Chapter 3

Exploring the Neighbourhood – the Sun, the Moon and Jupiter

3.1 The Sun

The idea that the Sun may emit radio waves has a long history. As Woody Sullivan (1982) has shown in his *Classics in Radio Astronomy*, the idea first gained credence in the 1890s, but initial searches by a number of different investigators proved fruitless (e.g. see Débarbat et al. (2007) for details of Nordmann’s search in 1901). Success would come half-century later, thanks largely to the development of war-time radar.

Solar radio astronomy had its foundations during WWII when independent detections of solar emission were made in the USA, Denmark (by German forces), England, Australia and New Zealand. Because of security issues this work was largely classified until after the war, but Joe Pawsey (1908–1962) must have been aware of some of these findings because in 1944 he carried out a very brief abortive attempt to detect solar radio emission from the Radiophysics Lab in Sydney. According to Mills (1920–2011; 1976), “... he stuck a simple parabolic reflector out of the window and looked at the Sun and saw nothing (because it was at 10 cm).” This was a hurried, solitary, opportunistic experiment, and it was not followed up.

Then in mid-1945 almost simultaneously the Radiophysics (henceforth RP) group received secret accounts of the independent discovery of solar radio emission at New Zealand and British radar stations, plus a copy of the 1944 *Astrophysical Journal* paper by American Grote Reber (1911–2002) reporting his detection of solar radio waves (see Fig. 3.1). It was these discoveries that collectively precipitated the Australian ‘solar noise’ program. The Sydney group (Fig. 3.2) would quickly gain world supremacy in solar radio astronomy, and maintain this position through until the mid-1980s when the closing of the Culgoora Radioheliograph and staff promotions and retirements saw the demise of the RP Solar Group. See Orchiston et al. (2006) for the genesis of solar radio astronomy in Australia; see also Stewart et al. (2011b) for an overview of Australian solar radio astronomy 1945 to 1960, and Stewart et al. (2011a) for Paul Wild’s impressive contribution to Australian

Fig. 3.1 Grote Reber's observations at 160 MHz, showing solar bursts superimposed on Galactic radio emission (after Reber, 1944: 286)

and international solar radio astronomy. Sullivan (2009) covers not only Australian solar research in the post-war decade, but places it in the context of other research done around the world.

3.1.1 *The first solar observations at Radiophysics*

The first serious Sydney observations were inspired by Dr Elizabeth Alexander (1908–1958; see Fig. 3.3 and Biobox 3.1) who was responsible for analysing and explaining observations of solar bursts made at 200 MHz in neighbouring New Zealand and on Norfolk Island (in the Tasman Sea between Australia and New Zealand). The future head of the RP radio astronomy group, Joe Pawsey (Fig. 1.13), noticed that Australia had similar 200 MHz COL (chain overseas low-flying) radar antennas deployed at RAAF radar stations around the country, so he arranged access to the antenna at Collaroy, a coastal suburb of Sydney, in an attempt to replicate Alexander's observations.

From 3 October 1945 RAAF personnel at Station 54 (see Fig. 2.1) agreed to carry out daily solar monitoring on behalf of RP for a 75 minute interval beginning about 10 minutes before sunrise, and this brought instant results:

Fig. 3.2 A Culgoora Radioheliograph antenna and members of the Radiophysics Solar Group during the mid-1960s. Key, inner circle, clockwise from top, centre Paul Wild (Group Leader), Masaki Morimoto, Charlie Attwood, John Sparks, Jack Palmer, Bill Bowie, Les Clague, Geoff Chandler and Kevin Sheridan; outer circle, Steve Smerd, Shigamasa Suzuki, Ron Stewart, Gopala Rao, Len Binskin, Joe Mack, Wayne Orchiston, Nick Fourikis, Warren Payten, Norman Labrum and Alan Weiss. Absent are T. Krishnan, Keith McAlister, Don McLean and Dick Mullaly [courtesy: CSIRO Radio Astronomy Image Archive (CRAIA)]

We observed, from the direction of the Sun, a considerable amount of radiation having the apparent characteristics of fluctuation ‘noise’ when observed on a cathode-ray oscillograph or head-phones. However, the output meter reading fluctuated considerably, a characteristic which is not typical of normal thermal agitation “noise”. (Pawsey et al., 1946).

Alexander also had concluded that the emission observed previously from New Zealand was non-thermal in origin. Joe Pawsey, Ruby Payne-Scott (1912–1981) and Lindsay McCready (1910–1976) were especially interested in any possible relationship between solar radio emission and optical features, but particularly sun-spots, and when these parameters were plotted for the period 3–23 October 1945 a general correlation was apparent. This confirmed the claims made earlier by Stanley Hey (1909–2000) and Alexander. Pawsey, Payne-Scott and McCready (1946) reported their results in the 9 February 1946 issue of *Nature*, shortly after Hey’s belated announcement of his wartime observations (Hey, 1946).

Fig. 3.3 Dr Elizabeth Alexander (1908–1958), the world's first female radio astronomer, moved in the upper echelons of New Zealand science (from left): Dr (later Sir) Ernest Marsden (Director of Scientific Developments, DSIR), Sir Cyril Newall (Governor-General of New Zealand), Alexander, Dr Ian Stevenson (Director of the Radio Development Laboratory) and the Governor-General's Aide de Camp (courtesy: Professor E.R. Collins)

Biobox 3.1: Elizabeth Alexander

Francis Elizabeth Somerville Alexander (née Caldwell) (Fig. 3.4) was born in Merton, England on 13 December 1908 and the following year moved to India where her father was a college professor. She returned to England for her secondary schooling, and then studied geology and physics at Cambridge graduating with a PhD in geology in 1934. Following her marriage Elizabeth moved to Singapore in 1936 where she worked with the Royal Navy on radio direction finding (later known as radar). In 1942, just before the Japanese occupation of Singapore, she and her three young children escaped to New

Fig. 3.4 Dr Elizabeth Alexander (1908–1958) was the world's first female radio astronomer (courtesy: Mary Harris)

(continued)

Biobox 3.1 (continued)

Zealand, where she was appointed head of the Operational Research Section of the Radio Development Laboratory.

At the Laboratory Elizabeth was involved in radar development, but also found time to investigate solar radio emission – the mysterious ‘Norfolk Island Effect’. At the end of the war, after her husband was released from a Japanese prisoner-of-war camp, they returned to Singapore in 1947. Elizabeth served for a period as Registrar of the University of Malaya and then became the Government Geologist for Singapore. In 1952 her family moved to Nigeria where Elizabeth died of a stroke in October 1958, shortly before her 50th birthday. Elizabeth Alexander was the world’s first woman to work in the field that would later be known as radio astronomy. After leaving New Zealand she never conducted any further astronomical studies, although she did publish a short paper on the ‘Norfolk Island Effect’ in 1946. Further details of Elizabeth’s life are provided in a captivating book written by her daughter, Mary Harris (2017), and in papers by Orchiston (2005, 2016).

Fig. 3.5 Chart record of the Sun passing through the sea interferometer fringes at Dover Heights on 7 February 1946. Time, in minutes, runs from right to left, and the chronological sequence is continued in the lower strip where intense burst emission is apparent just before the Sun rises above the beam of the aerial (after McCready et al., 1947: 366)

Solar monitoring at Collaroy Plateau was continued until March 1946, and soon was joined by parallel observations made with the antenna at the Dover Heights radar station (Fig. 2.1), about 17 km south of Collaroy. In order to obtain a visual record of solar radio emission, chart recorders were included in the receiving systems, and these provided a permanent record of the Sun’s passage through the sea interferometer fringes, not only revealing temporal variations in the background level of solar radiation but also intense bursts of short duration (see Fig. 3.5).

Meanwhile, McCready, Pawsey and Payne-Scott (1947: 363) continued to investigate the general relationship between sunspots and solar emission. By plotting the general background level of solar radiation from October 1945 to February 1946 against sunspot number and sunspot areas, the correlation noted earlier for October 1945 was confirmed, but in this instance they found that “... the correlation with

areas is somewhat closer than with sunspot number but neither is exact.” The Sun was particularly active during this period, and as Sullivan (1982: 183) has pointed out, “... these novice astronomers were somewhat lucky in being able to observe the great sunspot group of February, 1946, one whose main sunspot is amongst the largest ever photographed.”

McCready and his colleagues also investigated the location of the source of emission on the Sun by analysing the interference fringes in Fig. 3.5 and, during the presence of the great sunspot group of February 1946, were able to demonstrate conclusively that the solar radiation originated from a strip that in each case included this sunspot group. Examples deriving from Collaroy and Dover Heights are shown in Fig. 3.6, and

In each case the radiating strip has a width considerably less than that of the Sun’s disk, being of the order of the size of the sunspot group, and passes through the group. It moves across the Sun with the spots as the Sun rotates ... There seems no reasonable doubt that the source was localised in a small region in the vicinity of the spots. [However] The observations do not provide any information as to the detailed structure of the source within this region. (McCready et al., 1947: 368).

Although most of these pioneering observations were made at 200 MHz, a few observations were also carried out at 75 and 3000 MHz. At the higher frequency the low level of solar radiation detected was consistent with results George Southworth (1890–1972) published in 1945, whereas at 75 MHz the solar emission was comparable to that recorded at 200 MHz.

In addition to burst emission, Pawsey was interested in the quiescent level of solar radiation at 200 MHz, and by isolating and quantifying the non-burst component was able to demonstrate the existence of a ‘hot corona’, something that had been hinted at previously by optical astronomers. The announcement by Pawsey (1946) in *Nature* of a temperature of one million degrees immediately followed a theoretical paper by David Martyn (1906–1970) predicting a coronal temperature of this order. Originally the inaugural chief of the Radiophysics Lab, Martyn was at that time based at the Commonwealth Solar Observatory, near Canberra (Biobox 3.2).

Fig. 3.6 Drawings of the Sun made between 6 and 9 February 1946 showing the position and width of the ‘equivalent radiating strips’ from which the solar radiation originated (after McCready et al., 1947: 369)

Biobox 3.2: David Martyn

David Forbes Martyn (Fig. 3.7) was born in Cambuslang, near Glasgow, Scotland, in 1906, and died in Camden (near Sydney) in 1970. After completing BSc and PhD degrees at Imperial College and the University of London in 1926 and 1928, respectively, he was appointed a Research Officer with the Radio Research Board in Australia and moved to Melbourne. He then published a series of research papers on the ionosphere, most notably one in 1936, co-authored by Owen Pulley (1906–1966). Of this paper Piddington and Oliphant (1972: 49) later wrote: “It is no exaggeration to say that this paper, of itself, transformed all subsequent thinking on almost all aspects of the high atmosphere.”

In 1939 Martyn was selected to head the CSIR’s new Division of Radiophysics, then involved in the wartime development of radar. This did not prove a successful appointment and in March 1941 he was replaced by Fred White (1905–1994), while David was appointed the head of a new Operational Research Group. By the end of the War, Martyn was based at Mount Stromlo Observatory, where he continued his ionospheric research and wrote a number of seminal papers on solar radio emission. Although still on the CSIRO payroll, David remained at Mount Stromlo until 1958, when he took charge of the CSIRO’s new Upper Atmosphere Section at Camden, near Sydney.

