Chapter 5

Where did it all Lead?

5.1 Beyond the Doors of Radiophysics

At the end of World War II it would have been impossible to have foreseen the rapid growth of radio astronomy at the Radiophysics Lab. In the space of about five years radio astronomy not only became the dominant research program, but the RP group was easily the largest and most generously funded in the world. The two main rivals to Radiophysics were the Jodrell Bank group at the University of Manchester led by Bernard Lovell and the Cavendish Laboratory at Cambridge University led by Martin Ryle. However, both these English groups were relatively small sections within their University's physics departments and, with the post-war austerity in England, both groups operated on shoestring budgets. Around 1950, the combined budgets of the Jodrell Bank and Cambridge groups were only a small fraction of the RP radio astronomy budget (see e.g. Robertson, 1992: 131; Sullivan, 2009: 153).

And what of the United States? Even though Karl Jansky, Grote Reber and George Southworth had pioneered the field, the Americans had failed to capitalise on their early lead. It was a curious situation in view of the massive government funding of American science after the war – a level of support that saw international leadership in many fields of science shift from Europe to the United States. The potential for the Americans to add a radio astronomy string to their scientific bow had certainly been there. After the war many of the hundreds of scientists and engineers at the MIT Radiation Lab – the US equivalent of the Radiophysics Lab – returned to academic posts but, oddly, no major radio astronomy group emerged in any of the universities. A number of important, yet isolated discoveries in radio astronomy were made by physicists, most notably the discovery of the 21 cm hydrogen line by Ed Purcell and 'Doc' Ewen at Harvard (see previous chapter), but some of these discoveries never developed beyond interesting sidelines (Sullivan, 1988: 336–338). Perhaps the most significant radio astronomy program carried out in the immediate post-war years was by a group at the Naval Research Laboratory in Washington led by John Hagen and Fred Haddock. The Washington group

constructed a 15 m parabolic dish, at the time the largest in the world, built specifically to operate at wavelengths as short as 1 cm. In addition, from 1948 and during the 1950s a small group of astronomers and electrical engineers at Cornell University developed radio astronomy, and carried out solar, Galactic and extragalactic observations (see Campbell, 2019). As Sullivan (2009: 200–211) has pointed out, Cornell and MIT were the first US universities to mount post-war research programs in radio astronomy.

Mention should also be made of Grote Reber. After joining the National Bureau of Standards in Washington in 1947, he began designing a new telescope with a structure similar to the successful dish at his Wheaton home, but with a projected diameter of 67 m. Reber lobbied hard in Washington circles to get support for the project, but without success. In 1951 he resigned his position and returned to radio astronomy the way he had started, all by himself, first in Hawaii and then in Tasmania. Paradoxically, Reber believed the problem was not a shortage of funds, it was with the American scientists:

The situation was different in the United States. There was tremendous wealth and we could embark on huge projects such as nuclear energy. After the war that's where the real empires were made in science. Instead of tens of thousands of dollars, there were tens of millions to spend. The scientific community was totally mesmerised by these sums of money available to build big machines. Unlike Australia and England, the American scientists simply failed to see the potential in radio astronomy. (Robertson, 1986).

There were two significant events that helped to kick start radio astronomy in the United States. The first was the decision by the newly formed National Science Foundation to sponsor a nationwide symposium on radio astronomy. The symposium was held in Washington in January 1954 and brought together most American researchers in the field, many of whom were concerned that the US had fallen behind in this exciting new field. Taffy Bowen and Bernie Mills attended and 'flew the flag' for Australia. In 1952 there were only six American institutions active in radio astronomy, but by the time of the symposium the number had grown to ten, with several more still deciding whether to take the plunge. With a couple of exceptions all these institutions were universities, and a growing number of them were developing graduate programs in radio astronomy. A handful of Americans had already graduated with PhDs in the subject and there were a lot more on the way. The American giant was awakening. The most important outcome of the Washington meeting was the decision to support the idea of a National Radio Astronomy Observatory which would build and operate a number of large radio telescopes. Rather than individual university departments attempting to build large telescopes for their own use, the federally funded NRAO would do it for them and make the instruments available to the universities. This was a radical idea. Although progress at the national facility proved slower than expected, by the 1970s NRAO had become the powerhouse of world radio astronomy (for a comprehensive history of the NRAO, see Kellermann, Bouton and Brandt, 2020).

