicates a prominence, and FS marks the position of a sunspot group that was prominent 27 days earlier (after Christiansen et al., 1949: 513; modifications: Wayne Orchiston).



Figure 21 (left): Jack Piddington (courtesy CRAIA).  
Figure 22 (right): Jim Hindman in 1952 (courtesy: adapted from a CRAIA image).

sun. The existence of limb brightening, therefore, was not proved. (Christiansen et al., 1949b: 570).

The polarization analysis proved interesting in that Rockbank was the only site to provide relevant data. Before the eclipse the two modes of circular polarization differed in amplitude by less than 2%, but on 1 November 1948,

The eclipsing of the active areas produced changes that sometimes were confined to one or other circularly-polarized component, or in some cases involved both components. (Christiansen et al., 1949a: 521).

The changes were of short duration, and the two components quickly returned to equality. This is illustrated in Figure 19, where the most significant variations in the relative levels of left-hand and right-hand circular polarization are associated with active regions 1, 4 and 5. Since the difference in the two polarizations curves was <3% at the maximum phase of the eclipse, this indicated that the general magnetic field strength of the Sun at the poles was <8 gauss. We should note that this is in line with current think-

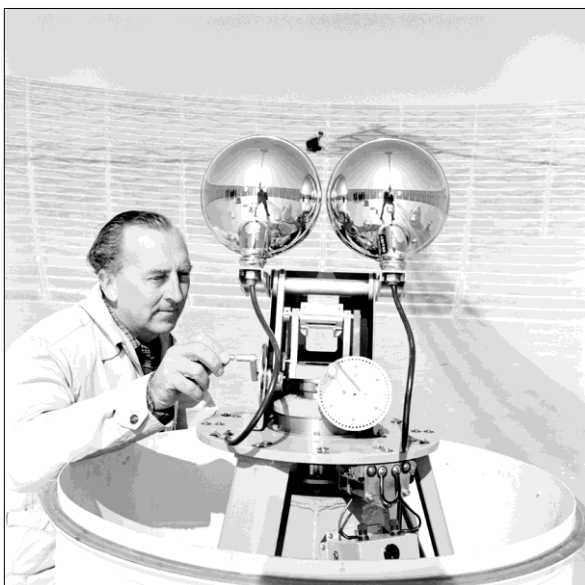


Figure 23: A photograph of Harry Minnett taken more than twenty years after his discovery of Sgr A, testing the surface accuracy of the 64-m Parkes Radio Telescope (courtesy: CRAIA, B7500-2).

ing, but that in 1948 a value of  $\sim 50$  gauss was assumed. Christiansen, Yabsley and Mills summarized their three-station observations in a letter to *Nature* (1949b) and provided a full account in a paper published in the *Australian Journal of Scientific Research* (1949a).

Two other small teams of RP radio astronomers carried out observations of the 1 November 1948 eclipse at Potts Hill in conjunction with Christiansen's group. Jack Piddington (1910–1997; Figure 21; Melrose and Minnett, 1998; Orchiston, 2014c) and Jim Hindman (b. 1919; Figure 22) used a 1.7-m (68-in) dish to make observations at 3,000 MHz, while Harry Minnett (1917–2003; Figure 23; Orchiston, 2014b; Thomas and Robinson, 2005) and Norman Labrum (1921–2011; Orchiston, 2011) observed at 9,428 MHz with the relocated 44-inch (1.1-m) Eagle's Nest antenna.

Neither team noticed obvious chart record variations during the eclipse, apart from one dip at 3,000 MHz that Piddington and Hindman associated with active region #3 in Figure 20. However, their eclipse curve supported the existence of limb-brightening, and from their polarization observations they concluded that "... if a general magnetic field exists at all it is considerably smaller than the usually accepted value of 50 gauss at the poles." (Piddington and Hindman, 1949: 534). Minnett and Labrum's observations at 9,428 MHz produced few memorable results, although they did notice that the radio event began seven minutes before first optical contact, which "... could possibly have been caused by a localized emitting region extending from the sun's limb." (Minnett and Labrum, 1950: 69).

We will meet up again with Piddington, Hindman and Minnett later in this paper.

Overall, the 1 November 1948 eclipse observations—led by the ex-Georges Heights radio telescope—were a resounding success. The emission at 600 and 1,200 MHz originated from the corona, and mainly coincided in position with photospheric sunspots or locations where sunspots were present one solar rotation earlier. Circular polarization showed that magnetic fields were implicated, and later RP's leading solar theoretician, Stefan ('Steve') Smerd (1916–1978; Orchiston, 2014d; Wild, 1980) used the 1948 eclipse to establish "... an upper limit of 11 gauss for the surface field-strength at the solar poles at the time of observation." (Smerd, 1950: 265). This figure was significantly lower than the commonly-accepted value at that time.

## 5 THE OCTOBER 1949 PARTIAL SOLAR ECLIPSE

Flushed with the success of their 1948 eclipse program, the RP radio astronomers looked with

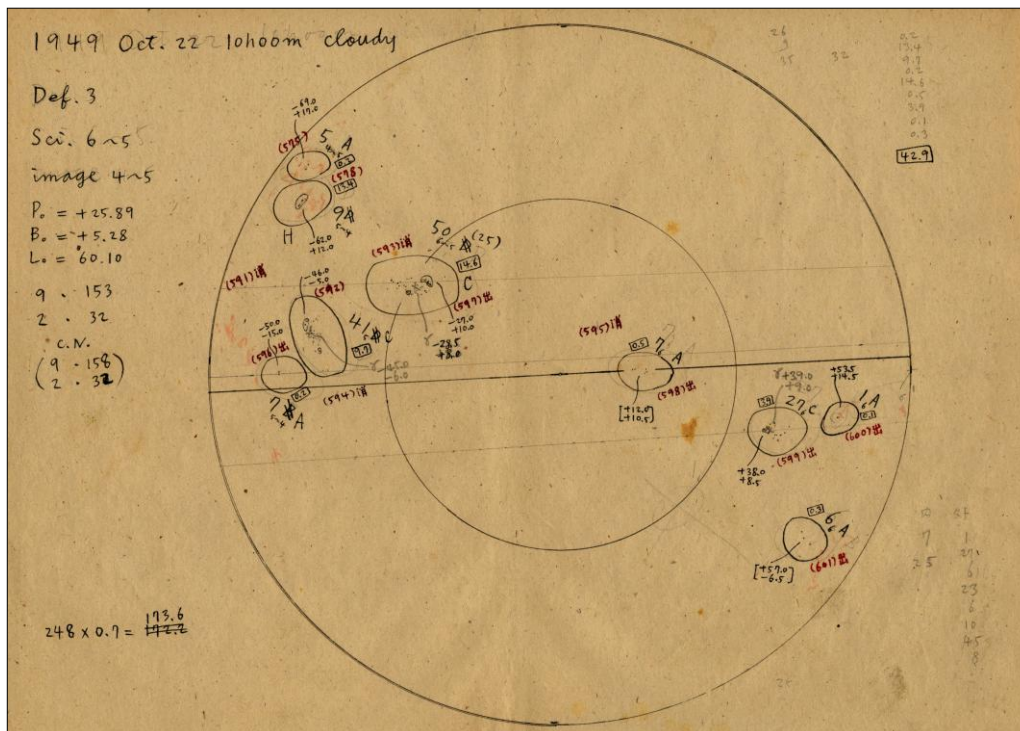


Figure 24: Sunspot observations on 22 October 1949. Note that North is at the top and East is to the right (courtesy: National Astronomical Observatory of Japan).

anticipation at another partial solar eclipse that would be visible from Australia on 22 October 1949. But unlike the 1948 sunset eclipse, this eclipse would begin soon after sunrise.

Once again a multi-site campaign was planned, centred on the ex-Georges Heights Radio Telescope at Potts Hill, while the two portable 10-ft U.S. Army radar dishes were readied for further service interstate, but at locations that offered a clear view of the eastern horizon. One dish was sited in Sale, in eastern Victoria, and the other at Eaglehawk Neck on the east coast of Tasmania, near Hobart (see Figure 15). However, all observations were to be made at 1,200 MHz instead of 600 MHz (as in 1948), and the intention also was to conduct polarisation measurements in order to examine further evidence of the existence of a general magnetic field of the Sun (Bowen, 1949b).

In addition, ancillary observations at 60, 100, 200, 600, 3,000 and 4,900 MHz would be made from the Dover Heights, Hornsby Valley and Potts Hill Field Stations (sites 5, 9 and 16, respectively in Figure 3), and from the Eagles Nest (site 17 in Figure 3) on top of the Radio-physics Laboratory (Bowen, 1949c).

As the eclipse occurred early in the morning, the observations would be complicated by ground reflection effects, and in order to allow for these, observations were made in the week leading up to the eclipse and for up to three days afterwards in order to obtain a base set of measurements.

Successful observations were made at all frequencies except 3,000 MHz (Christiansen, 1949) but, strangely, no research papers were published reporting on this second eclipse program. Why was this?

Christiansen (1950) noted that small changes on the eclipse chart records were not as clearly defined as those seen during the 1948 eclipse records, while Bowen (1950) mentioned that because the Sun was rather free of sunspots at the time "... more accurate measurements of the distribution of radio "brightness" across the "quiet" sun were obtained." (ibid.). In a letter to Ryle in Cambridge, Pawsey (1950) also mentioned a "... lack of solar activity ..." at the time, again suggestive that sunspots were rare or absent, but in fact nothing could be further from the truth: Carter Observatory in Wellington (New Zealand) sent Bowen (1949d) thirteen photographs of the eclipse that clearly showed the presence of sunspot groups, and a drawing made at the Tokyo Astronomical Observatory confirmed this (see Figure 24).

In our earlier analysis of the 1949 eclipse we concluded the

Unlike the earlier suggestions, it is clear that enhanced radio emission was observed and correlated with sunspot areas in much the same way as during the 1948 eclipse. The clearest results from the 1948 eclipse had come from the 600 MHz observations, with the higher frequencies showing less definitive results. It seems that at the higher frequency of 1,200 MHz there was also a correlation in

1949, but it was much less well defined ... *In our opinion, the most likely outcome was that after the very successful observations of 1948, the 1949 observations provided no 'new' information of sufficient importance to warrant publication.* (Wendt et al., 2008a: 76; our italics).

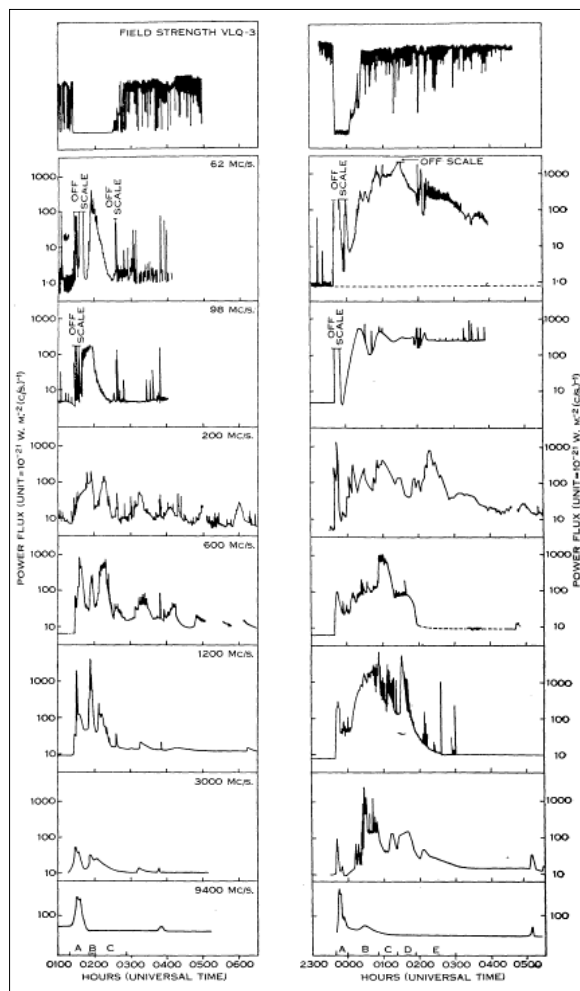


Figure 25: Multi-wavelength plots of two major outbursts, recorded on 17 February 1950 (left) and 21-22 February 1950 (right). The 600 and 1,200 MHz observations were made with the ex-Georges Heights radio telescope (after Christiansen et al., 1951: 53).