A Fellow of the Royal Society since 1950, Martyn received many awards. He served as President of the Radio Astronomy Commission and later the Ionospheric Commission of the International Union of Radio Science. David also chaired a United Nations sub-committee on the Peaceful Uses of Outer Space and was on the Executive Committee of the International Council of Scientific Unions. Martyn was largely responsible for the formation of the Australian Academy of Science in the early 1950s – he was its inaugural Secretary (Physical Sciences) and was its President at the time of his death (Orchiston, 2014a).

Fig. 3.7 David Martyn was the inaugural Chief of the Radiophysics Lab (courtesy: Mount Stromlo and Siding Spring Observatories)

While these pioneering observations were under way in Sydney, a young radar mechanic Bruce Slee (1924–2016) was busy carrying out his own solitary solar observations at an RAAF radar station near Darwin, in total ignorance of this new RP research initiative. Station 59 at Lee Point featured a British 200 MHz COL Mk5 radar unit situated about 500 m from the coast and mounted atop a 46 m high steel tower. Between October 1945 and March 1946 Slee carried out observations that were an independent discovery of solar radio emission. From time to time he noticed that in the hour leading up to sunset

... the “grass” on the range display increased its height by up to a factor of ten when the antenna was pointing towards the setting Sun. By slowly scanning backwards and forwards through the Sun, he was able to establish that the source of the signal lay at the solar azimuth to within the errors of measurement. Furthermore, when he stopped the antenna while pointing at the Sun, he noticed that the amplitude of the grass varied regularly by a large factor with a period of about 3 minutes. He concluded that this behaviour was consistent with the setting Sun passing through the sea interference fringes formed by the antenna and its image in the sea. (Orchiston and Slee, 2002: 27).

In March 1946, Slee read a newspaper account of the RP solar research and wrote a letter to Pawsey describing his own work. This drew an enthusiastic response, and a collaborative program of solar monitoring was arranged, only to be immediately stymied by the closing of the Lee Point radar station. In 1947 a tender of £1,200 was accepted for removal of the tower, and another phase in the wartime history of Australian radar came to an end. But at the same time Slee was enjoying a new career at RP in far-off Sydney, and he would go on to acquire a Doctor of Science degree and to build an international reputation as a radio astronomer (for biographical details see Orchiston, 2004a and Biobox 4.1).

One of the major problems with radar antennas – including those at Collaroy and Dover Heights – was that they could not track the Sun, so in early 1946 RP staff installed simple, movable 200 MHz Yagi-type antenna arrays (Fig. 2.13) at Dover Heights, at the North Head radar station (located at the entrance to Sydney Harbour – see Fig. 1.14), and at Mount Stromlo Observatory (see Fig. 2.8). Associated with the 4-Yagi array at Mount Stromlo was Cla Allen (1904–1987; Biobox 3.3), who specialised in solar spectroscopy and the terrestrial effects of solar flares. However, his wartime research into the causes of short-wave radio fadeouts whetted his appetite to investigate solar radio emission, and this fitted well with the desire of the Mount Stromlo Director, Richard Woolley (1906–1986; Fig. 1.36), to include an active radio astronomy program in the Observatory’s post-war research portfolio.

Between April 1946 and March 1947 Allen (1947) carried out solar monitoring and found that even on radio-quiet days

... there has always been a detectable amount of radiation which appears to be quite variable ... [In addition] there are occasional sudden “bursts” of solar radio-noise which last for periods of the order of 1 sec ... [and] rather rarely, sudden outbursts of radio noise, which last for a few minutes, fluctuating violently, and then disappear.

Allen confirmed that solar emission was closely related to the central meridian passage of sunspots, just as Pawsey et al. (1946) had reported, although not all sunspots produced solar noise. Meanwhile, his analysis failed to show a general correlation

Biobox 3.3: Cla Allen

Clabon ('Cla') Walter Allen (Fig. 3.8) was born in Perth, Western Australia, in 1904, and obtained BSc, MSc and DSc degrees from the University of Western Australia in 1926, 1929 and 1936 respectively. In 1926 he was appointed as one of the founding astronomers of the Commonwealth Solar Observatory near Canberra (later named Mount Stromlo Observatory). During the 1930s Cla mapped the solar spectrum at optical wavelengths and carried out a variety of atmospheric research projects.

Following the launch of the RP solar radio astronomy program in late 1945, Allen arranged for a 200 MHz four-element Yagi array (see e.g. Fig. 2.13) to be installed at Mount Stromlo. He used this radio telescope to monitor solar burst emission, and for an all-sky survey of Galactic radio emission. In 1951 Allen accepted the newly-created Perrin Chair of Astronomy at University College London, where he wrote *Astrophysical Quantities*, a book for which he is justly famous. Irish astronomer Derek McNally (1934–2020; 1990: 265) described Allen as "... a man of great personal integrity, sincerity, determination and modesty. He did not seek personal aggrandisement and devoted his energies to his research, his students and his department." After retiring in 1972 Cla returned to Canberra, where he had an honorary position at Mount Stromlo. He died in 1987.

Fig. 3.8 Cla Allen at Mount Stromlo Observatory was a strong supporter of the solar research at Radiophysics (courtesy: Mount Stromlo and Siding Spring Observatories)

between solar noise and hydrogen alpha line ($H\alpha$) features or geomagnetic storms, although some solar flares were associated with outbursts.

While Allen was conducting these investigations, his Mt Stromlo colleague David Martyn was using data obtained with the 200 MHz array to research the polarisation of solar radio emission. Martyn (1946) reasoned that since solar bursts were associated in some way with sunspots and in turn sunspots were associated

with strong magnetic fields, “... we should expect to find evidence of the magnetic field in the production of gyrotory effects at the source of the [radio] emissions, and/or in differential absorption of right-handed and left-handed components of polarisation during transmission through the corona.”

The passage of the large sunspot group of July 1946 provided an ideal opportunity for Martyn to test this hypothesis, by turning two of the Yagis in the array at right-angles to the other two Yagis. Observations made on July 26 revealed that “... the right-handed circularly polarised power received was some seven times greater than that received when the system accepted only left-handed circularly polarised radiation.” (Martyn, 1946). This result was mirrored during observations at 60 and 100 MHz made by John Bolton (1922–1993) and Gordon Stanley (1921–2001) at Dover Heights in March and April 1947.

Martyn followed up this important paper with a theoretical contribution in which he proposed the revolutionary idea that the solar corona, the tenuous outer atmosphere of the Sun, has a temperature of about one million degrees, far higher than the 6000 degrees that characterises the photosphere where sunspots are found. After contributing two further theoretical papers, Martyn moved on to other research interests, and when Allen accepted a professorship at University College London, in 1951, Mount Stromlo’s involvement in radio astronomy came to an abrupt end.

At about the same time that Allen was beginning his solar radio astronomy research at Mount Stromlo, Sydney Williams (1910–1979), a lecturer in physics at the University of Western Australia, set up a 75 MHz equatorially-mounted Yagi antenna on campus in suburban Perth. Williams had a background in optical astronomy at the Commonwealth Solar Observatory, and his three-year foray into radio astronomy was apparently inspired by what he heard at a seminar held at the Radiophysics Lab in January 1946. He was particularly interested in temporal variations in the intensity of solar radio emission, correlations with sunspots, solar flares and ionospheric radio fadeouts, and the shapes of short pulses of solar radio emission.

Parallel daily monitoring with these steerable antennas in Perth, at Mount Stromlo and in Sydney revealed almost identical patterns of solar emission, with a changing level of background radiation upon which were superimposed bursts of varying duration and intensity. The precise correspondence in the case of bursts, and the fact that burst activity did not vary systematically as the Sun rose from the horizon towards the zenith, proved conclusively that the emission was of solar origin and not caused by ionospheric scintillations.

The next challenge was to expand these multi-frequency observations, with particular emphasis on burst emission, and from mid-1946 the relative arrival times of bursts were recorded at 60, 75 and 200 MHz at Dover Heights. In 1947, Payne-Scott, Don Yabsley (1923–2003) and Bolton reported on their research in a short paper published in *Nature*. They found that small bursts often were not correlated at the three frequencies, whereas many of the larger bursts were present at all three frequencies, but did not occur simultaneously. Instead, they arrived in the sequence 200, 75 and 60 MHz, with a typical delay of about 2 s between bursts at 200 and 75 MHz, and a similar interval between bursts at 75 and 60 MHz. A few observations were also made at 30 MHz, and the delay in arrival times of bursts at 60 and 30 MHz was also a few seconds.

Very much rarer were major ‘outbursts’, which could last for hours, and in this instance the delays in the respective arrival times at the different frequencies were of the order of several minutes rather than seconds. An outburst recorded on 7 March 1947 was associated with a solar flare and short-wave radio fadeout, and an aurora was visible from some areas of Australia on the evening of 9 March. In interpreting their observations, Payne-Scott, Yabsley and Bolton (1947) concluded that “The successive delays between the onset of the outburst on 200, 100 and 60 Mc/s. suggest that the outburst was related to some physical agency passing from high-frequency to lower-frequency levels [in the solar corona].” This spectacular event would later be classed as a Type II burst, and its discovery played a crucial role in the subsequent development of solar radio astronomy.

3.1.2 *Solar eclipses and solar bursts*

At the end of 1946 Gordon Stanley began building radio equipment to observe a total solar eclipse in Brazil. The previous year, the Canadian radio astronomer Arthur Covington (1913–2001) had demonstrated that eclipses could be used to determine the positions of centres of radio emission in the solar corona, and this offered an excellent opportunity to look at their association with optically-active regions. In the end this project was torpedoed by “... the appalling difficulties in getting transport of men and equipment to Brazil.” (Bowen, 1947), and the equipment was transferred to Dover Heights where it was used in conjunction with other antennas by Stanley and Bolton.

By August 1947, Georges Heights had joined Dover Heights as a solar radio astronomy field station. One of the three ex-radar antennas there (see Fig. 2.25) was brought into operation, and solar monitoring was carried out for about two hours daily, from 18 August until 30 November. This resulted in the detection of many bursts at 200 MHz. In contrast, bursts were rare at 600 and 1200 MHz, where the general flux variations with time were correlated with sunspots (Fig. 3.9). This distinctive pattern was discussed by RP’s Fred Lehany (1915–1980) and Don Yabsley in papers published in *Nature* and the *Australian Journal of Scientific Research* (Lehany and Yabsley, 1948, 1949), along with those rare outbursts that would later be classed as Type II events.

During the first nine months of 1948, Payne-Scott studied solar emission at 18.3, 19.8, 60, 65 and 85 MHz at the Hornsby Valley field station, and detected many correlated bursts. In addition to the three different kinds of bursts noted by earlier workers, she also identified a fourth type of event: “The intensity reaches a high level and remains there for hours or days on end; there are continual fluctuations in intensity, both long-term and short-term ... This type of radiation will be called “enhanced radiation” ... [and] Superimposed on it may be bursts.” (Payne-Scott, 1949: 216–17). An example of enhanced radiation at 60 and 85 MHz is shown in Fig. 3.10. Payne-Scott found this enhanced emission was circularly polarised, and was usually associated with the presence of large sunspot groups.