The second boost to American radio astronomy came in 1954 with the announcement by the Californian Institute of Technology (Caltech) of its plans to build the world's finest observatory for radio astronomy. The Caltech astronomers in Pasadena already had access to the world's finest collection of optical telescopes on Mt Wilson and Palomar Mountain, so the new radio observatory would be a natural complement. Early in 1955 Caltech recruited John Bolton and Gordon Stanley from Australia to design and build the new observatory at Owens Valley in northern California (Cohen, 1994; Robertson, 2017: Chapter 7). Their departure led to the closure of Dover Heights, which for almost ten years had been one of the most important and successful of the RP field stations.

In addition to the NRAO at Green Bank, West Virginia, and the Caltech group at Owens Valley, a number of other university centres underwent rapid development in the late 1950s including Cornell, Harvard, Illinois, Michigan, Ohio State and Stanford. Most of these groups were in advanced stages of planning a major new instrument for the 1960s. In fact the main problem in the United States was not a shortage of new instruments (or of course funds), but the lack of suitably qualified radio astronomers. One study has estimated that, around 1960, for every American-born radio astronomer there was at least one other from either Radiophysics or Jodrell Bank active in the United States (Edge and Mulkay, 1976). As Hanbury Brown at Jodrell Bank half-joked to Joe Pawsey: "You have the best radio astronomy group in the world – the trouble with being a success is that everyone is after your staff! I do hope you are managing to manufacture some more. We have a good deal of the same trouble here – we lose them to the USA and can never get them back." (Hanbury Brown, 1960).

With the Radiophysics group as the world leader at this time, Australian radio astronomers were naturally in great demand in the United States. Although John Bolton returned to Australia to take charge of the Parkes telescope (see below), Gordon Stanley stayed on and became the Director of the Owens Valley Radio Observatory (Kellermann et al., 2005). Others such as Ron Bracewell (Stanford University) and Frank Kerr (University of Maryland) took up permanent academic posts and founded their own radio astronomy groups (e.g., see Bracewell, 2005). Other RP staff went for extended visits on fellowships and helped to accelerate the growth of radio astronomy in the United States, including Bernie Mills (1954 Caltech), Jim Roberts (1958–60 Owens Valley), Kevin Westfold (1958 Owens Valley), Brian Cooper (1959 Harvard), Don Yabsley (1960–62 Cornell), Alec Little (1963 Stanford) and Dick McGee (1963 Michigan). It would be wrong to label this migration of expertise to the United States as another alarming case of the 'brain-drain' which has adversely affected many other branches of Australian science; for example, the exodus over decades of many of Australia's best young physicists to overseas centres such as the Cavendish Laboratory in Cambridge. On the contrary, here was the first and probably only occasion when a major new science pioneered in Australia played a leading part in promoting the growth of its counterpart in the United States.

5.2 Big Science comes to Australia

Perhaps the single most important event at Radiophysics during the 1950s was the decision to build a Giant Radio Telescope. The decision transformed the future development of radio astronomy in Australia and led to a major upheaval of personnel at Radiophysics. Until then no university department or government research lab in Australia had anywhere near the resources to undertake such an expensive and technologically advanced project. The construction of the Parkes Radio Telescope brought what has been termed ‘Big Science’ to Australia. From the outset the Parkes dish was an international project. Approximately half the funds came from American philanthropic foundations, the design was carried out by a British engineering firm and, after an international tender, the construction was contracted to a German steel company.

During the early 1950s a debate arose within the RP group about where this rapid growth in radio astronomy was heading. Should the Lab continue with a number of small groups, each working independently, or should it begin to focus on one or two large projects that would bring these small groups together? Joe Pawsey and a number of senior staff were in favour of continuing with the status quo, an approach that had brought world acclaim to the Lab. Why make changes to something that was working so well? This approach was entirely consistent with Pawsey’s own background where he completed his PhD at the famous Cavendish Laboratory. He became an advocate of the so-called ‘string and sealing wax’ approach to research at the Cavendish, where innovative solutions to problems could be found using relatively simple and inexpensive equipment.

However, this was not the view of Taffy Bowen, Chief of the Radiophysics Lab (see Fig. 5.1). While Bowen directed the Rainmaking Group and left the day-to-day management of the Radio Astronomy Group to Pawsey, he took a very keen interest in the development of both groups. Bowen and several senior radio astronomers believed that radio astronomy would soon develop in the same way as conventional optical astronomy, where the most important discoveries were made with the largest and most powerful optical telescopes. The event that convinced Bowen that a large general purpose telescope was the way of the future came in 1951 when Bernard Lovell’s group at Jodrell Bank announced plans to build a giant parabolic dish. Bowen feared that the new telescope would scoop the pool of discoveries and that Radiophysics would soon lose its position as a world leader in radio astronomy. Bowen believed that to avoid being left behind, Radiophysics would have to build an instrument at least as good as, if not better than, the Jodrell Bank giant. Although the approach of small semi-autonomous groups at Radiophysics continued until the late 1950s, Bowen’s vision of a Giant Radio Telescope (GRT) eventually prevailed.