## 6 MULTI-WAVELENGTH SOLAR MONITORING AT POTTS HILL FIELD STATION

During 1949 and through to June 1951, the ex-Georges Heights antenna, Payne-Scott and Little's position interferometer, a 62 MHz Yagi and two small parabolas at Potts Hill were used to simultaneously record solar activity at 62, 97, 600, 1,200, 3,000 and 9,400 MHz, with support monitoring from Mount Stromlo Observatory (Figure 15) at 200 MHz.

The initial publication associated with this project reported on the observation of "... two large solar disturbances ..." (Christiansen et al., 1951: 51) that occurred on 17 February and 21-22 February 1950. These are shown in Figure 25. Both events were associated with solar flares,

and short-wave radio fadeouts were experienced at the Earth. The 17 February outburst also produced a magnetic crochet, and one was suspected following the 21-21 February outburst.

Later, the analysis of the 400 solar bursts recorded at all frequencies during the 18-month period from January 1950 was assigned to a young RP scientist, Rod Davies, and he also looked at their association with other solar events and with terrestrial magnetic crochets and radio fadeouts.

Davies found that these observations confirmed an earlier discovery, namely that over time intervals of many months variations in the level of solar emission at frequencies above 200 MHz mirrored changes in sunspot area. Many bursts were associated with solar flares and linked to terrestrial effects.

In his analysis, Davies (1954: 90) suggested:

... there may be two separate components of bursts, one which shows rapid fluctuations and predominates at the lower frequencies, and one which is smooth and is characteristic of the high frequencies (although it may occur at low frequencies also).

He further suggested that these components may be due to plasma oscillations and thermal emission, respectively.

Davies' 1954 research paper was published after he had left RP and joined the Jodrell Bank radio astronomers (Davies, 2009). Like others who received their initial training in radio astronomy at RP and then went overseas, he became a major figure in international radio astronomy. Rodney Deane Davies (1930–2015) advanced from an Assistant Lecturer to become a Professor of Astronomy at Manchester University. He was Director of Jodrell Bank Observatory from 1988 to 1997, and was President of the Royal Astronomical Society in 1987–1989. He was elected a Fellow of the Royal Society in 1992, and was awarded a CBE in 1995 (Professor Rod Davies ..., 2015).

## 7 THE DETECTION OF SAGITTARIUS A AND CYGNUS X

While the ex-Georges Height 16 × 18-ft parabola was being used during the day for the aforementioned solar monitoring project, Jack Piddington (Figure 21) and Harry Minnett (Figure 23), used it at night—in conjunction with one of the 10-ft U.S. radar dishes—to conduct an all-sky survey at 1,210 MHz (Figure 26).

They looked at known sources (e.g. Cygnus A, Centaurus A, Taurus A, and the Moon), and they searched for emission from the Galactic Centre, from M31, NGC 7293 (a large planetary nebula) and from the Andromeda Nebula. The results of their observations were published in the *Australian Journal of Scientific Research* (Pid-



Figure 26: A view of the ex-Georges Heights antenna and on the extreme right the 10-ft U.S. radar antenna used by Piddington and Minnett for their 1,210 MHz all-sky survey (courtesy: CRAIA, B2639).

dington and Minnett, 1951). This is an historically important paper because it includes the discovery at RA 17hr 44m and Dec  $-30^\circ$  of what

... appears to be a new, and remarkably powerful, discrete source ... [which] lies very close to the centre of the Galaxy ... (Piddington and Minnett, 1951: 465, 469).

This source (Figure 27) is now known as Sagittarius A, and the discovery isophote plot is shown in Figure 28. Goss and McGee (1996) and Orchiston and Slee (2002b) have discussed the many misconceptions relating to the discovery of Sagittarius A. Although Piddington and Minnett were the first to discover this source and they published evidence of it in 1951, credit for the discovery often is incorrectly assigned (e.g. see Kerr, 1983: 297) to the Dover Heights radio astronomers, John Bolton (1922–1993; Robertson, 2017), Richard Xavier ('Dick') McGee (1921

–2012), Bruce Slee and Gordon Stanley (1921–2001; Kellermann et al., 2005). In fact, McGee, Slee and Stanley only detected this source, at

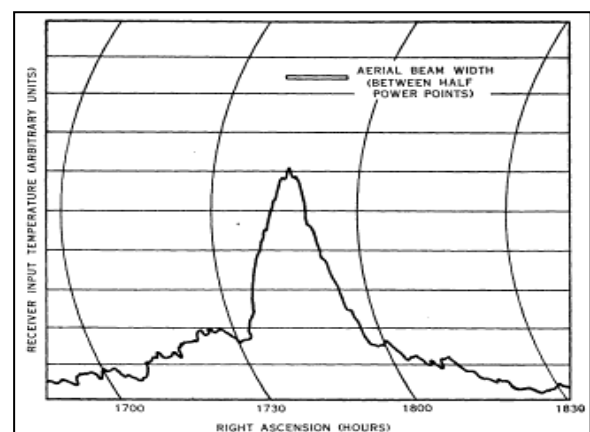


Figure 27: The chart record of Sagittarius A (after Piddington and Minnett, 1951: 463).

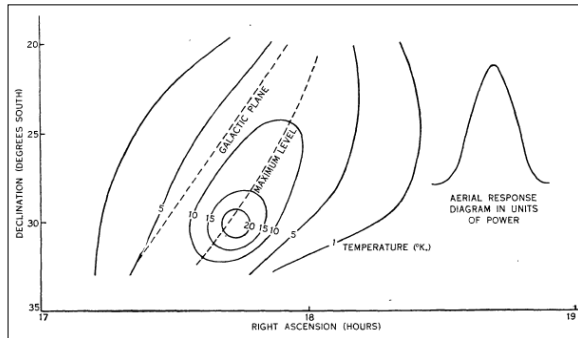


Figure 28: The contour plot showing Sagittarius A (after Piddington and Minnett, 1951: 465).

400 MHz in 1953 using the remarkable 'Hole-in-the-Ground' radio telescope (Orchiston and Slee, 2002b). The isophote plot of this source was first published by McGee and Bolton (1954) in *Nature*, so it quickly reached a wide international audience, while a more detailed account appeared later (McGee et al., 1955) in the *Australian Journal of Scientific Research (AJSR)*. RP's usual strategy at this time was to quickly send 'letters' to *Nature* announcing important

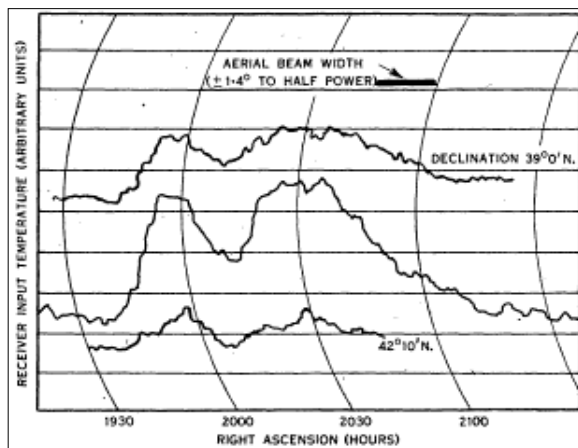


Figure 29: Chart records of Cygnus X at three different declinations (after Piddington and Minnett, 1952: 18).

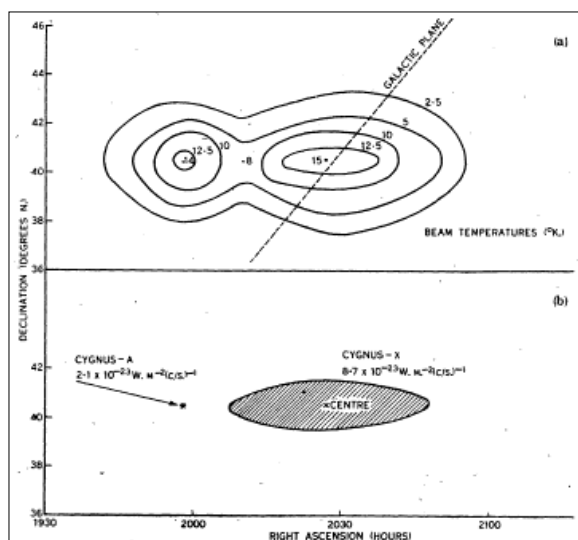


Figure 30: The upper plot shows contours of equal aerial beam temperature at 1,210 MHz. The lower chart shows the derived flux density of the sources Cygnus A and X (after Piddington and Minnett, 1952: 19).

new discoveries, whilst reserving the details for later publication in the *AJSR*. For some reason, Piddington and Minnett's discovery was not published in *Nature* (thereby effectively denying them credit for the discovery) whereas the later Dover Heights detection was. It is strange that Dick McGee and John Bolton were the sole authors of the *Nature* paper, because by this time Bolton had already abandoned radio astronomy and was working in the cloud physics and rain-making section of RP. The authorship of the later *AJSR* paper reflects the active research team that was involved in this project. Obviously political considerations came into play in selecting the authors of the *Nature* paper ...

In the course of their 1,210 MHz survey with the ex-Georges Heights antenna Piddington and Minnett (1952) detected a new diffuse discrete source near Cygnus A, which they designated Cygnus X (see Figures 29 and 30). They claimed in their published paper that this may be the first 'radio nebula' to be recognised by associating the strong Cygnus X source with the bright galactic nebulae surrounding the star  $\gamma$  Cygni. They determined that the radio spectrum of Cygnus X was consistent with thermal radiation from ionised gas, unlike the spectrum of Cygnus A.

Piddington and Minnett (1951) investigated three other known discrete sources. However, only Centaurus A could be detected at 1,210 MHz with a flux density of  $4.1 \times 10^{-24} \text{ W.m}^{-2}.\text{Hz}^{-1}$  and an uncertainty of 20%. An upper limit of  $1 \times 10^{-24} \text{ W.m}^{-2}.\text{Hz}^{-1}$  was set for Hercules A and Virgo A. Piddington and Minnett also were unsuccessful in detecting 1,210 MHz emission from the planetary nebula NGC 7293<sup>4</sup> and from the Andromeda Galaxy (M31). At about the same time Hanbury-Brown and Hazard (1950) detected emission from M31 at 158 MHz with an observed flux density of  $4 \times 10^{-24} \text{ W.m}^{-2}.\text{Hz}^{-1}$ . Piddington and Minnett noted that if the spectrum of M31 was similar to our own Galaxy then the flux density at 1,210 MHz would be  $2 \times 10^{-24} \text{ W.m}^{-2}.\text{Hz}^{-1}$ , well below the detection threshold of the ex-Georges Height radio telescope.