Fig. 3.9 The correlation between sunspot area and solar flux at 200, 600 and 1200 MHz (after Lehany and Yabsley, 1949)

So by the end of 1948 it was clear that the Sun produced ‘enhanced radiation’ – which typically occurred with small-scale bursts of short-duration and restricted in frequency – and at least two different types of major burst; larger relatively short-lived bursts which were represented over a range of frequencies and had starting times that varied by just a few seconds as one moved down in frequency; and long-lasting major outbursts, which were also present over a range of frequencies, but exhibited starting-time delays of several minutes from one frequency to the next. A

Fig. 3.10 Solar bursts and 'enhanced emission' recorded at 60 and 85 MHz (after Payne-Scott, 1949: 218)

magnificent example of this last type of solar burst is Fig. 3.11. This led naturally to two quite different types of research: investigation of the spectral features of the burst emission, and examination of the location, movement and polarisation of the bursts.

Determining the positions of the solar regions generating radio emission was a major challenge given the poor angular resolution of the radio telescopes available in the late 1940s. McCready, Pawsey and Payne-Scott had already shown how sea interferometer observations could reveal the radiating strip associated with burst emission (Fig. 3.6), but this did not give an unambiguous two-dimensional position. However, a solar eclipse could provide this, if observed simultaneously from two or more widely-spaced sites. In the course of the eclipse, as the Moon progressed across the solar disk it masked different regions of the Sun's atmosphere at different times. As seen from the different observing sites, the Moon's limb followed different paths, and by noting the times when different optically-active regions were masked and exposed again the sources of any associated radio emission could be pinpointed.

Fig. 3.11 The large outburst recorded at three different frequencies on 8 March (after Payne-Scott et al., 1947: 256). In 2020, the 1947 outburst at 60 MHz is still the strongest ever recorded

The partial solar eclipse of 1 November 1948 provided an ideal opportunity to exploit this method, and so observations were carried out at 600, 3000 and 9400 MHz from the Potts Hill field station and at 600 MHz from two remote sites, Rockbank, just north-west of suburban Melbourne (Fig. 2.8), and Strahan, on the west coast of Tasmania (Orchiston, 2004b). Collectively, these observations involved four different teams of scientists: W.N. ('Chris') Christiansen (1913–2007) and Bernie Mills (1920–2011) (Christiansen et al., 1949); Don Yabsley and John Murray; Harry Minnett (1917–2003) and Norman Labrum (1921–2011); and Jack Piddington (1910–1997) and Jim Hindman (1919–1999). Interestingly, all except Christiansen and Labrum would go on to build reputations in *non*-solar areas of radio astronomy.

The Rockbank eclipse results are representative, and can be used to illustrate the type of analysis involved. At the time of the eclipse, visual monitoring in Sydney revealed the presence of six different groups of sunspots. Although only 72% of the Sun's disk would be covered at the peak of the eclipse, it was noted that as the eclipse progressed the declining level of radio emission was punctuated by a succession of small peaks and troughs (Fig. 3.12). The troughs occurred when centres responsible for enhanced radio emission were covered, and their precise positions were obtained by plotting the intersections of the Sydney, Strahan and Rockbank lunar-limb paths across the Sun during the eclipse. These locations are shown in Fig. 3.13. Of the eight centres of enhanced solar emission, three coincided with the positions of sunspot groups, three others were close to positions occupied by sunspot groups exactly one solar rotation earlier, and a seventh was located about 170,000 km off the south-west limb of the Sun, directly above a magnetically-active region associated with a limb prominence. However, two small sunspot groups and one large group were not associated with measurable levels of radio radiation, showing that there was not always an exact correlation between sunspots and solar emission.

Fig. 3.12 Variations in 600 MHz radio emission recorded at Rockbank (Victoria) during the 1 November 1948 partial solar eclipse. The upper plot shows the actual chart record, while the lower plot has been corrected for the slope and the peaks have been magnified (after Christiansen et al., 1949: 511)

These eclipse observations confirmed the existence of two discrete components of non-burst solar emission: a basic component of thermal origin, which originates from the whole disk of the Sun, and a 'slowly-varying component' (first recognised by Jean-François Denisse (1949) in France) that is generated in small localised regions that are often associated with sunspots. This emission was discussed in detail by Pawsey and Yabsley and by Piddington and Minnett, in papers that were published in the *Australian Journal of Scientific Research* in 1949 and 1951 respectively (see also Pawsey, 1950).

There was another partial solar eclipse on 22 October 1949 that also was visible from Australia and, primed by the success of their 1948 campaign, RP mounted an equally ambitious program with radio telescopes sited in Sydney (at Potts Hill), Victoria and Tasmania (but at different sites to those used the previous year). On this occasion the selected observing frequency was 1200 MHz, while Cla Allen carried out parallel observations at 200 MHz from Mt Stromlo. Although observations of this eclipse also were successful, for reasons suggested by Wendt et al. (2008) no publications resulted from this particular campaign. American war-surplus AN/TPS-3 antennas were used at remote sites during these eclipse expeditions, and their

Fig. 3.13 Regions of enhanced solar emission at 600 MHz (hatching) recorded during the partial solar eclipse of 1 November 1948 shown in relation to locations of optical activity: VS = visible sunspots; FS = positions of sunspots during the previous solar rotation; and P = prominences (after Christiansen et al., 1949: 513)

significant role in early Australian radio astronomy is discussed by Wendt and Orchiston (2018).

While eclipses can tell us about the locations of solar emission, they are rare events, and as Paul Wild (1923–2008) reminded us, “... the analysis is complex and the result often inconclusive.” (Wild, 1953: 687). There had to be better ways of investigating the positions of these sources, and Ruby Payne-Scott and Alec Little (1925–1985) came up with an ingenious method (Payne-Scott and Little, 1951). Using 97 MHz swept-lobe and fixed-lobe interferometers set up at the Potts Hill field station (see Fig. 2.39), they were able to measure the positions and polarisation of sources of burst emission (Fig. 3.14). Between May 1949 and August 1950 observations were made on week days for about two hours either side of meridian transit of the Sun, and at times of high solar activity also on weekends. Records were obtained of 30 noise storms, 6 outbursts and 25 randomly-polarised bursts.

They found an association between noise storms and sunspots, but only with the largest spot in any group. Furthermore, sunspots were linked to strong magnetic fields that extended into the corona. Noise storms associated with spots with a south-seeking magnetic pole exhibited right-handed polarisation, and left-handed polarisation was found with north-seeking magnetic poles. The authors showed that these noise storms arose in the corona. In the case of the six outbursts, initially their

Fig. 3.14 Polarisation observations of a 97 MHz solar noise storm made with the Potts Hill interferometer (after Little and Payne-Scott, 1951: Plate 4)

positions and those of the related solar flares almost coincided, but the bursts were observed to move rapidly out from the Sun, at velocities of between 500 and 3000 km/s. Payne-Scott and Little suggested that the corpuscular streams responsible for terrestrial magnetic storms initiated the outbursts. These outbursts also showed the same polarisation features as observed with the noise storms.

Two exceptionally large outbursts occurred on 17 February and 21–22 February 1950, providing further evidence of the association of these rare events with solar flares and their terrestrial effects. Both outbursts lasted more than an hour and were observed from Potts Hill at 62, 97, 600, 1200, 3000 and 9400 MHz and from Mount Stromlo at 200 MHz, and reported on in a multi-authored paper published in 1951 in the *Australian Journal of Scientific Research*. Readings at four of these frequencies showed the two outbursts at times were strongly circularly polarised, while observations by Payne-Scott and Little with the two-element 97 MHz interferometer revealed that the sources of the emission began near the sites of the $H\alpha$ flares, but moved progressively with the passage of time. In the case of the 17 February outburst, the emission began successively later as one moved from high to low frequencies, whereas the second outburst did not exhibit this tendency. In the case of both outbursts, the maximum radio output tended to occur earlier at higher frequencies.

Rod Davies (1930–2015) followed up this study with another that reviewed bursts detected between January 1950 and June 1951 at Potts Hill and Mount Stromlo, at the above-mentioned seven frequencies. He also looked at the connection between bursts, solar flares and terrestrial phenomena. Davies found that bursts (of all types) were far more prevalent at the lower frequencies – below 200 MHz – but that at higher frequencies a greater proportion of bursts tended to be of longer duration. He also suggested that “... 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).” (Davies, 1954: 90). He further suggested that these components may be due to plasma oscillations and thermal emission, respectively. He also found evidence of the correlations between bursts and both sunspots and flares noted by other researchers, but “... a burst on a high frequency is more likely to be accompanied by a flare than one on a low frequency.” (Davies, 1954: 83). Short-wave radio fadeouts and magnetic crochets were overwhelmingly associated with bursts. Davies’ paper was published in *Monthly Notices of the Royal Astronomical Society* after he had left RP and joined the Jodrell Bank radio astronomers in England, and it contains a variety of interesting statistics relating to terrestrial phenomena and solar bursts. For his recollections of the Potts Hill observations see Davies (2005, 2009).

3.1.3 *Classifying solar bursts at Penrith and Dapto*

Another way of researching bursts and outbursts was to look at their spectral features, and from 1948 Paul Wild was doing this with the new radiospectrograph at the Penrith field station (Fig. 2.45) (see Stewart et al., 2010). This novel radio telescope provided a virtually simultaneous visual display of radio emission over the frequency band 70–130 MHz. In the first instance, observations were made for a total of 254 hours between February and June 1949, and whenever a solar burst of interest was detected the trace of this was photographed on a cathode ray tube. Successive photographs could be taken at intervals of one-third of a second, permitting the radio astronomers to investigate the ways in which burst intensity changed with frequency and with time. From these photographs, Wild could construct the spectra of different bursts (Fig. 3.15). Producing these spectra manually was a very trying and time-consuming process – today it would all be done automatically by computer! Wild (1978) recalled that

... in the early days we had a loaded camera, but we didn’t actually have a motor so we had to turn it by hand. And we changed the aerial every twenty minutes ... by ... adjusting a rope, and Bill [Rowe] and I used to take twenty minute watches, just looking at the screen, waiting for something to happen. Of course we didn’t know quite what to expect ... but when the first few [bursts] came there was tremendous excitement.

With the benefit of hindsight, RP Chief, E.G. ‘Taffy’ Bowen (1911–1991) came to view the spectral study of solar bursts as one of the most important early achievements of the Radiophysics Lab (Bowen, 1973).