The immediate problem Bowen faced was where would the money come from to build a GRT? Radio astronomy was only one of several research projects in the Lab and as Chief he had to work within a fixed annual budget. Similarly, the Radiophysics Lab was only one of a dozen Divisions within CSIRO, all clamouring for more funding to support their expanding post-war research programs. At Jodrell Bank,

Fig. 5.1 Taffy Bowen was the driving force behind the Parkes Radio Telescope. He believed that a giant all-purpose dish would be the best way for the Radiophysics group to stay at the forefront of international radio astronomy [courtesy: CSIRO Radio Astronomy Image Archive (CRAIA)]

Bernard Lovell had received a large grant from the philanthropic Nuffield Foundation to partly fund his large telescope. Lovell had then persuaded the UK's Department of Scientific & Industrial Research to fund the remainder of the projected costs. Bowen realised he would need to explore a similar path, but was faced with the reality that there were no comparable philanthropic foundations in Australia to support scientific research, especially in a new and relatively obscure area such as radio astronomy.

During WWII Bowen had spent several years shuttling back and forth between England and the United States, where he acted as the principal liaison officer coordinating the development of radar in the two countries. Bowen spent much of his time at the MIT Rad Lab near Boston where he got to know many powerful figures in American science, including some who had considerable influence within the network of large US philanthropic organisations. He would draw on this 'old-boy network' to provide the funds to build a GRT in Australia. The breakthrough occurred when Bowen learnt that the Carnegie Corporation administered a special

fund which had been established specifically to support projects within Britain and her Commonwealth countries. Bowen was informed that the trustees of the Fund had decided that, rather than support a range of small projects, they wanted to make one single large grant. Bowen was in the right place at the right time. In May 1954, the Carnegie Corporation announced that it would provide \$US250,000 towards the partial funding of a GRT in Australia. With the Carnegie promise, Bowen's next challenge was to seek funding from the Australian Government. With the support of CSIRO head office, the request went to Richard Casey, the Minister-in-Charge of CSIRO, who in turn discussed the GRT project with Prime Minister Robert Menzies. Although Menzies agreed to match the Carnegie grant with government funds, he insisted that at least one half of the total costs of the project were to be raised from private sources.

By early 1955 it was clear to Bowen that the funds promised would be nowhere near enough to build a GRT to rival the telescope already under construction at Jodrell Bank. Once again he flew to the US to visit a number of other philanthropic foundations. At the Sloan and Ford Foundations he was informed that funding scientific research in another country halfway round the world was not part of the charter of either organisation. His reception at the Rockefeller Foundation was, however, far more positive, helped no doubt by his wartime colleague Lee DuBridge who was an influential member of the Rockefeller Board of Trustees. In December 1955, the Rockefeller Foundation announced that, similar to Carnegie, it too would grant \$US250,000 towards the cost of an Australian GRT. With the Australian Government's pledge to match the US funding, just over \$US1 million was now in hand, enough for the project to proceed.

Immediately after the announcement of the Carnegie grant in May 1954, Bowen established a GRT Planning Committee consisting of senior Radiophysics staff and external engineering experts. The committee's brief was to invite organisations to submit design concepts and then to assess their viability. Various designs were received from a number of engineering firms in Australia and overseas, including one from the renowned American inventor Buckminster Fuller. For all the ingenuity of these designs (see Fig. 1.20), the real breakthrough in the design of the GRT came about by accident. During a trip to London in 1955 Bowen was introduced to Barnes Wallis, the leading British aeronautical engineer (Fig. 5.2). He was the designer of aircraft such as the famous Wellington bomber, which became the RAF's workhorse during WWII. Over lunch one day Bowen discussed with Wallis the GRT planned for Australia. Wallis immediately came up with a few ideas and agreed to work on a design concept. The plan was then to use Wallis' ideas and carry out the detailed design of the telescope in Australia, but it became clear that there were no local firms with sufficient experience or expertise. After several engineering firms in the UK were invited to bid, Freeman Fox & Partners in London were chosen for the detailed design. The firm specialised in the design of bridges and in fact it was the firm's founder, Sir Ralph Freeman, who designed the famous Sydney Harbour Bridge in Australia.