## 8 DETECTION AND OBSERVATIONS OF THE 1420 MHz HYDROGEN LINE

### 8.1 Introduction

Apart from the detection of Sgr A, arguably the most important research carried out with the ex-Georges Heights radio telescope was observation of the 1,420 MHz hydrogen line (H-line).

Nearly all of the early major discoveries in radio astronomy, including the original detection of cosmic radio emission by Karl Jansky (1905–1950), were serendipitous. Serendipitous discoveries in radio astronomy have been extensively

discussed in the literature (see Kellermann and Sheets, 1983). Perhaps the best example of an exception to this phenomenon was the discovery of the 1,420 MHz emission line of hydrogen. As Woody Sullivan (1982: 299) has noted, the prediction of the H-line was remarkable on two counts; both for its scientific prescience and for the conditions under which it was produced. Hendrik Van de Hulst (1918–2000) was a student at the time of the Nazi occupation of Holland and his supervisor from Utrecht University had been interned. Van de Hulst spent three months visiting Leiden (van Woerden and Strom, 2006: 17, Note 2), where under the guidance of Jan Oort (1900–1992) he examined the possibility of radio line emission from neutral hydrogen. In a paper published immediately after the war ended, van de Hulst cautiously noted the possibility of detecting an emission line:

The ground state of hydrogen is split by hyperfine structure into two levels with a separation of  $0.047 \text{ cm}^{-1}$ . The spins of the electron and proton are pointed in the same direction in one state and are opposite in the other state. A quantum of wavelength 21.2 cm is emitted due to a spontaneous flip of the spin. (van de Hulst, 1945).

Van de Hulst noted that the transition to the ground state was a forbidden transition and therefore it was necessary to assume a probability for the spontaneous transition to the preferred ground state. Provided that the lifetime of the hydrogen atom in the upper hyperfine-structure level was less than  $4 \times 10^8$  years, there was a possibility of detection. He also noted that the sensitivity of radio receivers would need to be improved by a factor of 100 over the 1940s levels of equipment for the emission to be detected.

The actual value of the emission frequency from the spin flip transition to the ground state is 1,420.47 MHz ( $\lambda = 21.1 \text{ cm}$ ) and is due to the hyperfine structure transition being  $5.9 \times 10^{-6} \text{ eV}$  (Wild, 1952). This is an extremely small energy level when compared (for example) to the Lyman-alpha transition of 10.19 eV which produces an emission at the much shorter wavelength of 122 nm. The probability of transition to the ground state is  $2.9 \times 10^{-15} \text{ sec}^{-1}$  ( $\sim 10^7$  years), and is within van de Hulst's original limit.

Joe Pawsey was well aware of the potential that detecting radio spectral lines could provide. He also was familiar with the predicted 1,420.47 MHz hydrogen emission and also the prediction of a deuterium emission line at 237.38 MHz.

It was the American radio astronomy pioneer Grote Reber (1911–2002; Kellermann, 2005) who had alerted Pawsey to the theoretical predictions and to the possibilities of detection during a visit Pawsey made to the U.S. in early

1948. Given the important implications that the detection of a radio-frequency spectral line would bring to radio astronomy, Pawsey alerted the Chief of the Division of Radiophysics, Dr E.G. ('Taffy') Bowen (1911–1991; Bowen, 1987; Hanbury Brown et al., 1992) to this potential in a letter dated 23 January 1948. Pawsey (1948) also included a section titled, "The Search for Atomic Spectral Lines in Noise" in the report that he wrote following his visit to the United States. After a discussion of the potential in the report he concluded:

The position is therefore quite uncertain. Lamb of Columbia, for example, did not expect we should be able to find lines owing to low probabilities of emission or absorption and "smearing", due to changes due to magnetic fields and so on. (ibid.).

During his U.S. visit Pawsey also visited Harvard and met Oort who was visiting Yerkes Observatory at the time. However, there is no mention of any discussion on the H-line potential with these parties.

Bowen responded to Pawsey's U.S. visit report in a letter dated 18 May 1948. In this he noted:

This [atomic spectral lines] possibility is certainly an interesting one but, in view of the present state of knowledge, I doubt very much whether we should yet devote a special effort to it. A search for the atomic hydrogen and deuterium lines could be made with the Georges Heights equipment ... but this would involve dislocation of other work which is scarcely justified at present. At the moment Harry Minnett is chasing up the references you supplied and we are hoping that Williamson will live up to the promise he made you to let us have a survey of the whole subject. (Bowen, 1948).

The report from Pawsey triggered some activity at RP. In early 1949, Paul Wild (1923–2008; Frater and Ekers, 2012; Stewart et al., 2011b) produced an internal report titled, "The Radio-Frequency Line-Spectrum of Atomic Hydrogen. 1. The Calculation of Frequencies of Possible Transmissions." This report was a comprehensive survey of the earlier theoretical work on the subject, and Bowen noted in a letter to F.W.G. White (Chief Executive Officer of the C.S.I.R.O. and former Chief of the Division of Radiophysics) on 21 March 1949: "There is nothing very original about it but it serves to indicate the direction in which this work might go." (Bowen, 1949a).

White replied to Bowen's letter on the 28 March 1949 and noted:

I have looked through it [the report] and find that, even to one who is not a spectroscopist, it is relatively easy to follow. The end results are certainly very interesting, and I hope that experimental data can now be found to which

these can be related. (White, 1949).

As Sullivan (2017) has reported, in 1949 Bernie Mills had considered taking on the H-line search as an independent line of research, but dismissed it as too speculative. John Bolton and Kevin Westfold (1921–2001) had also considered searching for the H-line (Robertson, 1992: 82). They had a copy of a Russian paper translated in an effort to obtain more details, however no search was undertaken. John Murray (pers. comm., 5 August 2007) also recalls that on a number of occasions at meetings of the Solar Noise Group Ruby Payne-Scott proposed a search for the H-line.

Despite this early insight, there was no detection attempt made by the RP Group. Westfold has attributed the lack of an immediate investigation to Pawsey's conservative nature (Robertson, 1992: 82). As late as February 1952, in a meeting of the Radio Astronomy Subcommittee on Galactic Work, Alex Shain (1922–1960; Pawsey, 1960) raised the possibility of looking for line spectra as part of the group's research efforts. In attendance at this meeting were Pawsey, Bolton, Mills, Minnett, Piddington and Shain. The outcome was recorded in the minutes as: "It was decided, however, not to plan for this as it could be easily fitted into other projects." (Mills, 1951).

## 8.2 DETECTION OF THE H-LINE

On 25 March 1951, H.I. Ewen (1921–2015) from the Lyman Laboratory at Harvard University detected the 1,420 MHz hydrogen emission line (Ewen and Purcell, 1951) while working on his doctoral thesis.

By a remarkable coincidence, van de Hulst was visiting Harvard at the time and he was able to discuss the detection with Ewen and his supervisor, E.M. Purcell (1912–1997). Van de Hulst indicated that a Dutch group under Oort and C.A. Muller (b. 1924) had been attempting to detect the H-line for some time. By Ewen's own account (2003), he was unaware of the Dutch group's work and had dismissed the possibility of the Dutch actively pursuing a detection attempt because he had interpreted van de Hulst's comments in his original paper as indicating that a detection was highly unlikely. In fact, Ewen thought it likely that his thesis would indicate a negative result. Ewen believed that if anyone would undertake a detection attempt it would be a group from the Soviet Union on the basis of the independent prediction proposed in 1949 by I. Shklovsky (1916–1985) (with which Ewen was familiar).

Also visiting Harvard at this time was Frank Kerr (1918–2000; Westerhout, 2000) from RP. Kerr (1984: 137) was on a fellowship to Harvard University to undertake an M.Sc. in Astronomy

and had written to Pawsey on 17 March 1951 (Kerr, 1951a) drawing his attention to the fact that Ewen and Cornell University's Leif Owren (b. 1918) had made unsuccessful attempts to detect the H-line (Kerr, 1951). Owren had used an 8-ft parabola, and a receiver similar to Ewen's but with less sensitivity.

On making the initial discovery Purcell and Ewen shared details of the discovery with the Dutch group and were keen to obtain an independent confirmation of the detection. Kerr (1951b) sent Pawsey an airmail letter dated 30 March 1951 alerting him to the discovery and asking if the RP group could assist in the confirmation, even though no prior work had been done in Sydney. The letter included a hand-drawn sketch of the H-line response on Ewen's receiver. In a letter dated 20 April 1951, Pawsey (1951b) wrote to Purcell saying that because of the "... great potentialities ..." he had assigned two separate groups to attempt the independent detection and they were optimistically hoping to get results "... in a few weeks." He also asked about Purcell's plan to publish the discovery, and suggested that the RP team would privately advise the Americans of any detection and then publish a confirmation note at the same time Ewen and Purcell published their result.

## 8.3 THE DIVISION OF RADIOPHYSICS CONFIRMATION OF THE DETECTION

In his letter to Purcell, Pawsey had referred to "... two independent groups ..." working on attempting a confirmation. A meeting had been held on 12 April to coordinate the RP activities in attempting a confirmation observation, and in attendance were Pawsey, Arthur Higgs (b. 1904), Piddington, Christiansen, Wild and Bolton. The minutes state:

It was agreed that parallel investigations to check detectability of lines were desirable in order to obtain independent checks but that, in order to avoid cut-throat competition, the groups who were experimenting in the same field, e.g. Piddington, Christiansen and Wild, should consider themselves, at least on the 1420 Mc/s line, as a single group and possible publication should be joint.

Wild outlined the theoretical results he had obtained (mainly in RPL. 33 and 34). The chief point of interest is the existence of fine-structure lines at 10,905, 3,231 & 1,363 Mc/s with "inherent" line widths of the order of 100 and 20 Mc/s respectively.

It was agreed to recommend Wild to write up this material for publication.

Christiansen and Bolton outlined schemes for attempting to detect the 1420 Mc/s line with which they were proceeding (also corresponding deuterium line). They hope to have equipment for tests to start in a week or so.





Figure 31: The ex-Georges Heights radio telescope at the time it was used for the H-line observations (courtesy: CRAIA, B2649-3).

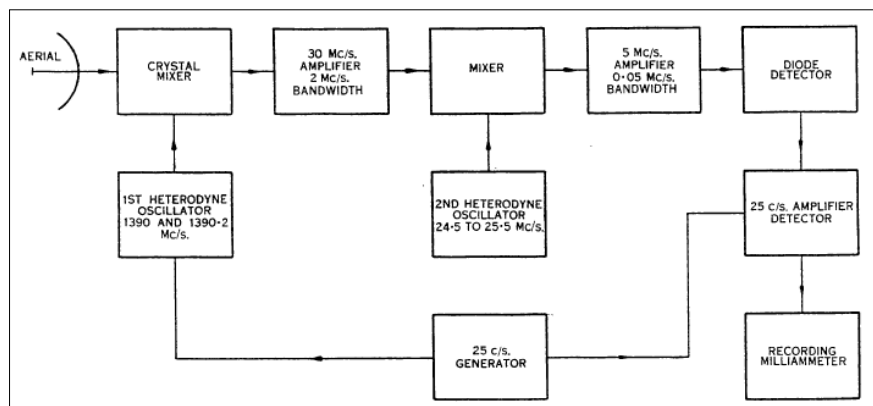


Figure 32: Block diagram of the Potts Hill H-line receiver (after Christiansen and Hindman, 1952a: 439).