Analysis of the spectra of the bursts that were recorded during the first half of 1949 showed that many belonged to one of three distinct types, and these were designated Types I, II and III and described in a series of four papers written by Paul Wild in the *Australian Journal of Scientific Research* in 1950–51. Type I bursts (Fig. 3.16), described as “... little things popping up all over the place, like a choppy sea ...” (Wild, 1978), occurred in large numbers (hundreds or more typically thousands) during so-called ‘noise storms’, which usually lasted for many hours, or even

Fig. 3.15 Spectra of three quite different types of solar events constructed from data contained in the Penrith spectra (after Wild and McCready, 1950: Plate 2): Type I (upper left), Type II (right) and Type III (lower left)

days. Bursts normally came in small discrete groups, were strictly localised in both frequency (most were between 3 and 5 MHz) and time (typically 1–8 s), and showed strong circular polarisation. Type II bursts were rare, and outbursts like the ones shown in Fig. 3.15 were shown to be Type II events. These lasted from ten to tens of minutes, and had clearly-defined upper and lower frequency boundaries at any one point in time. The emission drifted from higher to lower frequencies with the passage of time at a mean rate of 0.22 MHz per second. Type II bursts often were associated with solar flares.

Fig. 3.16 Examples of the five main types of solar bursts taken with the Dapto spectrograph over the frequency range 15–200 MHz (courtesy: CRAIA)

A third distinct group of bursts belonged to Type III, characterised by narrow-band events that only lasted a few seconds and drifted rapidly from high to low frequencies (at mean rates of 20 MHz per second). Type III bursts were particularly common, and sometimes occurred in groups near the start of solar flares. Wild (1978) would later reminisce that at first he and his colleagues saw the identification of these three spectral types as “... a low key thing ...”, and it was only when Pawsey announced them at the Rome IAU meeting, causing “... a great deal of interest ... that one realised that there was something to it.”

Another interesting feature noted of some Type II and Type III bursts was that they sometimes exhibited harmonic structure, with a near mirror image of the initial burst following in close succession at a frequency separation of 2:1. The first Type II burst with harmonic structure was observed on 21 November 1952, just four months after the start of regular solar monitoring at Dapto, and was reported by Wild and assistants John Murray and Bill Rowe in research papers published in *Nature* and the *Australian Journal of Physics* in 1953 and 1954 respectively.

Once the Dapto field station was operational further observations were made, but over a wider frequency range (initially from 40 to 210 MHz), and actual spectra – such as those shown in Fig. 3.16 – were recorded on cathode ray tubes and were

filmed directly with cine-cameras. This represented a quantum jump in efficiency; no longer was it necessary to generate spectra manually.

By 1958, three further spectral classes of solar events had been identified, which were respectively termed Type IV noise storms, Type V bursts and ‘reverse drift pairs’. Type IV noise storms, well-documented at Dapto, but first described by a French radio astronomer, were rare continuum events, characterised by a high-intensity broadband featureless spectrum and linear polarisation. They lasted from around half an hour to six hours, and generally occurred after Type II bursts (but not *all* Type II bursts). Some of Payne-Scott’s ‘enhanced radiation’ can be identified as Type IV events. Type V bursts looked like Type IIIs but with broadband continuum ‘tails’ that lasted anywhere from half a minute to three minutes and were associated with between 25% and 33% of all Type III bursts. Reverse drift pairs (RDPs) were first described by RP’s Jim Roberts in 1958 (see Biobox 3.4). These rare very short-duration bursts were seen only at low frequencies (below 50 MHz), and occurred in pairs separated in time by only 1.5–2 s. The pairs typically drifted rapidly from lower to higher frequencies at rates of 2–8 MHz per second. RDPs tended to occur in storms lasting from hours to days, and about 10% were associated with weak Type III bursts. Roberts believed that RDPs were generated high in the solar corona.

Fig. 3.18 conveniently brings all of these spectral types of solar bursts together in the one diagram, and it is important to note that this RP classification scheme was quickly adopted worldwide.

During the 1950s as further spectral, positional and polarisation data on solar bursts emerged from Dapto, Paul Wild (Fig. 2.46) and his Solar Group colleagues began a series of detailed studies of the different types of events. This resulted in the

Biobox 3.4: Jim Roberts

James Alfred Roberts (Fig. 3.17) was born in Tamworth, New South Wales, on 27 April 1927, and completed BSc (First Class Honours) and MSc degrees at the University of Sydney in 1948 and 1949 respectively. He then undertook a PhD on solar bursts at Cambridge, supervised by the renowned English astronomer Fred Hoyle. From November 1952 he worked at the Radiophysics Lab initially as a member of the solar group. Jim then took up a postdoctoral fellowship (1958–61) at Caltech where he helped former RP colleagues John Bolton and Gordon Stanley establish the Owens Valley Radio Observatory in northern California.

Following his return to Australia, Roberts joined the group at Parkes and played a significant part in the commissioning of the new 64 m telescope. Although he took a lead role in observing radio emission from Jupiter, Jim considered himself a theoretical physicist first and a radio astronomer second. His research focus shifted to studies of the emission mechanisms from Galactic objects such as pulsars and from extragalactic objects such as quasars. He became well known for his review papers surveying particular branches of radio astronomy, such as his masterful ‘Radio Emission from the Planets’ published in 1963.

(continued)

Biobox 3.4 (continued)

Fig. 3.17 Jim Roberts began his career in solar radio astronomy and then transitioned to theoretical work on Galactic and extragalactic sources (courtesy: CRAIA)

At various times between 1973 and 1987 Roberts served as acting leader of the Astrophysics Group. He was also responsible for vetting all RP publications before their submission to journals, a role once played by Joe Pawsey. Jim took early retirement in 1987, by which time he had reached the rank of Senior Principal Research Scientist.

publication of a number of seminal papers. Don McLean (b. 1938; Fig. 3.19) found that Type I noise storms were relatively uncommon: between 1952 and 1958 only ten were recorded at Dapto. These often followed, and presumably were associated with, solar flares. The available evidence suggested that some sources giving rise to Type I emission moved upwards through the solar corona with velocities of ~ 100 km/s, while others showed downwards motion. Wild (1957: 324) noted that “Such behaviour is reminiscent of ascending and descending prominence material.” In 1958 Max Komesaroff (d. 1988; Fig. 3.19) confirmed the earlier findings of Payne-Scott and Little that Type I noise storms were strongly polarised. By the early 1960s, there was a unique assemblage of Dapto spectral, positional and polarisation data at RP, and in 1964 Alan Weiss and Wayne Orchiston (b. 1943; see Fig. 3.2) drew on this to prepare a detailed review of Type I storms, but at the end of that year Weiss died from leukemia and this paper was never published. Consequently, by 1965 less was known about Type I storms than any other spectral type.

In a long review paper published in 1959, Jim Roberts summarised the findings from a study of 65 different Type II bursts observed at Dapto between September 1952 and March 1958. In another, shorter paper he noted that Type II bursts were rare: “Even at sunspot maximum the average rate of occurrence is only about one burst every 50 hours, so that a long series of observations is needed to define the characteristics of the bursts.” (Roberts, 1959: 194). About 60% of all Type II bursts

Fig. 3.18 The five radio burst types following a solar flare, with the origin of the mechanism producing the radiation (courtesy: CRAIA)

Fig. 3.19 Two members of the Dapto group were Don McLean (left) and Max Komesaroff. Don showed that Type I noise storms are relatively uncommon, while Max confirmed earlier evidence that Type I storms are strongly polarised (courtesy: CRAIA)

were preceded some minutes earlier by a group of Type III bursts. The optical solar expert Ronald Giovanelli (1915–1984) from CSIRO's Division of Physics and Roberts found that most Type II bursts were also associated with optical features, such as flares, surges, ejecting prominences or disappearing filaments. Quantitative studies revealed that in about 60% of cases, Type II bursts exhibited fundamental and second harmonic bands, and in about 20% of these that the two bands were themselves split and typically separated by 4–8 MHz. Stefan ('Steve') Smerd (1916–1978) and colleagues at RP noticed an interesting feature of Type II bursts

exhibiting harmonic structure: the harmonic radiation always originated from a lower region of the corona than the fundamental emission.

On the basis of positional observations, Weiss reported that some Type II events were in fact made up of two or more bursts that occurred simultaneously or in quick succession, with source positions and rates of frequency drift that differed widely. Most Type II bursts were featureless, but around 20% of them exhibited considerable fine structure. One of the most prominent forms was the so-called ‘herring-bone structure’, characterised by elements that drift rapidly towards higher and lower frequencies. The first example of herring-bone structure was recorded at Dapto in April 1956. Type II bursts are thought to be caused by shock fronts that cause plasma oscillations as clouds of ionised matter pass through successively higher regions of the corona with velocities of 750 to 1500 km/s; these values are derived from Weiss’ analysis of observations made with the position interferometer at Dapto. It is likely that these same streams of particles are the ones that impact the Earth 1–3 days after a flare, and cause geomagnetic disturbances (including aurorae). Where Type II bursts are associated with Type III bursts, the evidence very strongly suggests “... that the sources of the emission of these two distinctive types of burst are located in equivalent regions in the corona ... [although] the excitors of these two types of burst differ widely in physical nature and in speed of motion through the corona ...” (Weiss, 1963a: 263).

Unlike Type II bursts, Type III bursts are common, occurring at a rate of about one every few minutes. In a study of over 300 flares and microflares made between November 1955 and July 1956, Giovanelli’s optical colleague from CSIRO’s Division of Physics, Ralph Loughhead (1929–2018), together with Jim Roberts and Marie McCabe from the RP Lab, showed that about 20% were associated with Type III bursts, with the figure rising to about 60% for flares of Class 1 or greater. Ron Giovanelli found an even higher correlation between Type III bursts and flares that exhibited what he called ‘puffs’, sudden explosive expansion that occurred at the outbreak of some flares.

Contrary to the earlier findings of Komesaroff, when he analysed about 100 Type III bursts captured by the Dapto swept-frequency interferometer between 1960 and 1962, visiting Indian scientist Gopala Rao (Fig. 3.2) found that the great majority were either only slightly or moderately polarised. Just 13% of all bursts showed polarisation readings in excess of 40%, and the degree of polarisation for all bursts varied inversely as the duration of the burst. Positional observations of Type III bursts made in 1958 and reported in two 1959 papers by Wild and three RP colleagues revealed that radiation at decreasing frequencies originated from successively higher levels in the corona (Fig. 3.20), confirming the impression that the emission was due to plasma oscillations caused by disturbances that moved rapidly out from the Sun at velocities of 0.2–0.8 times the speed of light. These rates are considerably greater than those inferred earlier from spectral data alone, and a subsequent study of 50 Type III bursts by Ron Stewart (b. 1939; Fig. 3.21) produced a mean figure of 0.33. However, the positional observations showed clearly that the corona was considerably denser in regions where Type III bursts were generated than in other parts of the corona, suggesting that these bursts were associated with

Fig. 3.20 Positions of Type III bursts observed at different frequencies (adapted from Wild et al., 1959a: 382)

Fig. 3.21 A study of Type III bursts by Ron Stewart showed that they move out rapidly from the Sun, on average, at one-third the speed of light. After his retirement, Ron completed a PhD on the history of the Penrith and Dapto field stations and their contribution to international radio astronomy (courtesy: CRAIA)

coronal streamers. The disturbances giving rise to the Type III bursts may correlate with the cosmic ray showers that reach the Earth about one hour after a major flare.