Fig. 5.2 Britain's leading aeronautical engineer Barnes Wallis carried out the initial design study for the Australian Giant Radio Telescope and most of his innovative ideas were incorporated into the final design. Based on the funds available, the engineering firm of Freeman Fox chose a dish diameter of 64 m (210 ft). Although this was less than the 76 m diameter of the Jodrell Bank dish, the greater surface and pointing accuracies made the Australian dish a superior instrument (courtesy: Vickers London and CRAIA; all rights reserved)

Throughout the planning of the GRT, Bowen and the Radiophysics group followed the progress of the telescope at Jodrell Bank with great interest. Early in the project Lovell made a number of design changes in an attempt to improve its performance. The major change, following the discovery of the hydrogen line in 1951, was the decision to operate down to a 21 cm wavelength, compared with the previous metre-wavelength lower limit. This meant finer, and heavier, mesh surface panels and the need to strengthen the support structure. The various changes led to delays in the project, contractual problems with suppliers and, worst of all, a massive cost blow out (Lovell, 1968). The Australians learnt a lesson from Lovell's troubles. Jodrell Bank had been designed in relative haste and took over five years to build. In contrast, Parkes took three years to design, but only two years to build.

The selection of the site near Parkes in central New South Wales for the new telescope took the best part of four years to settle. Preliminary discussions on a suitable site began in mid-1954 and by early 1956 a list of over thirty possible locations had been compiled. Several technical requirements were taken into consideration in shortlisting a site. The ideal location would need to be geologically stable to provide a solid foundation capable of supporting a structure weighing close to 2000 tonnes. The site would also need to have a mild climate free from ice and snow, with a low average windspeed all year round. Above all, the site had to offer a very low level of radio interference. To add to his troubles at Jodrell Bank, Lovell had been drawn into a long battle trying to persuade a local electricity authority to reroute a new high-voltage line away from the site.

While Cheshire – where Jodrell Bank was located – proved an uncomfortably noisy part of England, it was clear that a country as large and as sparsely populated as Australia would have no shortage of sites free of radio noise, and which would also meet the other geological and meteorological requirements. Although for a time a site near Canberra was in the mix, the issue settled down into a two-way contest – a site close to Sydney, or one ‘over the mountains’ well to the west of Sydney. A site close to Sydney had the strong advantage of convenience. From the beginning, most of the RP field stations had been no more than an hours’ drive away. Staff had grown accustomed to a pattern of frequent, often daily visits to and from home to carry out their observing programs. For these reasons most of the sites examined initially fell within a comfortable radius of Sydney, the best candidate to emerge being an area known as Cliffvale, at the foot of the Blue Mountains, 80 km south-west of Sydney.

While the Cliffvale site became the favoured option, an extensive search was also made during 1957 for a location further west of Sydney, and west of the mountain range known as the Great Dividing Range. Large areas in the sparsely populated region were inspected, with a site near Parkes, about 400 km west of Sydney, chosen as the best of these ‘over the mountains’ candidates. Situated in the Goobang Valley, 20 km to the north of the Parkes township, this site was particularly well shielded from radio interference by a surrounding ring of hills. Tests at both sites showed that Parkes had much lower noise levels than Cliffvale. More importantly, with the rapid expansion of Sydney’s western suburbs, the quality of the Cliffvale site would only deteriorate over the long term. The decision by the RP group in favour of Parkes was unanimous. Construction began at the site early in 1959 (Fig. 5.3).

Fig. 5.3 The construction of the Parkes dish during 1959–1961 was carried out by the German steelmaker MAN. Most of the components of the telescope were cast at the MAN plant near Frankfurt and then shipped to Sydney (courtesy: CRAIA)

5.3 Changing of the Guard

The inauguration of the Parkes Radio Telescope in October 1961 marked an important stage in the development of science in Australia. On a scientific level the telescope provided Australian astronomers with the most powerful and versatile instrument of its type in the world, one which immediately produced a stream of significant and, at times, fundamental discoveries. On another level the Parkes telescope also had a major impact in shaping the way astronomy developed in Australia. In contrast to the 1950s, when small teams at Radiophysics built and had exclusive use of their own telescopes, Parkes would operate as an observatory and have more in common with the great optical telescopes of the world. A specialist group of technicians would look after the routine maintenance and operation of the telescope and radio astronomers would now have to compete with their peers for observing time on the new instrument. A new breed of radio astronomer emerged and also a new way of doing radio astronomy. In this respect the Parkes telescope marked the arrival of radio astronomy in Australia as a mature scientific discipline. In some respects too, it marked the end of the most innovative and interesting period. And for those of us personally involved in the pre-Parkes era (including the first author WO of this book), it was also a particularly exciting era to be involved in radio astronomy, when we felt genuine affection for the field stations (e.g., see Orchiston and Slee, 2017: 498–499).