Piddington outlined a different scheme with which he was proceeding. (Pawsey, 1951a).

After a short period, Christiansen took over the leadership of the group, with support from Hindman. It is unclear when Bolton's and Piddington's detection attempts were abandoned. However, later, in 1953–1954, an unsuccessful attempt to detect the deuterium line was made by Gordon Stanley and Robert Price using the 'hole-in-the-ground' antenna at Dover Heights (see Stanley and Price, 1956; cf. Orchiston and Slee, 2002b).

Purcell replied to Pawsey in a letter dated 9 May 1951. He welcomed the efforts of the Sydney group and provided further details of the detection and the receiver equipment. He also indicated that he and Ewen intended announcing their discovery in *Nature* "... fairly soon ...", but would allow time for a reply before proceed-

ing. Pawsey replied on 18 May 1951, saying that Christiansen would be, "... attempting the first observations tonight ..." and since he (Pawsey) would be away for the next fortnight Christiansen would communicate directly if the attempt was successful, although he noted it would likely take several weeks. He also suggested (Pawsey, 1951c) that Ewen might wish to publish a detailed report in the newly created *Australian Journal of Scientific Research*.

Christiansen and Hindman (1952a: 438) were able to construct a 'makeshift' receiver very quickly thanks to a great deal of improvisation. The receiver was in principle similar to those used by Ewen and by Muller and Oort. Upon coupling the receiver to the ex-Georges Heights antenna (Figure 31), they were able to confirm the detection by the beginning of June.

Figure 32 shows a block diagram of the maj-

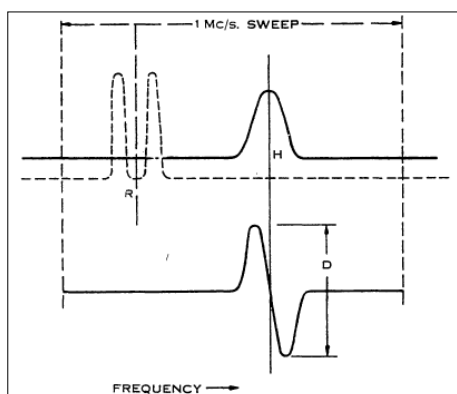


Figure 33: Illustration of H-line receiver operation and theoretical output signal. R = receiver pass-bands, H = H-line signal, D = recorder signal output (after Christiansen and Hindman, 1952a: 440).

or components of the receiver. It consisted of a super-heterodyne receiver with double-frequency change. It had two intermediate-frequency channels. The first operated at 30 MHz with a bandwidth of 2 MHz and the second at 5 MHz with a bandwidth of 0.05 MHz. A second heterodyne oscillator was used to continuously sweep the tuning of the receiver back and forth over a 1 MHz range. The signal from the hydrogen emission-line was detected as a small increase in signal when the pass-band of the receiver swept over the H-line frequency. As the signal increase was very small an additional balancing method was used to improve sensitivity. This was done by switching the first heterodyne oscillator at 25 Hz between two frequencies 0.16 MHz apart at around 1,390 MHz. This caused the centre frequency of the band-pass to alternate between the two frequencies and therefore allowed comparison between the signals. Any difference between the signals appeared as a 25 Hz component of the rectified receiver output. This component could then be recognised by using a selective amplifier and a phase-sens-

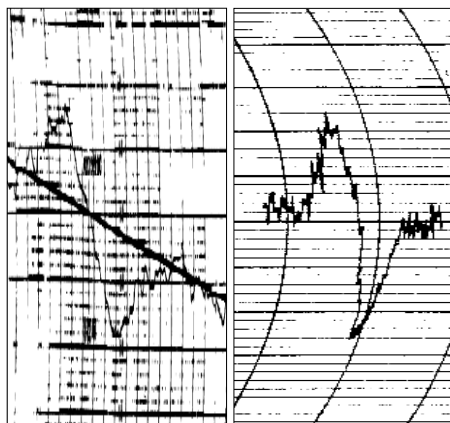


Figure 34: A rescaled example of an H-line observation made by Ewen on 9 April 1951 (left) and a later observation made by Christiansen and Hindman (right) (after Ewen, 2003; and Christiansen and Hindman, 1952a: 444, respectively).

itive detector which was synchronised with the 25 Hz generator. As the receiver was tuned over the 1 MHz frequency band where detection of the H-line was predicted to appear, the energy produced by the H-line was first detected in one band-pass of the two switch components 0.16 MHz apart. This caused an in-phase 25 Hz signal. It was then detected in the other component as an out of phase signal. This caused a characteristic sine-wave signal on the recorder output as illustrated in Figure 33.

This H-line receiver was assembled in just six short but hectic weeks, an incredibly short time period for so challenging a project, and was "... the most terrible piece of equipment I've ever seen in all my life ... It was a monster ..." (Christiansen, 1976). Later, Christiansen also commented:

Our research was done crudely but it was good fun and the results were exciting. When Purcell's research student Ewen came over and saw the gear I had, with cables lying all over the floor and ancient oscillators, he said, 'My God. I can understand why you could do it in six weeks and it took me two years.' (Chrompton, 1997).

And

We knew when we started that our gear was so rotten it mightn't work at all. Without exaggeration it was held together with string and sealing wax; Pawsey said it kept going through sheer will power. To make matters worse sparrows kept nesting in the aerial. We were stuck out at Potts Hill reservoir and it rained like all hell all the time. After observing for 10 days, without any luck we got fed up and went home, leaving the machine switched on. The next morning we found what we were after sitting up on the chart. (Christiansen, 1954).

Figure 34 shows an example of the H-line chart record obtained by Christiansen and Hindman, and this can be compared and contrasted with Ewen's original observations, a rescaled example of which has been included in this same figure.

Ewen and Purcell's discovery was published in the 1 September 1951 issue of *Nature* in a letter dated 14 June 1951, and was followed by a confirmation paper from the Dutch group dated 26 June (Muller and Oort, 1951). After the Dutch paper was a short cabled communication dated 12 July that reported the Australian detection of the H-line. This read:

Referring to Professor Purcell's letter of June 14 announcing the discovery of hyperfine structure of the hydrogen line in galactic radio spectrum, confirmation of this has been obtained by Christiansen and Hindman, of the Radio Physics Laboratory, Commonwealth Scientific and Industrial Research Organization, using narrow-beam aerial. Intensity and line-width are of same order as reported, and

observations near declination  $20^\circ$  S. show similar extent about galactic equator. (Pawsey, 1951e).

The following day Pawsey sent Bowen a letter advising of the confirmation:

Christiansen has worked ... for the last two months trying to get this gear working and it is a very creditable performance on his part. The line is really exceedingly weak and it is necessary to make the right compromises all along the way in order to make the spectrum line evident. (Pawsey, 1951d).

#### 8.4 THE RADIOPHYSICS SOUTHERN SKY H-LINE SURVEY

Following the initial confirmation, between June and September 1951 Christiansen and Hindman proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of this survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman, 1952a), and a summary paper appeared in *The Observatory* (Christiansen and Hindman, 1952b).

By taking a series of measurements in progressive steps of declination they were able to obtain a series of line profiles. Figure 35 shows an example of a series of records taken along the Galactic Equator.

From these individual records, the maximum deflections could be measured and hence a series of brightness intensities could be calculated. Figure 36 shows an example of the profile of peak brightness for the declination  $+10^\circ$ .

By combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 37 shows the final contour map of H-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman (1952a) noted that there were two likely causes of these variations: (1) line broad-

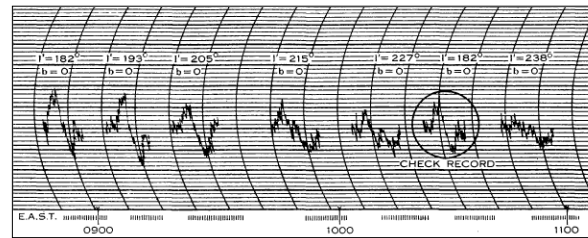


Figure 35: A series of six records taken along the Galactic Equator. A 'check record' was performed near the end of each observing run to check the receiver stability (after Christiansen and Hindman, 1952a: 445).

ening caused by rotation of the Galaxy, and (2) structural features in the Galaxy (a more interesting proposition).

The line profiles were calculated based on the receiver response in the two swept band filters. Figure 38 shows examples of arbitrary line profiles and their corresponding receiver outputs.

The process of reconstruction of the line profiles from the receiver records was essentially the reverse of that shown in Figure 38. Figure 39 shows examples of the smoothed records and reconstructed line profiles from the Galactic Centre, the Anti-centre and Cygnus regions.

Based on the broadening of line profiles, random velocities of the order of 12 to 18 km/s were estimated to be present in the neutral hydrogen clouds. In a number of cases double line profiles were also detected as shown in Figure 40.

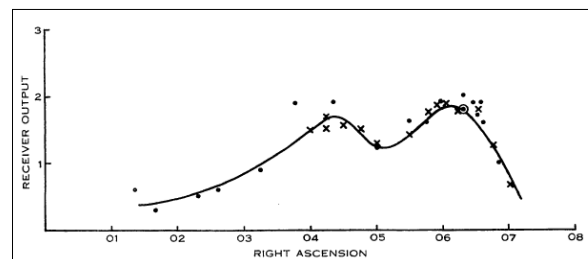


Figure 36: An example of the peak brightness profile in a strip along a declination of  $+10^\circ$  (after Christiansen and Hindman, 1952a: 445).

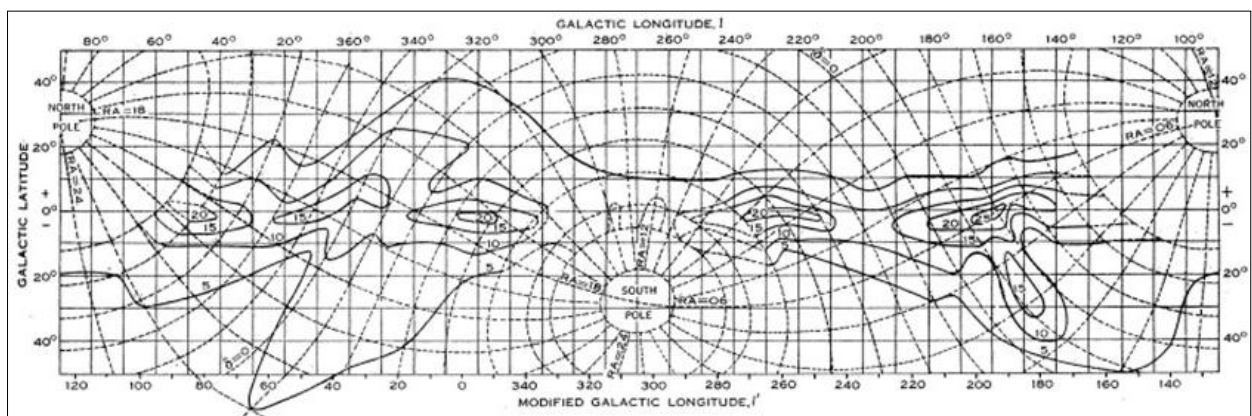


Figure 37: Southern sky contour map of H-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman, 1952a: 446).