Alan Weiss published a major review paper on Type IV storms in 1963, based on observations carried out at Dapto over the frequency range 40–70 MHz, between 1952 and 1961. During this period 17 Type IV storms were recorded, highlighting their comparative rarity. Weiss (1963b: 530) found that “The sources of type IV bursts almost invariably exhibit movement at some stage during their lifetimes. The movement may be irregular, or consist of quasi-periodic oscillations about some stable position, or be systematic in time.” Even when there was clear evidence of motion, this was generally small and the average height of Type IV sources was ~ 2.11 solar radii, with little or no difference in position at different frequencies in the 45–65 MHz range. This indicates that the emission cannot result from plasma oscillations, and synchrotron radiation (electrons spiraling in a magnetic field) is the

most likely explanation. Weiss termed these ‘stationary’ Type IV events, and distinguished them from the much rarer ‘moving’ Type IV events, which typically were of shorter duration and were associated with a source that moved rapidly out through the solar corona. Weiss believed it is highly likely that the two different varieties of Type IV event “... are distinct phenomena related only through a common initiating disturbance low in the solar atmosphere.” (Weiss, 1963b: 541).

Indian visitor, Thiruvengkata Krishnan (1934–2019, Fig. 3.22), and RP’s Dick Mullaly (1924–2001; Fig. 2.5) observed a number of Type IV storms with the 1420 MHz Chris Cross at Fleurs and found that at this frequency these events originated in the chromosphere or lower corona, and did not exhibit any obvious motion outwards from the Sun. The sizes of the emitting regions were also small at this frequency, measuring just 2–5 arcsec in diameter. Don McLean noted that Type IV storms almost always were associated with major solar flares and that they were followed by geomagnetic storms. With the advent of the Culgoora Radioheliograph and real-time television-like images of solar events, Paul Wild and his colleagues would come to realise that their earlier ideas about Type IV events were over-simplified. This sophisticated new radio telescope gave a completely new picture of Type IV bursts and showed that they were not one type but rather a range of different phenomena.

Type V bursts were first described by Wild, Kevin Sheridan (Biobox 3.5) and Gil Trent, and by Alan Neylan (d. 2015), in 1959 on the basis of spectral observations at 40–240 MHz made at Dapto in 1957 and 1958. Wild, Sheridan and Neylan (1959a: 393) pointed out that “In some cases the emission appears merely as a diffuse prolongation of the type III burst, in others as a detached blob or patchiness.” In a sample of 27 Type V bursts, Neylan found that 20 of them (i.e. 74%) were associated with bursts that occurred nearly simultaneously at between 1000 and 9400 MHz (whereas the great majority of ‘standard’ Type III bursts (96.2%) were unaccompanied by emission at these higher frequencies), so this association with higher frequency emission can be regarded as a diagnostic feature of these bursts. But as with Type III events, most Type

Fig. 3.22 Indian solar astronomer Thiruvengkata Krishnan (right) with Chris Christiansen at the Fleurs field station (courtesy: Krishnan collection; all rights reserved)

V bursts were associated with flares, particularly what Giovanelli (1958) termed ‘flare puffs’. Several Type V bursts investigated by Wild, Sheridan and Trent (1959b: 182) exhibited outward motion, at velocities ~ 3000 km/s, and they noted that “... while the duration, intensity, and frequency range of these enhancements differ markedly from those of the type IV bursts, their transverse motion appears to be similar.” Alan Weiss and Ron Stewart later revised this figure downwards to ~ 2000 km/s. Moreover, “... at the start of the burst the type V source does not, in general, coincide in position with the associated type III source.” (Weiss and Stewart, 1965: 147). There is no evidence of harmonic structure and Type V bursts are, at most, weakly polarised. In explaining the origin of a Type V burst, Weiss and Stewart tentatively suggested that part of the cloud of electrons that generates the associated Type III burst is trapped in the corona, and it is these electrons which cause the plasma oscillations that produce the Type V emission. Much harder to explain are the rarer detached Type V bursts.

Sometimes when data from the Dapto radiospectrographs, the position interferometer and the solar polarimeter were combined they showed that what at first sight might seem to be simple solar events were in fact exceptionally complex. For example, a Type III event might be followed in quick succession by a Type V burst, a Type II outburst and a Type IV storm. By pooling the various Dapto data, the RP

Biobox 3.5: Kevin Sheridan

Kevin V. Sheridan (Fig. 3.23) was born in Brisbane on 4 August 1918 and died in Sydney in 2010. He received a BA in mathematics from the University of Sydney, and BSc and DSc degrees from the University of Queensland. In 1945 he joined the Radiophysics Lab and after working on aircraft distance measuring equipment, Joe Pawsey invited him to join the radio astronomy group, where he became involved in the design, construction and early use of the Mills Cross at Fleurs.

Fig. 3.23 Kevin Sheridan specialised in the design and development of instruments for solar radio astronomy (courtesy: CRAIA)

(continued)

Biobox 3.5 (continued)

Sheridan then became a leading member of the solar group, and played a key role in the development of the Dapto radiospectrographs and swept-frequency interferometer at the Dapto field station. Kevin's contribution to the design and development of the Culgoora Radioheliograph in northern NSW was central to the success of the instrument. In a review of the Radioheliograph, Paul Wild wrote: "I should acknowledge in particular the instrumental work of Kevin Sheridan (without whom the thing would never have worked)." (Wild, 1974: 3).

From 1978 until his retirement in 1983 Sheridan was head of the RP solar group. In 1966 he was appointed the Foundation Secretary of the newly-formed Astronomical Society of Australia. Kevin was made a Member of the Order of Australia (AM) in 1984 for his significant service to radio astronomy.

radio astronomers were able to investigate the spectral signatures of these events, and temporal variations in source position and size, in polarisation and in total intensity of the emission.

3.1.4 *Studies of the 'quiet Sun' at Potts Hill*

When single-frequency observations were carried out at frequencies well above the initial upper limit of the Dapto radiospectrograph (i.e. 210 MHz), few solar bursts were found to be present, the notable exceptions being Type II outbursts and some Type IV storms. Instead, observations during the early 1950s with Christiansen's grating arrays at the Potts Hill field station revealed the existence of localised regions of enhanced emission, which were located in the chromosphere and lower corona and survived for one or sometimes two or even three solar rotations. Spectrohelioscopic observations carried out concurrently at Potts Hill showed that these radio-active regions usually were situated above large sunspot groups and chromospheric hydrogen and calcium plage regions, and so they were assigned the name 'radio plages'. The daily motion of these radio plages reflected the rotation of the Sun (e.g. see Fig. 3.24). We now know that these radio plages are responsible for the slowly-varying component of solar radiation.

Chris Christiansen and Don Mathewson (b. 1929; Fig. 3.25) presented the 'latest word' on these radio plages at the 1958 Paris Symposium on Radio Astronomy and in a multi-authored paper published in the *Annales d'Astrophysique* (Christiansen et al., 1960). But it was only with the construction of the innovative Chris Cross at Fleurs that it became possible to obtain precise two-dimensional data on these features and confirm their chromospheric associations (e.g. see Fig. 3.26). From 1957, the advent of daily 1420 MHz solar maps allowed the Fleurs radio astronomers to

Fig. 3.24 Averaged daily east–west scans of the Sun showing the development and decay of radio plages (courtesy: CRAIA)

Fig. 3.25 Don Mathewson began his career in solar radio astronomy and then in 1958 he began a PhD at Jodrell Bank using the newly completed 250 ft dish. In 1966 he joined the staff at the Mt Stromlo Observatory and became one of the very first radio astronomers to make the transition to optical astronomy. He served as Director of the Observatory from 1977 to 1986 (courtesy: Mt Stromlo and Siding Spring Observatories)

Fig. 3.26 Isophote map of solar radio emission at 1420 MHz, showing its correlation with chromospheric features (courtesy: CRAIA)

Fig. 3.27 A succession of 1420 MHz solar maps obtained at Fleurs in June 1959 (courtesy: CRAIA)

follow the evolution of these radio plagues over the course of a single solar rotation. Fig. 3.27 shows a succession of such solar maps, as published in the IAU's *Quarterly Bulletin on Solar Activity*. Radio plagues have typical diameters of 2–6 arcmin (representing 100,000–300,000 km in actual areal extent), are situated from 30,000 to 100,000 km above the photosphere (with an average height of ~40,000 km), and have peak temperatures of less than 200,000 K up to about 1,600,000 K (with a median value of ~600,000 K). It would appear that these radio plagues physically “...

consist of large clouds of gas (principally hydrogen) ... [that are] much denser than the surrounding atmosphere ... [and] are prevented from dissipating presumably by magnetic fields.” (Christiansen and Mullaly, 1963: 171). The virtual absence of circular polarisation indicates that the emission from these radio plages is thermal in origin.

Not all RP solar researchers were interested in burst emission or active regions. Some were interested in determining the nature of the ‘quiet Sun’ – its quiescent level when burst emission and radio-active regions were absent. Harry Minnett and Norman Labrum (Fig. 3.28) were able to reflect on this back in 1948 when they analysed data from the 1 November solar eclipse. They concluded that the solar radiation received at 9400 MHz could be explained in terms of two quite different models: (1) that 74% of the radio emission came from the Sun’s visible disk, with the balance from a bright ring around the circumference; or (2) all radiation came from a uniform disk with a diameter 1.1 times that of the optical Sun.

The first alternative suggested that at 9400 MHz the Sun exhibited ‘limb-brightening’, in marked contrast to the distinctive ‘limb-darkening’ observed at optical wavelengths, so this proposition was easy to test. Chris Christiansen and Joe Warburton (1923–2005) began by superimposing numbers of east–west scans obtained with the 32-element solar grating array at Potts Hill over a nine month period (Fig. 3.29). By ignoring all active regions and isolating the common lower envelopes of these accumulated curves, they were able to derive a mean profile of the ‘quiet Sun’ which supported the limb-brightening proposition (Christiansen and Warburton, 1953a, 1953b). Their results were consistent with those developed earlier by their RP colleague, Steve Smerd (Biobox 3.6), on the basis of theoretical considerations.

With the advent of the second (16-element) Potts Hill grating array, Christiansen and Warburton (1955) were able to synthesise ‘processed’ north–south and east–west scans obtained between 1952 and 1954 and derive “... a two-dimensional brightness distribution of the “quiet” Sun ...” at 1420 MHz (see also Christiansen et al., 1957). The resulting radio isophote plot (Fig. 3.31) shows clear pictorial

Fig. 3.28 Norm Labrum had a long career at RP working mostly on solar radio emission, culminating in the comprehensive and highly-regarded book *Solar Radiophysics*, which he co-edited with Don McLean (see McLean and Labrum, 1985) (courtesy: CRAIA)

Fig. 3.29 Superimposed east–west scans of the Sun at 1420 MHz obtained with the original Potts Hill grating array in 1952 (after Christiansen and Warburton, 1953a: 200)

Biobox 3.6: Steve Smerd

Stefan Frederick Smerd (Fig. 3.30) was born in Austria in 1916. He studied physics at the Technische Hochschule in Vienna before fleeing from the Nazis in 1938 and moving to England. In 1942 he completed a BSc at the University of Liverpool, and spent the remainder of WWII working in the microwave magnetron laboratory at the University of Birmingham and at the Admiralty Signals Establishment.