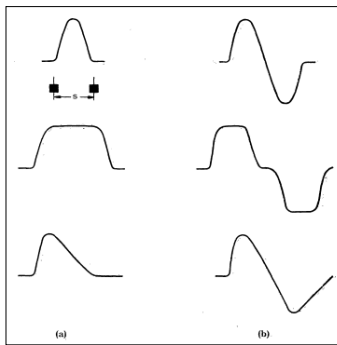


Figure 38: Example line profiles (a), and the corresponding receiver outputs (b). The sweep (s) of the two pass-bands (black boxes) is shown in the top left (after Christiansen and Hindman, 1952a: 442).

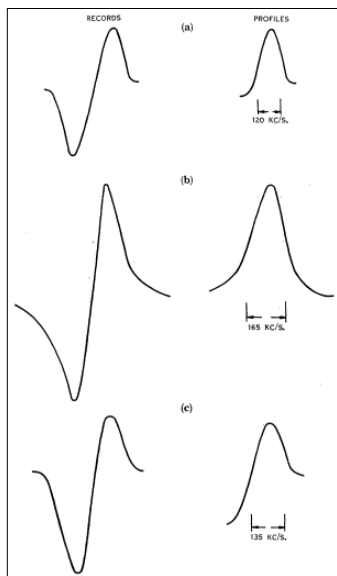


Figure 39: Examples of smoothed records and the calculated line profile in the region of the Galactic Centre (a), the Anti-centre (b) and the Cygnus region (c) (after Christiansen and Hindman, 1952a: 447)

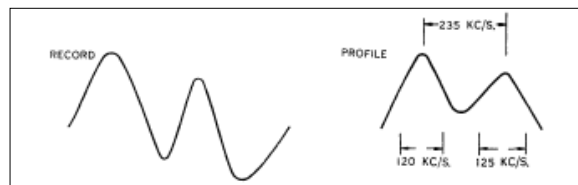


Figure 40: Examples of a smoothed record and a double line profile (after Christiansen and Hindman, 1952a: 448).

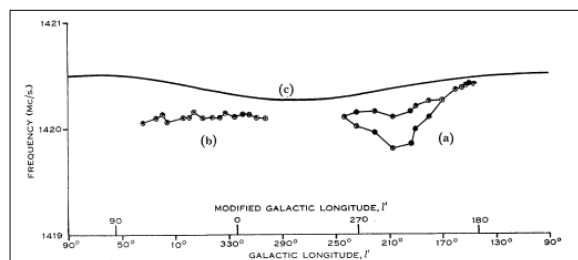


Figure 41: Plot of centre frequencies for line profiles showing double line profiles (a) and single line profile (b) regions. Line (c) is the expected frequency variation due to the Earth's relative motion (after Christiansen and Hindman, 1952a: 448).

The existence of these double line profiles indicated regions with different radial velocities. Assuming a circularly symmetrical rotating galaxy, the radial velocity ( $v$ ) of different regions is given by:

$$v = r.A.\sin 2l' \tag{1}$$

where  $r$  is the distance of the source from the Sun,  $A$  is  $6 \times 10^{-16} \text{ sec}^{-1}$ , and  $l'$  is the modified galactic longitude with respect to the galactic centre. From this equation, given a radial velocity estimate derived from the Doppler frequency shift compared to the rest frequency, a distance to the source can be estimated. The estimate for the two major regions showing double lines was 1,000 and 4,000 parsecs. Given the large size and the constant separation of the double lines as shown in Figure 41, the structure was suggestive of spiral arms in the Galaxy.

Further evidence supporting the detection of galactic structure was found by comparing the theoretical effect of galactic rotation with the actual observations. Assuming a uniform medium producing radiation, it is possible to calculate the brightness profiles for different hydrogen densities. Figure 42 shows the theoretical plots where ( $n$ ) is the number of ground state hydrogen atoms per  $\text{cm}^3$ .

This plot showed reasonable agreement with a density of somewhere between 1 and 0.5 atoms per  $\text{cm}^3$ . However, there were clearly regions that had factors other than rotation causing brightness variations. Also, by comparing the overall hydrogen emission to the general radio emission, which would not be effected by rotation, it is clear that there was general agreement between structural areas as shown in Figure 43. These factors suggested the existence of spiral arms in the Galaxy, and Christiansen and Hindman concluded that a much more detailed investigation was warranted.<sup>4</sup>

Overall there were clear indications that the hydrogen-line emission had approximately the same distribution in the sky as the visible Milky Way. This association, and the ability to penetrate the obscuring medium to discover galactic structure, heralded the beginning of a very important branch of investigations in radio astronomy.<sup>5</sup> It also marked the beginning of a major international collaboration, particularly with the Dutch group working at Leiden, and was characterised by close cooperation that started with the pre-publication communications by Ewen and Purcell to both the Dutch and Australian groups.

It is coincidental that at the same time that the breakthrough discovery of a radio frequency emission line occurred, the first optical evidence for the spiral arm structure of our Galaxy was also published (Morgan et al., 1952).

Immediately following the Australian confirm-

ation of the H-line, Wild decided to update and publish the internal report he had written prior to the detection of the line (Wild, 1952). This was a comprehensive review of the radio-frequency line spectrum of atomic hydrogen and is largely in accordance with modern theory. The report provided a very solid theoretical base for planning further observations by the Australian radio astronomers. The one exception in this analysis was the conclusion that the 1,420 MHz emission would be the only detectable line emission and that it would be unlikely the higher order recombination lines would be detectable. It would be

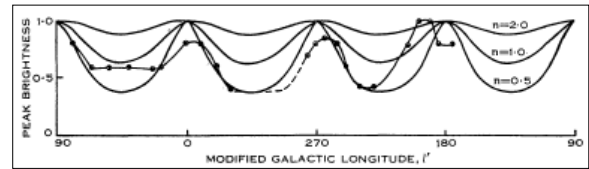


Figure 42: Calculated brightness peaks due to galactic rotation for given hydrogen densities ( $n$ ). Dots indicate actual observations (after Christiansen and Hindman, 1952a: 450).

nearly two decades before recombination lines were finally detected by Soviet Union radio astronomers (Sullivan, 1982: 300).

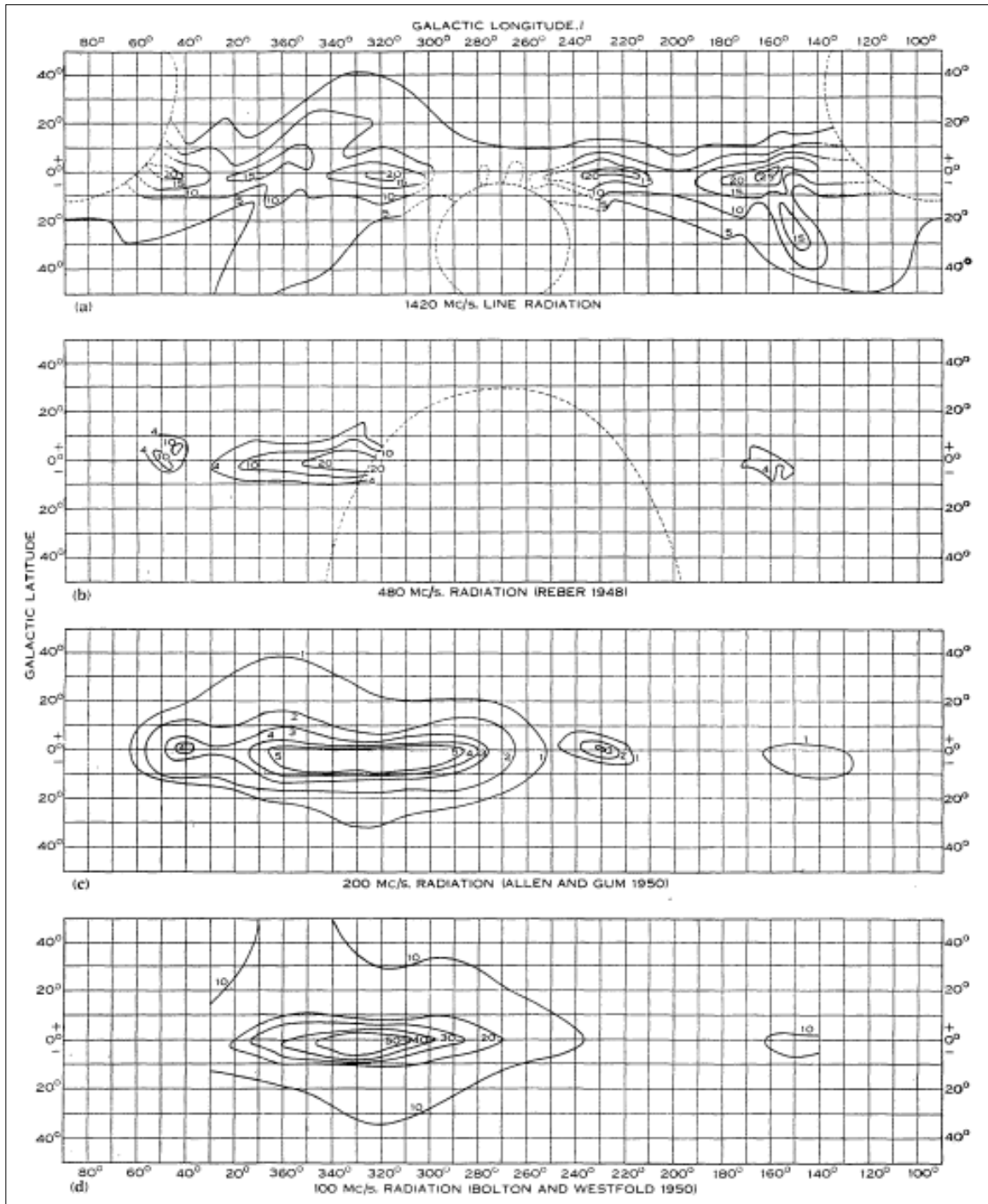


Figure 43: Comparison of H-line emission (top) and continuum emission at 480 MHz, 200 MHz and 100 MHz (bottom). Structural similarities are evident (after Christiansen and Hindman, 1952a: 451)

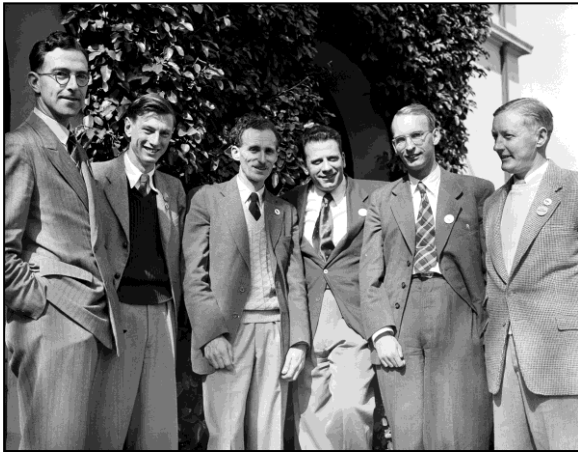


Figure 44: Gathering at the 1952 U.R.S.I. meeting in Sydney of those involved in the initial detection and confirmation of the H-line. From left to right: Kerr, Wild, Hindman, Ewen, Muller and Christiansen. Note also that all wore special U.R.S.I. 'Kangaroo' lapel buttons (courtesy: CRAIA, B2842-45).

The H-line survey carried out by Christiansen and Hindman was to be the last major research program using the old ex-Georges Heights 16-ft x 18-ft antenna. Having originally been designed as an experimental radar, it was far from ideal as a survey radio telescope. It suffered from sagging and distortion of the reflector surface and the multiple dipoles at the prime focus caused further losses in sensitivity (see Piddington and Trent, 1956b: 490n). These problems notwithstanding, it was used for one final short-lived project, as outlined below in Section 9.

### 8.5 THE 1952 URSI CONGRESS AND AUSTRALIAN H-LINE STUDIES

In recognition of the growing contribution of Australian researchers to the new field of radio astronomy, the Tenth General Assembly of the International Union of Radio Science (U.R.S.I) was held in Sydney between 8 and 22 August 1952 (see Robinson, 2002). Among those who attended the Congress were Ewen from Harvard and Muller from Leiden. This meant that those who had been involved in the initial detection of the H-line were able to meet face-to-face for the first time (see Figure 44).

Table 1: Initial distribution list of the H-line newsletter.

H.I. Ewen	Ewen Knight Corporation, Massachusetts, U.S.A
B.J. Bok	Harvard Observatory, U.S.A
C.R. Burrows	Cornell University, U.S.A.
H. Tatel	Carnegie Institution, U.S.A.
J. Hagen	Naval Research Laboratory, Washington, U.S.A.
F.J. Kerr	Radiophysics Laboratory, Sydney, Australia
J.L. Pawsey	Radiophysics Laboratory, Sydney, Australia
O. Storey	T.R.E., Malvern, U.K.
A.C.B. Lovell	Jodrell Bank, U.K.
M. Ryle	Cambridge University, U.K.

At the Congress those shown in Figure 44 decided to arrange a regular exchange of information by way of a newsletter that tracked the progress of the various groups undertaking H-line research. The first issue appeared in December 1952, and it was circulated to those listed in Table 1.

### 9 THE APRIL 1959 SOLAR ECLIPSE

The final solar research paper from Potts Hill was based on observations of the 8 April 1959 partial solar eclipse (Krishnan and Labrum, 1961). The eclipse was observed both at Potts Hill using the ex-Georges Heights parabola as a high sensitivity total power radiometer at 1,423 MHz. Meanwhile, the Chris Cross at Fleurs, the world's first cross-grating interferometer (Orchiston and Mathewson, 2009), was used to help identify areas of enhanced radiation.

No spectroheliogram observations were available in Australia at the time. However, these were provided by Dobson at the McMath Hulbert Solar Observatory in the U.S., and this allowed Krishnan and Labrum to compare the distribution of calcium K-line plages with their radio observations. They found a very close correlation between optical and radio plages, both in their intensity and their overall shape.

Krishnan and Labrum also were able to test a number of quiet Sun models against the eclipse observations. They found that the best fit was achieved by a model based on Christiansen and Warburton's (1955) work for sunspot minimum which showed limb-brightening at the equator, but absent at the poles. After allowing for an overall increase in brightness temperature by a factor of two to allow for the sunspot maximum, Krishnan and Labrum found that a stepped-up gradient of limb-brightening (the ear component) provided the best fit. It is likely that the lower resolution of the grating arrays used by Christiansen and Warburton for measurements of limb-brightening would have washed out the steeper gradient and therefore the ear would not appear as pronounced. The higher resolution of the eclipse observation allowed the steeper gradient to be more accurately measured.

The 1959 eclipse observation marked the end of the 'research career' of the ex-Georges Heights experimental radar antenna, and the end of solar research at Potts Hill. By this time, the solar focus had shifted to the Dapto (Stewart et al., 2011a) and Fleurs (Orchiston and Mathewson, 2009) Field Stations.

### 10 DISCUSSION

#### 10.1 Lehany, Yabsley and Christiansen

In one way or another the Georges Heights experimental radar antenna marked the end of

an era for some of those who used it.

For Fred Lehany it provided his sole research foray into radio astronomy, a field in which he admitted to having little interest (Lehany, 1978), whereas it proved the perfect radio astronomy training ground for a youthful Don Yabsley. However, Yabsley spent 1951–1961 working in the air navigation group at RP, and only returned to radio astronomy once the Parkes Radio Telescope was commissioned. He was involved in a number of collaborative research projects and in the up-grading of the dish, and his unexpected death late in 2003 robbed Australian radio astronomy of one of its pioneers.

Following the initial H-line survey with the ex-Georges Heights antenna, Chris Christiansen returned to solar radio astronomy, and constructed the world's first solar grating arrays, which were used for the observation of 1,420 MHz radio plagues and to establish the distribution of quiet Sun radio emission across the solar disk (see Stewart et al., 2011c; Wendt et al., 2008b).

But RP certainly was not going to abandon H-line research after so auspicious a start (even if a belated one—see Section 10.2, below). By this time Frank Kerr had returned from Harvard University, and he and Hindman focused on the construction a new multi-channel H-line receiver and on the construction of a new 36-ft (11-m) purpose-built dedicated H-line transit parabola (Figure 45). These would replace the aging ex-Georges Heights radio telescope, and would be used for a dedicated H-line survey of the southern sky. Kerr and Hindman were joined by a recent graduate student, Brian Robinson, who would go on to lead the CSIRO's Radio Astronomy Group within RP during the 1970s (Whiteoak and Sim, 2006: 265).

## 10.2 AUSTRALIA AND THE H-LINE: A MISSED OPPORTUNITY?

In retrospect, the H-line confirmation was a missed opportunity for Radiophysics (Sullivan, 2005: 14). Had a serious effort been made to detect the 1,420 MHz emission line when the possibility was first raised it appears very likely that the Group would have been successful.

The Group's early success in both solar and cosmic research and the wealth of discoveries made in the late 1940s and early 1950s meant that they were reluctant to pursue the more speculative search for the emission line even though they were aware of the significance that such a discovery would bring to radio astronomy. Joe Pawsey was a dynamic, inspirational, research leader but in this instance his decision not to pursue the H-line (that is, until after its discovery by Ewen) led perhaps to RP's greatest 'missed opportunity'.

## 11 CONCLUDING REMARKS

In its first year of operation as a radio telescope, the 16 × 18-ft Georges Heights experimental radar antenna played a significant role in the early development of solar radio astronomy in Australia. Research carried out at the short-lived Georges Heights Field Station by Lehany and Yabsley aided our understanding of the association of 200 MHz bursts and solar flares, and of the correlation between sunspots and radio emission at 600 and 1200 MHz. However, consolidation of research at the Dover Heights and Potts Hill Field Stations saw the close down of radio astronomy at Georges Heights towards the end of 1948, and the transfer of the experimental radar antenna to Potts Hill. Once there, it received a new lease of life, and a brand new (equatorial) mounting.

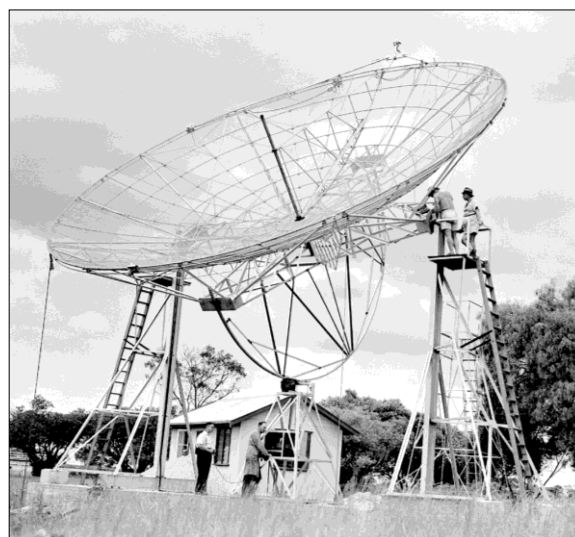


Figure 45: The 36-ft H-line dish at Potts Hill, soon after its completion. This was built to replace the aging ex-Georges Heights experimental radar antenna. The receiver hut shown in this photograph is the only radio astronomy structure still at Potts Hill. As Orchiston and Slee relate (2017: Figure 19.95), in 2015 it was renovated, and it now serves as a fitting reminder to the pioneering radio astronomy that once occurred on this site (courtesy: CRAIA, B2975-21).

The 1948 eclipse program was one of the research highlights of the Potts Hill Field Station, as for the first time it provided precise 2-dimensional positions for the radio-emitting regions that were in the solar corona at that time. The ex-Georges Heights radar antenna played a key role in this innovative project.

By way of marked contrast, the 1949 solar eclipse program is an enigma. Once again the ex-Georges Height radar antenna played a key role. Although successful observations were made at all sites, nothing was published to justify the enormous outlay in time, effort and expenditure associated with what at first sight would seem to have been a successful project. There certainly were adequate sunspots in attendance to aid searching for the locations of radio-emitting



Figure 46: The new 10-m dish with the old ex-Potts radar antenna mounting that was installed at Dapto Field Station in 1963 (courtesy: CRAIA, 004032).

regions, but perhaps the choice of 1,200 MHz, instead of 600 MHz (as in 1948), was a critical error in judgement. Whether this decision was made by Pawsey, Christiansen, or the entire research team, is not known.

As an aside, this conspicuous non-event was the trigger that inspired Chris Christiansen (1984: 117)

... to devise some method of viewing the Sun [at high resolution] more frequently than was possible with eclipse observations. This of course meant devising some antenna system of very great directivity.

We now come to undoubtedly the most important research carried out with the Georges Heights radio telescope: the initial confirmation of the 1,420 MHz hydrogen emission line, and subsequent observations of the distribution of H-line emission in our Galaxy.



Figure 47: A recent view at Potts Hill of the concrete pad that supported the ex-Georges Height experimental radar antenna (photograph: Harry Wendt).

The achievement of Chris Christiansen and Jim Hindman in constructing an H-line receiver from scratch in just six weeks is nothing short of remarkable. They then went on to conduct the world's first detailed H-line survey, and in the process produced the first radio evidence for the spiral arm structure of our Galaxy.

The 1959 partial solar eclipse was a fitting finale to the 'career' of the aging ex-Georges Heights radio telescope as a major research instrument. In just over a decade it made important contributions to solar and cosmic radio astronomy, and played a vital role in pinpointing the positions of radio-emitting regions in the solar corona, and revealing the distribution of neutral hydrogen along the plane of our Galaxy.

After this eclipse the experimental radar antenna became 'surplus to requirements' and was probably categorised as scrap metal. However, the cannibalisation of radio telescope (and receiver) components was an important feature of the RP field station era, and in this fine tradition part of Potts Hill antenna's distinctive equatorial mounting was recycled in 1963, and was attached to a new 10-m (33-ft) parabolic dish (Figure 46) with a log-periodic feed that was installed at the Dapto Field Station (site 4 in Figure 3). This dish was used to extend the upper frequency limit of the field station's solar spectrographic coverage from 210 MHz to 2,000 MHz (see Suzuki et al., 1965). Stewart et al., (2011a) have published an excellent review of developments at Dapto Field Station.

Now all that remains at the Potts Hill site as a reminder of the historic ex-radar antenna that once played so important a role there is the concrete base that originally supported the radio telescope (see Figure 47).