Fig. 3.30 Steve Smerd was the resident theorist in the RP solar group (courtesy: CRAIA)

(continued)

Biobox 3.6 (continued)

In 1946 Smerd joined the Radiophysics Lab, first working in the valve group, and then in early 1947 he became a member of the solar group with responsibility for theoretical issues relating to the solar observations. Steve rapidly gained an international reputation for his work on thermal processes in the ‘quiet Sun’, and for his research on the extremely energetic non-thermal phenomena associated with solar disturbances. Joe Pawsey referred to Steve as a ‘walking encyclopaedia’ on the subject. Smerd went on to establish a world data centre for solar radio emission during the International Geophysical Year (1957–58) and he became an active member of the International Astronomical Union.

In 1971 Smerd succeeded his long-term colleague Paul Wild as head of the solar group and Director of the solar observatory at Culgoora. Steve and his guitar were always welcome at RP parties and other functions (see Fig. 2.51). He died in December 1978 during heart surgery. For an entertaining biography see Wild (1980); see also Orchiston (2014b) and Robertson (2002).

Fig. 3.31 Isophote map of the ‘quiet Sun’ at 1420 MHz in 1952–53, together with a photograph of the solar corona (after Christiansen and Warburton, 1955: 482 and Plate 2)

evidence of limb-brightening. Moreover, the radio Sun is seen to be non-circular, confirming the earlier suspicions of both optical and radio researchers, with the limb-brightening confined to the near-equatorial regions. Christiansen and Warburton cautioned that these results were obtained from observations taken at or near sunspot minimum; given that the 1420 MHz emission derived in the main from the corona, it was reasonable to assume that the temporal changes in the brightness distribution would occur in the course of a sunspot cycle as the form and extent of

the (optical) corona underwent change. Nevertheless, Christiansen regarded the 1955 paper as particularly important given that “[We] got this earth-rotational synthesis put down [in print]. And it was also very important as ... it hadn’t been suspected that it [limb brightening] would only be a purely equatorial effect ... This was quite a new sort of thing.” (Christiansen, 1976).

In 1958, near sunspot maximum, Norm Labrum used the Chris Cross to test Christiansen and Warburton’s proposition that the solar brightness distribution at 1420 MHz should change in the course of a solar cycle. Data derived from north–south strip scans of the Sun and from daily isophote maps both produced similar results: an apparent disk temperature of $\sim 140,000$ K, or twice the value obtained at sunspot minimum. Even more surprising, Labrum (1960: 700) found that “There is limb darkening at the poles, and the distribution does not appear to have changed in shape between sunspot minimum (1953) and the time of the present series of observations.” Visiting Indian radio astronomer T. Krishnan and Labrum (1961) confirmed this conclusion in a later paper, where they combined data obtained using a radiometer and the Chris Cross during the partial solar eclipse of 8 April 1959. Further information about solar research carried out using the Chris Cross is provided by Orchiston and Mathewson (2009).

One final aspect of RP’s solar research program should be mentioned. Between 1957 and 1960, Bruce Slee used the north–south arm of the Mills Cross (Fig. 2.59) and a number of antennas at remote sites to investigate the outer solar corona and the solar wind. Interference fringes associated with 13 discrete sources were examined as they passed close to the Sun with a view to establishing the extent of coronal scattering. He found that “Sporadic large increases in the scattering first became noticeable when the angular separation was as much as $100R_{\odot}$ and at separations of less than $60R_{\odot}$ the effects of scattering could be detected on every record.” (Slee, 1961: 225). These findings are illustrated graphically in Fig. 3.32.

Two RP staff, Jack Piddington and Steve Smerd, were primarily theoreticians, and used their knowledge and mathematical skills to investigate the nature of the Sun’s atmosphere. Piddington was particularly proud of the first paper he published in this area, which appeared in the prestigious *Proceedings of the Royal Society* in 1950. Titled, ‘The derivation of a model solar chromosphere from radio data’, this was

... the first model that used the radio data ... With the other models being developed [by other researchers] if you tested them with the radio data you immediately found that they failed dismally ... [My model] caused a moderate stir in those days amongst the theorists.” (Piddington, 1978).

In reflecting on the success of RP’s solar work and its pre-eminent status in world radio astronomy during the 1940s through to the 1970s, Steve Smerd remarked:

Wild built up a group which was quite unusual compared to all the other research teams I have seen. I think our Solar Group under Paul was perhaps the happiest, frictionless collection of people you can imagine. We were keen and dedicated and would have done anything that Paul even half-mentioned or suggested, let alone explicitly asked. (Smerd, 1978).

This beautifully summarises the ethos of the RP Solar Group in the 1960s, when one of the authors of this book (WO) enjoyed several years as a junior member of its ranks.

Fig. 3.32 Evidence of coronal scattering is indicated by the closed circles, and is primarily restricted to the region enclosed by the dashed line. The Sun is marked by the cross at centre, and the concentric circles are at 20 solar radii intervals (after Slee, 1961: 227)

3.2 The Moon

The Sun was not the only body in our Solar System to interest the RP radio astronomers. Back in the 1950s, the Moon and Jupiter were also known to emit radio waves, and both were targets of research.

Three different lunar astronomy programs were carried out by RP staff during the field stations era, although only two of these were associated with field stations. All three projects were short-lived, and two took place in the year 1948 and were probably inspired by the appearance of a paper by Robert H. Dicke (1916–1997) and Robert Beringer in the *Astrophysical Journal* (Dicke and Beringer, 1946). In this paper the two Americans reported observing the Moon at a frequency of 24 GHz, and deriving a disk temperature of 292 K. Two years later, Jack Piddington

(Biobox 3.7) and Harry Minnett (Biobox 3.8) noted that lunar temperature varied according to phase, and that Dicke and Beringer's value therefore required a correction factor, which produced a corrected figure of 270 K.

Piddington and Minnett then decided to investigate the Dicke and Beringer result empirically, and between April and July 1948 they carried out observations at an identical frequency with a small radio telescope mounted on the 'Eagle's Nest', atop the Radiophysics Lab (Fig. 2.9). They expected that the radio emission would directly mimic the lunar phase, but to their surprise it did not. Years later Minnett (1978) was to reflect on this: "It was a strange thing and that got us excited straight away. It had this phase lag of three days." They ended up making observations over three lunar cycles, which yielded a temperature of 234 K for subsurface layers of the Moon's crust. These results were consistent with the existence of a thin layer of dust covering the solid lunar

Biobox 3.7: Jack Piddington

Jack Hobart Piddington (Fig. 3.33) was born in Wagga Wagga, New South Wales, on 6 November 1910 and died in Sydney on 16 July 1997. He completed a combined BE–BSc degree (for which he was awarded the University Medal), an MSc degree at the University of Sydney, and in 1938 a PhD on ionospheric work, under Edward Appleton, at Cambridge. Upon joining the Radiophysics Lab in 1939, he worked on the wartime development of radar – including units suitable for tropical climates (see Fig. 1.7).

After the War Piddington worked initially on distance measuring equipment for civilian aviation before transferring to the radio astronomy group. Over the next two decades he made valuable contributions to observational

Fig. 3.33 Jack Piddington was best known for his work on theoretical problems in radio astronomy (courtesy: CRAIA)

(continued)

Biobox 3.7 (continued)

radio astronomy, including the discovery with Harry Minnett of the intense source Sagittarius A at the centre of our Galaxy (see next chapter). However, Jack was best known for his theoretical contributions to our understanding of a range of astronomical phenomena. In 1967 he transferred to the CSIRO Division of Physics and was promoted to Chief Research Scientist.

Piddington received the Syme Medal from the University of Melbourne in 1958 and the T.K. Sidey Medal from the Royal Society of New Zealand the following year. He was a Visiting Professor at the Universities of Maryland (1960) and Iowa (1967) and was elected a Fellow of the Royal Astronomical Society. Apart from his numerous research papers, Jack was also known for his books, *Radio Astronomy* (1961) and *Cosmic Electrodynamics* (1969, 1981). For further details see Melrose and Minnett (1998) and Orchiston (2014c).

Biobox 3.8: Harry Minnett

Harry Clive Minnett (Fig. 3.34) was born in Hurstville, Sydney on 12 June 1917 and died in Sydney on 20 December 2003. After completing a BSc–BE double degree at the University of Sydney in 1939, he accepted a post at the newly-formed Radiophysics Lab, where he worked on wartime radar developments. After the war he carried out lunar and solar research in collaboration with Jack Piddington. They were the first to detect the intense radio source Sagittarius A, shown later to be the centre of our Galaxy. Harry also worked on radio navigational aids for civilian aircraft and a traffic radar system for the police force (Fig. 1.10).

Fig. 3.34 In 1978 Harry Minnett became the fifth Chief of Radiophysics, following on from Paul Wild (courtesy: CRAIA)

(continued)

Biobox 3.8 (continued)

Following the decision in 1954 to construct the Parkes Radio Telescope, Minnett spent four years in London liaising with the firm of Freeman Fox on the planning and design of the instrument. Once it was built he was responsible for surveying the surface of the dish and overseeing its subsequent upgrades. He also spent two years in Canberra on secondment as project manager for the design and construction of the optical 3.9 m Anglo-Australian Telescope. After returning to Radiophysics, Harry worked on the Interscan Microwave Landing System, and from 1978 to 1981 he was Chief of the Division. Following his retirement, Harry continued to take an interest in Radiophysics and its successor, the Australia Telescope National Facility, proudly presenting a paper on ‘Fifty Years of Radio Science and its Applications’ at the IAU General Assembly in Sydney in 2003. For further details see Orchiston (2014d) and Thomas and Robinson (2005).

surface, and this interpretation was confirmed in person by the Apollo 11 astronauts 21 years later. In September 1950, two years after their initial study, Piddington and Minnett recorded lunar emission at 1210 and 3000 MHz from Potts Hill, obtaining values of 212 ± 64 K and 215 ± 65 K respectively for the apparent disk temperature.

In a very different project, Frank Kerr (1918–2000) and Alex Shain (1922–1960; Fig. 2.28) decided to bounce radar signals off the Moon in order to investigate properties of the Earth’s upper atmosphere. Like Piddington and Minnett, they too were responding to earlier American experiments, reported in the April 1946 issue of *Electronics*, in which engineers from the US Army Signal Corps had successfully recorded radar signals bounced off the Moon. However, the Americans found large variations in signal strength with time, presumably of ionospheric origin, and it was this feature that attracted Kerr and Shain. Their experiment was carried out in 1948–49 using the signals broadcast at 21.54 and 17.84 MHz from a ‘Radio Australia’ station at Shepparton, Victoria, and received at RP’s Hornsby Valley field station. Thirty different experiments were carried out over a year, and echoes were received on 24 occasions (Fig. 3.35). From our viewpoint, the interesting part of their reports, published in *Nature* (Kerr et al., 1949) and subsequently in *Proceedings of the Institute of Radio Engineers* (Kerr and Shain, 1951), is the conclusion that they drew regarding the nature of the lunar surface. Kerr and Shain found the radar echoes showed two types of fading, one due to ionospheric effects, and the other as a result of the Moon’s libration. This fact, together with the elongation of short pulses on reflection, showed that the Moon’s rocky surface was ‘rough’ rather than smooth on scales of tens of metres.