## 12 NOTES

1. This later became the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
2. The first author of this paper worked at the Fleurs Field Station from December 1961 until this Field station was handed over to the University of Sydney in 1965. At first he assisted Dr Bruce Slee (Orchiston, 2004) with research involving the Mills and Shain cross-type radio telescopes, and then he was responsible for operating the Chris Cross (see Orchiston and Mathewson, 2009) and producing the daily maps of 1420 MHz solar radio emission.
3. These were AN/TPS-3 radar aerials that had been developed during WWII by the U.S. Army Signal Corps as a light weight portable 600 MHz early warning radar (Orr, 1964). These aerials also were known as the 'British Type-63 Radar' (Wendt et al., 2008a: 74).



Each aerial was made up of eight 45° aluminium frame sections covered with wire-mesh that could be packed in a very compact bundle and quickly reassembled through a series of speed-clips. In 2007, one of the RP radio astronomers informed the second author of this paper that two people could assemble an aerial in about five minutes (John Murray, pers. comm., 2007).

4. This planetary nebula was first successfully observed from Australia in 1963 when Orchiston detected it at 11cm with the 64-m radio telescope at Parkes (see Orchiston, 1965). This detection led to the subsequent multi-wavelength survey of southern planetary nebulae by Slee and Orchiston (1965).
5. James Lequeux (pers. comm., December 2017) stresses the remarkable quality of the Christiansen and Hindman (1952a) paper, which paved the way for a new field of galactic radio astronomy six years before the appearance of the famous paper by Oort, Kerr and Westerhout (1958). However, Christiansen and Hindman's paper appeared in the relatively little-known *Australian Journal of Scientific Research*, and Oort et al. do not even mention it in their *Monthly Notices* paper.

### 13 ACKNOWLEDGEMENTS

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### 14 REFERENCES

- Bowen, E.G., 1946. Letter to the Chief Executive of C.S.I.R.O., dated 12 August. National Archives of Australia (972177 – C3830 – A1/2/12B – Box 3).
- Bowen, E.G., 1948. Letter to Dr J.L. Pawsey, dated 18 May. Sydney, National Archives of Australia (972098 – C3830 – A1/1/1 Part 3 Box 1).
- Bowen, E.G., 1949a. Letter to F.W.G. White, dated 21 March. Sydney, National Archives of Australia (972099 – C3830 – A1/1/1 Part 4 Box 1).
- Bowen, E.G., 1949b. Letter to the Secretary of C.S.I.R.O., dated 14 September. National Archives of Australia (972423 – C3830 – A1/3/19 – Box 19).
- Bowen, E.G., 1949c. Internal Memo noting observations would be conducted from 04:30 to 08:00 on roof of Radiophysics building, dated 18 October. National Archives of Australia (972423 – C3830 – A1/3/19 – Box 19).
- Bowen, E.G., 1949d. Letter to the Carter Observatory dated 7 December. National Archives of Australia (972423 – C3830 – A1/3/19 – Box 19).
- Bowen, E.G., 1950. C.S.I.R.O. Division of Radio-physics Annual Report for Year Ended 30 June. National Archives of Australia (972423 – C3830 – D2/49-50 – Box 50).
- Bowen, E.G., 1984. The origins of radio astronomy in Australia. In Sullivan, 85–111.
- Bowen, E.G., 1987. *Radar Days*. Bristol, Adam Hilger.
- Christiansen, W.N., 1949. Minutes of Radio Astronomy Committee Meeting – November 17, 1949. National Archives of Australia (972807 – C3830 – B2/2 Part 2).
- Christiansen, W.N., 1950. Minutes of Radio Astronomy Committee Meeting – January 10, 1950. National Archives of Australia (972807 – C3830 – B2/2 Part 2).
- Christiansen, W.N., 1976. Taped interview with Woody Sullivan, 27 August. Tape and transcript in the Sullivan Collection, National Radio Astronomy Observatory Archives, Charlottesville (henceforth NRAO).
- Christiansen, W.N., 1984. The first decade of solar radio astronomy in Australia. In Sullivan, 113–131.
- Christiansen, W.N., and Hindman, J.V., 1952a. A preliminary survey of 1420 Mc/s. line emission from galactic hydrogen. *Australian Journal of Scientific Research*, A5, 437–455.
- Christiansen, W.N., and Hindman, J.V., 1952b. 21cm line radiation from galactic hydrogen. *The Observatory*, 72, 149–151.
- Christiansen, W.N., and Warburton, J.A., 1955. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part III. The quiet Sun—Two-dimensional observations. *Australian Journal of Physics*, 8, 474–486.
- Christiansen, W.N., Yabsley, D.E., and Mills, B.Y., 1949a. Measurements of solar radiation at a wavelength of 50 centimetres during the eclipse of November 1, 1948. *Australian Journal of Scientific Research*, A2, 506–523.
- Christiansen, W.N., Yabsley, D.E., and Mills, B.Y., 1949b. Eclipse observations of solar radiation at a wave-length of 50 cm. *Nature*, 164, 569–570.
- Christiansen, W.N., Hindman, J., Carpenter, M.S., Payne-Scott, R., Yabsley, D.E., and Allen, C.W., 1951. Radio observations of two large solar disturbances. *Australian Journal of Scientific Research*, 4, 51–61.
- Christiansen, W.N., 1954. Stargazers. Australian radio astronomers J.L. Pawsey and his group lead the world in this new science. *People Magazine*, 2 October.
- Chrompton, B., 1997. Interviews with Australian Scientists – Professor Chris Christiansen. Australian Academy of Science.
- Covington, A.E., 1947. Microwave solar noise observations during the partial solar eclipse of November 23rd, 1946. *Nature*, 159, 405–406.
- Davies, R.D., 1954. An analysis of bursts of solar radio emission and their association with solar and terrestrial phenomena. *Monthly Notices of the Royal Astronomical Society*, 114, 74–92.
- Davies, R.D., 2008. A history of the Potts Hill radio astronomy field station. *Journal of Astronomical History and Heritage*, 8, 87–96.
- Davies, R.D., 2009. Recollections of two and a half years with 'Chris' Christiansen. *Journal of Astronomical History and Heritage*, 12, 4–10.
- Dickie, R.H., and Beringer, R., 1946. Microwave radiation from the Sun and Moon. *Astrophysical Jour-*

- nal, 103, 375–376.
- Ewen, H.I., 2003. Doc Ewen: The horn, HI, and other events in US radio astronomy. In Bouton, E. (ed.). *National Radio Astronomy Observatory: Archives: Doc Ewen*. Green Bank, National Radio Astronomy Observatory.
- Ewen, H.I., and Purcell, E.M., 1951. Radiation from galactic hydrogen at 1420 MHz. *Nature*, 168, 356–358.
- Frater, R.H., and Ekers, R.D., 2012. John Paul Wild 1923–2008. *Historical Record of Australian Science*, 23, 212–227.
- Frater, R.H., and Goss, W.M., 2011. Wilbur Norman Christiansen 1913–2007. *Historical Record of Australian Science*, 22, 215–228.
- Frater, R.H., Goss, W.M., and Wendt, H.W., 2013. Bernard Yarnton Mills 1920–2011. *Historical Records of Australian Science*, 24, 294–315.
- Goss, M., 2013. *Making Waves. The Story of Ruby Payne-Scott: Australian Pioneer Radio Astronomer*. New York, Springer.
- Goss, W.M., and McGee, R.X., 1996. The discovery of the radio source Sagittarius A (Sgr A). In Gredel, R. (ed.). *The Galactic Center. 4<sup>th</sup> ESO/CTIO Workshop*. San Francisco, Astronomical Society of the Pacific (Conference Series, Volume 102). Pp. 369–377.
- Goss, M., and McGee, R.X., 2009. *Under the Radar: The First Woman in Radio Astronomy: Ruby Payne-Scott*. New York, Springer.
- Hanbury Brown, R., Minnett, H.C., and White, F.W.G., 1992. Edward George Bowen 1911–1991. *Historical Records of Australian Science*, 9, 151–166.
- Hey, J.S., 1955. Solar radio eclipse observations. *Vistas in Astronomy*, 1, 521–531.
- Hockey, T. et al. (eds.), 2014. *Biographical Encyclopedia of Astronomers. 2nd Edition*. New York, Springer.
- Jarrell, R., 2005. “Radio astronomy, whatever that may be.” The marginalization of early radio astronomy. In Orchiston, 2005b, 191–202.
- Kellermann, K.I., 2005. Grote Reber (1911–2002): a radio astronomy pioneer. In Orchiston, 2005b, 43–70.
- Kellermann, K., and Sheets, B. (eds.), 1983. *Serendipitous Discoveries in Radio Astronomy: Proceedings of a Workshop held at the National Radio Astronomy Observatory Green Bank, West Virginia on May 4, 5, 6, 1983*. Green Bank, National Radio Astronomy Observatory.
- Kellermann, K.I., Orchiston, W., and Slee, B., 2005. Gordon James Stanley and the early development of radio astronomy in Australia and the United States. *Publications of the Astronomical Society of Australia*, 22, 13–23.
- Kerr, F.J., 1951. Letter to J.L. Pawsey, dated 17 March. Sydney, National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Kerr, F.J., 1951. Letter to J.L. Pawsey, dated 30 March. Sydney, National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Kerr, F.J., 1984. Early days in radio and radar astronomy in Australia. In Sullivan, 133–165.
- Krishnan, T., and Labrum, N.R., 1961. The radio brightness distribution on the Sun at 21cm from combined eclipse and pencil-beam observations. *AJP*, 14, 403–419.
- Lehany, F.J., 1978. Taped interview with Woody Sullivan. Tape and transcript in the Sullivan Collection, NRAO.
- Lehany, F.J., and Yabsley, D.E., 1948. A solar noise outburst at 600 Mc/s. and 1,200 Mc/s. *Nature*, 161, 645–646.
- Lehany, F.J., and Yabsley, D.E., 1949. Solar radiation at 1200 Mc/s., 600 Mc/s., and 200 Mc/s.. *Australian Journal of Scientific Research*, A2, 48–62.
- McCready, L.L., Pawsey, J.L., and Payne-Scott, R., 1947. Solar radiation at radio frequencies and its relation to sunspots. *Proceedings of the Royal Society*, A190, 357–375.
- McGee, R.X., and Bolton, J.G., 1954. Probable observation of the galactic nucleus at 400 mc/s. *Nature*, 173, 985–987.
- McGee, R.X., Slee, O.B., and Stanley, G.J., 1955. Galactic survey at 400 Mc/s between declinations  $-17^\circ$  and  $-49^\circ$ . *Australian Journal of Physics*, 8, 347–367.
- Melrose, D.B., and Minnett, H.C., 1998. Jack Hobart Piddington 1910–1997. *Historical Records of Australian Science*, 12, 229–246.
- Millett, R.S.B., and Nester, B., 1948. Notes on photographing the eclipse of 1 November, 1948. Sydney, Division of Radiophysics (RPL 29).
- Mills, B.Y., 1951. Minutes of the Meeting of the Radio Astronomy Sub-Committee on Galactic Work, 12 February. Sydney, National Archives of Australia (972135 – C3830 – A1/1/7 – Box 3).
- Minnett, H.C., and Labrum, N.R., 1950. Solar radiation at a wavelength of 3.18 centimetres. *Australian Journal of Scientific Research*, A3, 60–71.
- Morgan, W.M., Sharpless, S., and Osterbrock, D., 1952. Some features of galactic structure in the neighbourhood of the Sun. *Astronomical Journal*, 57, 3.
- Muller, C.A., and Oort, J.H., 1951. The interstellar hydrogen line at 1,420 Mc./sec., and an estimate of galactic rotation. *Nature*, 168, 357–358.
- Nakamura, T., and Orchiston, W. (eds.), 2017. *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe*. Springer International Publishing.
- Oort, J.H., Kerr, F.J., and Westerhout, G., 1958. The Galactic System as a spiral nebula. *Monthly Notices of the Royal Astronomical Society*, 118, 379–389.
- Orchiston, W., 1965. On the observation of planetary nebulae at radio wavelengths. Unpublished manuscript.
- Orchiston, W., 2004a. From the solar corona to clusters of galaxies: the radio astronomy of Bruce Slee. *Publications of the Astronomical Society of Australia*, 21, 23–71.
- Orchiston, W., 2004b. Radio astronomy at the short-lived Georges Heights field station. *ATNF News*, 52, 8–9.
- Orchiston, W., 2005a. Sixty years in radio astronomy: a tribute to Owen Bruce Slee. *Journal of Astronomical History and Heritage*, 8, 3–10.
- Orchiston, W. (ed.), 2005b. *The New Astronomy: Opening the Electromagnetic Window and Expanding our View of Planet Earth. A Meeting to Honor Woody Sullivan on his 60th Birthday*. Dordrecht, Springer.
- Orchiston, W., 2011. Norman Labrum. IAU Historic Radio Astronomy Working Group web site: [http://rahist.nrao.edu/labrum\\_bio-memoir.shtml](http://rahist.nrao.edu/labrum_bio-memoir.shtml)

- Orchiston, W., 2014a. Mills, Bernard Yarnton. In Hockey et al., 1482–1484.
- Orchiston, W., 2014b. Minnett, Harry Clive. In Hockey et al., 1495–1496.
- Orchiston, W., 2014c. Piddington, Jack Hobart. In Hockey et al., 1714–1715.
- Orchiston, W., 2014d. Smerd, Stefan Friedrich. In Hockey et al., 2019–2020.
- Orchiston, W., and Mathewson, D., 2009. Chris Christiansen and the Chris Cross. *Journal of Astronomical History and Heritage*, 12, 11–32.
- Orchiston, W., and Robertson, P., 2017. The origin and development of extragalactic radio astronomy: the role of the C.S.I.R.O.'s Division of Radiophysics Dover Heights Field Station in Sydney. *Journal of Astronomical History and Heritage*, 20, 289–312.
- Orchiston, W., and Slee, B., 2002a. The flowering of Fleurs: an interesting interlude in Australian radio astronomy. *ATNF News*, 47, 12–15.
- Orchiston, W., and Slee, B., 2002b. Ingenuity and initiative in Australian radio astronomy: the Dover Heights 'hole-in-the-ground' antenna. *Journal of Astronomical History and Heritage*, 5, 21–34.
- Orchiston, W., and Slee, B., 2017. The early development of Australian radio astronomy: the role of the CSIRO Division of Radiophysics field stations. In Nakamura, and Orchiston, 497–578.
- Orchiston, W., Nakamura, T., and Strom, R. (eds.), 2011. *Highlighting the History of Astronomy in the Asia-Pacific Region. Proceedings of the ICOA-6 Conference*. New York, Springer.
- Orchiston, W., Slee, B., and Burman, R., 2006. The genesis of solar radio astronomy in Australia. *Journal of Astronomical History and History*, 9, 35–56.
- Orr, W.I., 1964. The secret tube that changed the war. *Popular Electronics*, March, 57–59, 103–105.
- Pawsey, J.L., 1946a. Letter to Dr E.G. Bowen, dated 20 September. National Archives of Australia (972177 – C3830 – A1/2/12B – Box 3).
- Pawsey, J.L., 1946b. Letter to J.A. Ratcliffe, dated 24 December. Archives of Australia (972177 – C3830 – A1/2/12B – Box 3).
- Pawsey, J.L., 1946c. Notes on proposed 20 May 1947 Brazilian eclipse expedition, dated 11 October. National Archives of Australia (972177 – C3830 – A1/2/12B – Box 3).
- Pawsey, J.L., 1948. Solar and Cosmic Noise Research in the United States, 15 April 1948. Sydney, National Archives of Australia (972132 – C3830 – A1/1/5 Part 2 – Box 3).
- Pawsey, J.L., 1950. Letter to M. Ryle, dated 31 March. National Archives of Australia (972100 – C3830 – A1/1/1 Part 5 Box 1).
- Pawsey, J.L., 1951a. Atomic Spectral lines (Radio Frequency) – Minutes of meeting held on 12th April to discuss Laboratory programme, 24th April 1951. Sydney, National Archives of Australia (972135 – C3830 – A1/1/7 – Box 3).
- Pawsey, J.L., 1951b. Letter to E.M. Purcell, dated 20 April. National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Pawsey, J.L., 1951c. Letter to E.M. Purcell, dated 18 May. National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Pawsey, J.L., 1951d. Letter to E.G. Bowen, dated 13 July. Sydney, National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Pawsey, J.L., 1951e. [Note.] *Nature*, 168, 358.
- Pawsey, J.L., 1960. Obituary Notices: Charles Alexander Shain. *Quarterly Journal of the Royal Astronomical Society*, 1, 244–245.
- Piddington, J.H., and Minnett, H.C., 1951. Observations of galactic radiation at frequencies of 1210 and 3000 Mc/s. *Australian Journal of Scientific Research*, A4, 459–475.
- Piddington, J.H., and Minnett, H.C., 1952. Radio-frequency radiation from the constellation of Cygnus. *Australian Journal of Scientific Research*, 5, 17–31.
- Piddington, J.H., and Trent, G.H., 1956. A survey of cosmic radio emission at 600 MHz. *Australian Journal of Physics*, 9, 481–493.
- Professor Rod Davies CBE FRS. Jodrell Bank Centre for Astrophysics.
- Purcell, E.M., 1951. Letter to Dr J.L. Pawsey, dated 9 May. National Archives of Australia (972420 – C3830 – A1/3/17 Part 1).
- Ratcliffe, J.A., 1946. Letter to Dr E.G. Bowen, dated 24 September. National Archives of Australia (972177 – C3830 – A1/2/12B – Box 3).
- Robertson, P., 1992. *Beyond Southern Skies. Radio Astronomy and the Parkes Radio Telescope*. Cambridge, Cambridge University Press.
- Robertson, P., 2017. *Radio Astronomer: John Bolton and a New Window on the Universe*. Sydney, New South Publishing.
- Robinson, B., 2002. Recollections of the URSI Tenth General Assembly, Sydney, Australia, 1952. *Radio Science Bulletin*, 300, 22–30.
- Sander, K.F., 1947. Radio noise from the Sun at 3.2 cm. *Nature*, 159, 506.
- Shklovsky, I.S., 1949. Monochromatic radio emission from the Galaxy and the possibility of its observation. *Astronomicheski Zhurnal SSSR*, 26, 10–14.
- Slee, O.B., and Orchiston, D.W., 1965. A preliminary radio survey of planetary nebulae south of declination 24 degrees. *Australian Journal of Physics*, 18, 187–191.
- Smerd, S.F., 1950. The polarisation of thermal "S18, olar Noise" and a determination of the Sun's general magnetic field. *Australian Journal of Scientific Research*, 3, 265–273.
- Stanley, G.J., and Price, R., 1956. An investigation of monochromatic radio emission of deuterium from the Galaxy. *Nature*, 177, 1221–1222.
- Stewart, R., Orchiston, W., and Slee, B., 2011a. The contribution of the Division of Radiophysics Dapto field station to solar radio astronomy, 1952–1964. In W. Orchiston et al., 481–526.
- Stewart, R., Orchiston, W., and Slee, B., 2011b. The Sun has set on a brilliant mind: Paul Wild (1923–2008). In Orchiston et al., 527–542.
- Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2010. The Radiophysics field station at Penrith. *Journal of Astronomical History and New South Wales*, and the world's first solar radio-spectrograph *Heritage*, 13, 2–15.
- Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2011c. A retrospective view of Australian solar radio astronomy 1945 to 1960. In Orchiston et al., 589–629.
- Sullivan, W.T. III, 1982. *Classics in Radio Astronomy*. Dordrecht, Reidel.
- Sullivan, W.T. III, 1984. *The Early Years of Radio Astronomy*. Cambridge, Cambridge University Press.
- Sullivan, W.T. III, 2009. *Cosmic Noise. A History of*

- Early Radio Astronomy*. Cambridge, Cambridge University Press.
- Sullivan, W.T. III, 2017. Early years of Australian radio astronomy. In Nakamura and Orchiston, 453–496.
- Suzuki, S., Attwood, C.F., and Sheridan, K.V., 1963. dynamic spectra of solar radio bursts in the continuous frequency range 5-2,000 MHz. *The Observatory*, 84, 55–56.
- Swarup, G., 2008. Reminiscences regarding Professor W.N. Christiansen. *Journal of Astronomical History and Heritage*, 11, 194–202.
- Thomas, B.MacA., and Robinson, B.J., 2005. Harry Clive Minnett 1917–2003. *Historical Records of Australian Science*, 16, 199–220.
- van de Hulst, H.C., 1945. Herkomst der radiogolven uit het wereldruim. *Nederlandsch Tijdschrift voor Natuurkunde*, 11, 210.
- van Woerden, H., and Strom, R.G., 2006. The beginnings of radio astronomy in the Netherlands. *Journal of Astronomical History and Heritage*, 9, 3–20.
- Wendt, H., Orchiston, W., and Slee, B, 2008a. The Australian solar eclipse expeditions of 1947 and 1949. *Journal of Astronomical History and Heritage*, 11, 71–78.
- Wendt, H., Orchiston, W., and Slee, B, 2008b. W.N. Christiansen and the development of the solar grating array. *Journal of Astronomical History and Heritage*, 11, 173–184.
- Wendt, H., Orchiston, W., and Slee, B, 2008c. W.N. Christiansen and the initial Australian investigation of the 21cm hydrogen line. *Journal of Astronomical History and Heritage*, 11, 185–193.
- Wendt, H., Orchiston, W., and Slee, B, 2011a. An overview of W.N. Christiansen's contribution to Australian radio astronomy, 1948–1960. In Orchiston et al., 547–587.
- Wendt, H., Orchiston, W., and Slee, B, 2011b. The contribution of the Division of Radiophysics Potts Hill Field Station to international radio astronomy. In Orchiston et al., 379–431.
- Westerhout, G., 2000. Obituary: Frank John Kerr, 1918–2000. *Bulletin of the American Astronomical Society*, 32, 1674–1676.
- White, F.W.G., 1949. Letter to E.G. Bowen, dated 28 March. Sydney, National Archives of Australia (972099 – C3830 – A1/1/1 Part 4 Box 1).
- Whiteoak, J.B., and Sim, H.L., 2006. Brian John Robinson 1930–2004. *Historical Records of Australian Science*, 17, 263–281.
- Wild, J.P., 1952. The radio-frequency line spectrum of atomic hydrogen and its applications in astronomy. *Astrophysical Journal*, 115, 206–221.
- Wild, J.P., 1980. The Sun of Stefan Smerd. In Kundu, M.R., and Gergely, T.E. (eds.). *Radio Physics of the Sun*. Dordrecht, Reidel. Pp. 5–21.
- Yabsley, D.E., 1978. Taped interview with Woody Sullivan. Tape and transcript in the Sullivan Collection, NRAO.
- Yabsley, D.E., 1986. Letter to Woody Sullivan dated 10 October. Original in Sullivan Collection, NRAO.

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