After undertaking the Moon-bounce experiment, Kerr (1971) spent a year “... studying and writing up all the Moon work and also thinking about possibilities of echoes from the Sun and other planets.” He published his calculations and ideas about doing radar far beyond the Moon in the *Proceedings of the Institute of Radio Engineers* (Kerr, 1952), and since it was the first paper ever written on this topic he later came to regard it as a classic. RP scientists, however, decided not to do any

Fig. 3.35 Three successive Moon echoes, showing rapid fading due to libration (the slow rotation of the Moon on its axis) (after Kerr and Shain, 1951: 232)

further radar astronomy “... because it was quite clear that it would involve building a pretty expensive transmitter and antenna system.” (Kerr, 1971). Funding for major projects like this would always be a problem within the limited RP budget.

3.3 Jupiter

In 1955 American radio astronomers, Bernie Burke (1928–2018) and Ken Franklin (1923–2007), surprised the astronomical world by reporting the existence of Jovian bursts at the low frequency of 22 MHz (Franklin, 1984). Although RP scientist Alex Shain and colleague Charlie Higgins were quick to report confirmatory observations, this serendipitous discovery of radio emission from Jupiter was one of RP’s most notable ‘lost opportunities’. Back in 1950–51, Shain and Higgins were at Hornsby Valley investigating Galactic emission at 18.3 MHz, and on various occasions they recorded intervals of intense static (Fig. 3.36) which they attributed to terrestrial interference – or so it seemed at the time. Immediately following the Burke and Franklin announcement, Shain revisited the 1950–51 records and discovered that some of their episodes of ‘interference’ occurred when Jupiter was within the beam of their radio telescope. Furthermore, when the occurrence of these bursts was plotted against Jupiter’s rotation period (of just under 10 hours) he noticed that they were not uniformly distributed in Jovian longitude but instead clustered between 0° and 135° (see Fig. 3.37). In other words, the radiation seemed to come from a localised region of the planet with a period of rotation of $9\text{h } 55\text{m } 13 \pm 5\text{s}$, remarkably close to the so-called System II value (Fig. 3.38) based on visual observations.

Shain was intrigued by these bursts. Where did they originate? He began by examining the atmospheric features of Jupiter, and noticed that when the Jovian bursts were recorded in 1950–51 there was a group of visual spots associated with the South Temperate Belt that also rotated in $9\text{h } 55\text{m } 13\text{s}$ – precisely the same as the radio source. Could these be the cause of the radio bursts, and if so, what kind of

Fig. 3.36 Examples of 18.3 MHz Jovian bursts recorded on 17 October 1950 (above) and 29 October 1950 (below) by Shain and Higgins, five years before Burke and Franklin’s reported discovery (after Shain, 1956: 65)

Fig. 3.37 Occurrence frequency of 18.3 MHz Jovian emission for 5° intervals of longitude and assuming a rotation period of 9h 55m 13s (after Shain, 1956: 68)

emission mechanism was involved? In order to pursue this interesting research challenge further, Shain and Frank Gardner (Biobox 3.9) observed Jupiter between June 1955 and March 1956, using a 19.6 MHz interferometer at Fleurs, and occasionally the newly-constructed east–west arm of the 19.7 MHz Shain Cross (Fig. 2.63). Between November 1955 and March 1956 they also used antennas operating at 14 and 27 MHz at Fleurs, and a small 19.7 MHz antenna located at Potts Hill.

Jovian emission was regularly recorded at 19.6 MHz, generally in the form of groups of bursts that varied rapidly in intensity, with large-scale changes taking place over time intervals as short as 0.2 s. Similar variations characterised bursts observed at 27 MHz, but unlike the 19.6 MHz bursts – which were comparatively common – these were only detected on about 20% of all observing nights. The results at 14 MHz were severely affected by manmade interference, but Jovian bursts also appeared to be far less frequent than at 19.6 MHz. Meanwhile, from

Fig. 3.38 Occurrence of 18.3 MHz Jovian emission plotted against the longitude of the central meridian at the time of the observations. The sloping bars in the left-hand plot indicate the rotation period of the Jovian radio source differs markedly from that of System I, whereas the near-vertical stacking of the bars in the right-hand plot shows it is very similar to System II (after Shain, 1956: 67)

observations at all three frequencies, Gardner and Shain (1958) concluded that peak burst intensity probably occurred at around 20 MHz.

Biobox 3.9: Frank Gardner

Francis Frederick Gardner (Fig. 3.39) was born in Sydney in 1924. He obtained degrees in Science and Electrical Engineering (First Class Honours) from the University of Sydney in 1943 and 1945, before completing a PhD on ionospheric properties at Cambridge University in 1949. He joined the Radiophysics Lab in 1950 and worked on ionospheric research until 1955 when he began investigating Jovian decametric emission at Fleurs and Potts Hill in collaboration with Alex Shain.

Fig. 3.39 Frank Gardner made a major contribution to the list of research successes during the early days of the Parkes Radio Telescope (courtesy: CRAIA)

(continued)

Biobox 3.9 (continued)

In 1957 Frank (known affectionately as ‘FF’) began developing low-noise amplifiers for the Parkes Radio Telescope. From 1962 until his retirement in 1989 he carried out research at Parkes that produced cutting edge results in fields as diverse as the polarisation of Galactic radio emission and interstellar chemistry through molecular line studies. Frank was also a key member of the Parkes team that carried out extensive sky surveys first at 408 MHz and then at 2.7 GHz.

Two of his close colleagues wrote: “Frank was always modest, quiet and unassuming. He was endowed with dry humour and a sense of fun that made working with him anything but boring. These characteristics were enhanced by an uncanny ‘feel’ for microwave engineering ...” (Milne and Whiteoak, 2005). FF died in 2002 at the age of 78.

These findings merely built on those Shain came up with in his analysis of the 1950–51 observations, and when he and Gardner examined the longitude distribution of the 19.6 MHz bursts they found a rotation period for the source of 9h 55m 34s, close to the earlier result (Fig. 3.40). However, when they considered the 19.6 and 27 MHz data separately, these tended to indicate the presence of three different sources: the main one at a Jovian longitude in System II of 0° and two much less active secondary sources at longitudes of –100° and +80°. Furthermore, the apparent correlation between the main source and visual spots in the South Temperate Belt – as suggested by the 1950–51 evidence – was not sustained. In the light of these latest observations, and others made by Burke and Franklin, Shain and Gardner considered the emission mechanism responsible for the bursts and concluded that they were generated by plasma oscillations associated with an ionised region in the atmosphere of Jupiter.

Alex Shain’s intention was to conduct simultaneous radio and optical observations of Jupiter, with a view to investigating any optical features that could conceivably be associated with this emission mechanism, but his untimely death in 1960 put paid to these plans. Instead, it was Bruce Slee and Charlie Higgins who took up the challenge, and during Jupiter’s 1962 opposition they employed long baseline interferometry in order to investigate the identity and nature of the emitting source (or sources). For this project, they used square arrays of 19.7 MHz half-wave dipoles, one located at Fleurs and the other at a remote site, Freeman’s Reach, about 32 km to the north. Their observations showed that the “... angular diameter of a burst source was ... less than a third of the planet’s diameter, and that all bursts contributing to a noise storm originated in a single area less than a half of the size of the planet’s disk.” (Slee and Higgins, 1963: 781–82).

Slee and Higgins decided to move to longer baselines, and in 1963 and 1964 they employed effective spacings between 10 and 200 km. Simple arrays of dipoles at Fleurs and three other sites, Dapto and Jamberoo south of Sydney, and Heaton to the north (see Fig. 2.8), were phased and oriented to receive Jovian emission over an

Fig. 3.40 Occurrence frequency of 19.6 MHz Jovian emission for 5° intervals of longitude and assuming a rotation period of 9h 55m 34s (after Gardner and Shain, 1958: 66)

hour-angle range of ± 4 hr, and a radio link was used to transmit the signals from the remote sites to Fleurs.

Analysis of the observations suggested that the emitting regions were typically 10–15 arcsec in size, but Slee and Higgins concluded that they were probably very much smaller and that scattering in the interplanetary medium gave anomalously large results. This conclusion turned the Jovian decametric project at RP in a new direction: what had started as a quest for emission source size now became an investigation of scattering by the interplanetary medium. Slee and Higgins then used their 1963–64 data on burst arrival times, burst rates, angular position scintillations and apparent angular size to successfully investigate interplanetary diffraction patterns and electron irregularities in the solar wind.

This would mark the final contribution of the Fleurs site to planetary radio astronomy. We now know that the Jovian bursts are associated with spiraling electrons in the magnetic torus that extends from the inner moon, Io, to Jupiter's magnetosphere. They have nothing whatsoever to do with the spots or other features seen in Jupiter's ever-changing atmospheric 'cloud belts'.

References

- Allen, C.W., 1947. Solar radio-noise at 200 Mc/s. and its relation to solar observations. *Monthly Notices of the Royal Astronomical Society*, 107, 386–396.
- Bowen, E.G., 1947. Letter to S.B. Nicholson, dated 21 January. In CSIRO Archives, file A1/3/1a. Sullivan collection.
- Bowen, E.G., 1973. Taped interview with Woody Sullivan, dated 24 December.
- Christiansen, W.N., 1976. Taped interview with Woody Sullivan, dated 27 August.

- Christiansen, W.N., and Mullaly, R.F., 1963. Solar observations at a wavelength of 20 cm with a crossed-grating interferometer. *Proceedings of the Institution of Radio Engineers Australia*, 24, 165–173.
- Christiansen, W.N., and Warburton, J.A., 1953a. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part I. A new highly directional aerial system. *Australian Journal of Physics*, 6, 190–202.
- Christiansen, W.N., and Warburton, J.A., 1953b. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part II. The quiet Sun – one-dimensional observations. *Australian Journal of Physics*, 6, 262–271.
- 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., Warburton, J.A., and Davies, R.D., 1957. The distribution of radio brightness over the solar disk at a wavelength of 21 cm. Part IV. The slowly varying component. *Australian Journal of Physics*, 10, 491–514.
- Christiansen, W.N., Mathewson, D.S., Pawsey, J.L., et al., 1960. A study of a solar active region using combined optical and radio techniques. *Annales d'Astrophysique*, 23, 75–101.
- Christiansen, W.N., Yabsley, D.E., and Mills, B.Y., 1949. 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.
- 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., 2005. 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.
- Débarbat, S., Lequeux, J., and Orchiston, W., 2007. Highlighting the history of French radio astronomy. I: Nordmann’s attempt to observe solar radio emission in 1901. *Journal of Astronomical History and Heritage*, 10, 3–10.
- Denisse, J.-F., 1949. Relation entre les émissions radioélectriques solaires décimétriques et les taches du soleil. *Comptes Rendus de l’Académie des Sciences*, 228, 1571–1572.
- Dicke, R.H., and Beringer, R., 1946. Microwave radiation from the Sun and Moon. *Astrophysical Journal*, 103, 375.
- Franklin, K.L., 1984. The discovery of Jupiter bursts. In Kellermann, K.I., and Sheets, B. (eds). *Serendipitous Discoveries in Radio Astronomy*. Green Bank (WV), National Radio Astronomy Observatory. Pp. 252–257.
- Gardner, F.F., and Shain, C.A., 1958. Further observations of radio emission from the planet Jupiter. *Australian Journal of Physics*, 11, 55–69.
- Giovanelli, R.G., 1958. Flare-puffs as a cause of Type III radio bursts. *Australian Journal of Physics*, 11, 350–352.
- Harris, M., 2017. *Rocks, Radio and Radar: The Extraordinary Scientific, Social and Military Life of Elizabeth Alexander*. New Jersey, World Scientific.
- Haynes, R., Haynes, R., Malin, D., and McGee, R., 1996. *Explorers of the Southern Sky. A History of Australian Astronomy*. Cambridge, Cambridge University Press.
- Hey, J.S., 1946. Solar radiations in the 4–6 metre radio wave-length band. *Nature*, 157, 47–48.
- Kerr, F.J., 1952. On the possibility of obtaining radar echoes from the Sun and planets. *Proceedings of the Institute of Radio Engineers*, 40, 660–666.
- Kerr, F.J., 1971. Taped interview with Woody Sullivan, dated 3 October.
- Kerr, F.J., and Shain, C.A., 1951. Moon echoes and transmission through the ionosphere. *Proceedings of the Institute of Radio Engineers*, 39, 230–242.
- Kerr, F.J., Shain, C.A., and Higgins, C.S., 1949. Moon echoes and penetration of the ionosphere. *Nature*, 163, 310–313.

- Krishnan, T., and Labrum, N.R., 1961. The radio brightness distribution on the Sun at 21 cm from combined eclipse and pencil-beam observations. *Australian Journal of Physics*, 14, 403–419.
- Labrum, N.R., 1960. The radio brightness of the quiet Sun at 21 cm wavelength near sunspot maximum. *Australian Journal of Physics*, 13, 700–711.
- 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.
- Little, A.G., and Payne-Scott, R., 1951. The position and movement on the solar disk of sources of radiation at a frequency of 97 Mc/s. *Australian Journal of Scientific Research*, A4, 489–507.
- 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.
- McLean, D.J., and Labrum, N.R. (eds), 1985. *Solar Radiophysics – Studies of Emission from the Sun at Metre Wavelengths*. Cambridge, Cambridge University Press.
- McNally, D., 1990. Obituary. C.W. Allen (1904–1987). *Quarterly Journal of the Royal Astronomical Society*, 31, 259–266.
- Martyn, D.F., 1946. Polarisation of solar radio-frequency emissions. *Nature*, 158, 308.
- Melrose, D.B., and Minnett, H.C., 1998. Jack Hobart Piddington 1910–1997. *Historical Records of Australian Science*, 12, 229–246.
- Mills, B.Y., 1976. Taped interview with Woody Sullivan, dated 25 August.
- Milne, D.K., and Whiteoak, J.B., 2005. The impact of F.F. Gardner on our early research with the Parkes Radio Telescope. *Journal of Astronomical History and Heritage*, 8, 33–38.
- Minnett, H.C., 1978. Taped interview with Woody Sullivan, dated 2 March.
- 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. The 1948 solar eclipse and the genesis of radio astronomy in Victoria. *Journal of Astronomical History and Heritage*, 7, 118–121.
- Orchiston, W., 2005. Dr Elizabeth Alexander: first female radio astronomer. In Orchiston, W. (ed.). *The New Astronomy: Opening the Electromagnetic Window and Expanding Our View of Planet Earth*. Dordrecht, Springer. Pp. 71–92.
- Orchiston, W., 2014a. Martyn, David Forbes. In Hockey, T. et al. (eds.). *Biographical Encyclopedia of Astronomers. Second Edition*. New York, Springer. Pp. 1405–1406.
- Orchiston, W., 2014b. Smerd, Stefan Friedrich. In Hockey, T. et al. (eds.). *Biographical Encyclopedia of Astronomers. Second Edition*. New York, Springer. Pp. 2019–2020.
- Orchiston, W., 2014c. Piddington, Jack Hobart. In Hockey, T. et al. (eds.). *Biographical Encyclopedia of Astronomers. Second Edition*. New York, Springer. Pp. 1714–1715.
- Orchiston, W., 2014d. Minnett, Harry Clive. In Hockey, T. et al. (eds.). *Biographical Encyclopedia of Astronomers. Second Edition*. New York, Springer. Pp. 1495–1496.
- Orchiston, W., 2016. Elizabeth Alexander and the mysterious ‘Norfolk Island Effect’. In Orchiston, W. (ed.). *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits*. Cham (Switzerland), Springer. Pp. 629–651.
- Orchiston, W., and Mathewson, D., 2009. Chris Christiansen and the Chris Cross. *Journal of Astronomical History and Heritage*, 12, 11–32.
- Orchiston, W., and Slee, B., 2002. The Australasian discovery of solar radio emission. *AAO Newsletter*, 101, 25–27.
- 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., Sim, H., and Robertson, P., 2016. Dr Owen Bruce Slee, 10 August 1924 – 18 August 2016. *Australian Physics*, 53, 214.
- Orchiston, W., Slee, B., and Burman, R., 2006. The genesis of solar radio astronomy in Australia. *Journal of Astronomical History and Heritage*, 9, 35–56.

- Pawsey, J.L., 1946. Observation of million degree radiation from the Sun at a wavelength of 1.5 metres. *Nature*, 158, 633.
- Pawsey, J.L., 1950. Solar radio-frequency emission. *Proceedings of the Institution of Electrical Engineers*, 97, 290–310.
- Pawsey, J.L., Payne-Scott, R., and McCready, L.L., 1946. Radio-frequency energy from the Sun. *Nature*, 157, 158–159.
- Payne-Scott, R., 1949. Bursts of solar radiation at metre wavelengths. *Australian Journal of Scientific Research*, A2, 214–227.
- Payne-Scott, R., and Little, A.G., 1951. The position and movement on the solar disk of sources of radiation at a frequency of 97 Mc/s. *Australian Journal of Scientific Research*, A4, 508–525.
- Payne-Scott, R., Yabsley, D.E., and Bolton, J.G., 1947. Relative times of arrival of bursts of solar noise at different radio frequencies. *Nature*, 160, 256–257.
- Piddington, J.H., 1978. Taped interview with Woody Sullivan, dated 13 March.
- Piddington, J.H., and Oliphant, M.L., 1972. David Forbes Martyn. *Records of the Australian Academy of Science*, 2(2), 47–60.
- Reber, G., 1944. Cosmic static. *The Astrophysical Journal*, 100, 279–287.
- Roberts, J., 1959. Some aspects of Type II bursts. In Bracewell, R. (ed.). *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press. Pp. 194–200.
- Robertson, P., 2002. Stefan Friedrich Smerd (1916–1978): CSIRO solar physicist. In Ritchie, J. (ed.). *Australian Dictionary of Biography, Volume 16*. Melbourne, Melbourne University Press. P. 266.
- Shain, C.A., 1956. 18.3 Mc/s radiation from Jupiter. *Australian Journal of Physics*, 9, 61–73.
- Slee, O.B., 1961. Observations of the solar corona out to 100 solar radii. *Monthly Notices of the Royal Astronomical Society*, 123, 223–231.
- Slee, O.B., and Higgins, C.S., 1963. Long baseline interferometry of Jovian decametric radio bursts. *Nature*, 197, 781–782.
- Smerd, S., 1978. Taped interview with Woody Sullivan, dated 6 March.
- Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2011a. A retrospective view of Australian solar radio astronomy 1945 to 1960. In Orchiston, W. et al., 2011. Pp. 589–629.
- Stewart, R., Orchiston, W., and Slee, B., 2011b. The Sun has set on a brilliant mind: John Paul Wild (1923–2008), solar radio astronomer extraordinaire. In Orchiston, W. et al., 2011. Pp. 527–542.
- Stewart, R., Wendt, H., Orchiston, W., and Slee, B., 2010. The Radiophysics field station at Penrith, New South Wales, and the world's first solar radio spectrograph. *Journal of Astronomical History and Heritage*, 13, 2–15.
- Sullivan, W.T., 1982. *Classics in Radio Astronomy*. Cambridge, Cambridge University Press.
- Sullivan, W.T., 2009. *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge, Cambridge University Press.
- Thomas, B.M., and Robinson, B.J., 2005. Harry Clive Minnett, 1917–2003. *Historical Records of Australian Science*, 16, 199–220.
- Weiss, A.A., 1963a. The positions and movements of the sources of solar radio bursts of spectral Type II. *Australian Journal of Physics*, 16, 240–271.
- Weiss, A.A., 1963b. The Type IV solar radio burst at metre wavelengths. *Australian Journal of Physics*, 16, 526–544.
- Weiss, A.A., and Stewart, R.T., 1965. Solar radio bursts of spectral type V. *Australian Journal of Physics*, 18, 143–165.
- Wendt, H., and Orchiston, W., 2018. The contribution of the AN/TPS-3 radar antenna to Australian radio astronomy. *Journal of Astronomical History and Heritage*, 21, 65–80.
- Wendt, H., Orchiston, W., and Slee, B., 2008. The Australian solar eclipse expeditions of 1947 and 1949. *Journal of Astronomical History and Heritage*, 11, 71–78.
- Wild, J.P., 1953. Techniques for observation of radio-frequency radiation from the Sun. In Kuiper, G.P. (ed.). *The Solar System. Volume 1. The Sun*. Chicago, University of Chicago Press. Pp. 676–692.

- Wild, J.P., 1957. Spectral observations of solar activity at metre wavelengths. In Hulst, H.C. van de (ed.). *Radio Astronomy*. Cambridge, Cambridge University Press. Pp. 321–326.
- Wild, J.P., 1974. A new look at the Sun. In Contopoulos, G. (ed.). *Highlights of Astronomy*, Volume 3. Dordrecht, Reidel. Pp. 3–19.
- Wild, J.P., 1978. Taped interview with Woody Sullivan, dated 3 March.
- 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.
- Wild, J.P., and McCready, L.L., 1950. Observations of the spectrum of high-intensity solar radiation at metre wavelengths. I. The apparatus and spectral types of solar bursts observed. *Australian Journal of Scientific Research*, A3, 387–396.
- Wild, J.P., Sheridan, K.V., and Neylan, A.A., 1959a. An investigation of the speed of the solar disturbances responsible for Type III radio bursts. *Australian Journal of Physics*, 12, 369–398.
- Wild, J.P., Sheridan, K.V., and Trent, G.H., 1959b. The transverse motions of the sources of solar radio bursts. In Bracewell, R. (ed.). *Paris Symposium on Radio Astronomy*. Stanford, Stanford University Press. Pp. 176–185.

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