The Parkes telescope also had major repercussions on the broader development of astronomy in Australia. With the massive investment of staff and funds in Parkes, only limited resources remained to support the other research programs which had flourished at Radiophysics in the 1950s. In this section we see how this heavy commitment to Parkes sparked off a fierce struggle for these remaining resources that, in turn, precipitated the departure of several leading members of the RP group to continue their careers in astronomy elsewhere.

Even before the first blueprint had been drafted for the Parkes dish, the RP group realised it faced a major reorganisation of its resources. As we have noted earlier, radio astronomy began as an unlisted item in the 1946 budget and then in a few short years had grown to become the dominant research area at RP. This rapid expansion had been funded essentially by winding back on other RP research areas such as air navigation and computing. However, this changed after a crucial meeting in October 1956 between senior RP staff and the CSIRO Executive in Melbourne. The meeting agreed that resources would be provided to the Parkes dish not by further cuts to the other RP research areas, but by winding back other parts of the radio astronomy program (Robertson, 1992: 131). For the Parkes group the future was clear cut. With a superlative instrument on the way, the main tasks ahead were to ensure that the telescope was brought into operation as quickly as possible and then to start working through the wide variety of possible observing programs.

In sharp contrast, for the radio astronomers who would not be directly involved in the Parkes project, the future seemed far less certain. As we have seen earlier, Radiophysics operated a number of instruments at this time – the solar

radiospectrograph at Dapto, two small dishes for 21 cm work at Potts Hill and Murraybank, and the Mills Cross, the Shain Cross and the Chris Cross at the Fleurs field station. Each of these instruments had been brought into operation during the period 1952–57 and, though none was ready for the scrap-heap, serious thought had to be given to a new generation of telescopes over the decade ahead. Any new instrument would inevitably be larger and more expensive than its predecessor, and clearly not all of the research programs of the 1950s could continue to flourish. The Parkes telescope now meant that only about half the staff and financial resources were available to stretch across all these programs. Unavoidably, cutbacks were the order of the day for the remainder of the radio astronomy group.

Two proposals for new instruments emerged as the major contenders for the 1960s. One was a metre-wavelength Radioheliograph devised by Paul Wild to supersede the Dapto spectrograph as the principal instrument for studying solar radio bursts. This would provide real-time TV-like images of the radio Sun and show the motion and evolution of bursts. The other proposal by Bernie Mills called for a SuperCross, a larger version of the instrument built at the Fleurs field station in 1954 to continue the highly successful program on the detection and cataloguing of radio sources. Both proposals had outstanding scientific merit. And yet, because of the limited resources available there was little possibility of proceeding with both. The issue would be one resolved on non-scientific grounds and here, on two counts, Wild's proposal gained the upper hand. The Dapto spectrograph had been built in 1952 and since then the Cosmic Group had constructed both the Mills and the Shain Crosses. For what it was worth, fair play suggested that the Solar Group should have the next turn. Another consideration was the question of diversification. The SuperCross would continue a research program separate and complementary to the Parkes telescope, but nevertheless it would mean a total commitment by the RP group to Galactic and extragalactic radio astronomy. Inevitably the Solar Group, by then widely recognised as the world leader, would run down and eventually be disbanded. A vote for the Radioheliograph would be a vote for diversification of the group's activities. For these reasons, at a meeting in August 1959 the radio astronomy group decided in favour of Wild's proposal.

Wild had initially proposed an instrument in the form of a cross and, only later, devised an array consisting of 96 identical aerials positioned at equal distances around a large circle. The plan had been to build the instrument at Parkes but the sheer size of the circular array, 3 km in diameter, proved too large for the 170 hectare site. This led to the decision to head north to less expensive farming country and to the eventual selection of the site at Culgoora, near Narrabri in northern New South Wales. Funding for the Radioheliograph was obtained from the US Ford Foundation in two instalments totalling \$US630,000 – approximately the same amount as the combined Carnegie and Rockefeller grants made earlier towards the Parkes dish. In contrast to Parkes and the engineering challenges it presented, the simple form for each of the 96 aerials enabled the entire Radioheliograph to be built by RP staff (Fig. 5.4). After eight years of planning and construction, the Radioheliograph recorded its first signals in August 1967 (Frater et al., 2017: Chapter 5).

Fig. 5.4 Paul Wild shortly after the completion of the Radiotelescope. Originally the plan had been to build the instrument on the Parkes site, but it needed a much larger area. A new site was found at Culgoora in northern NSW which, in 1988, also became the location of the Australia Telescope Compact Array (see Section 5.3). (right) Four of the 96 antennas equally spaced around a circle 3 km in diameter (courtesy: CRAIA)

The decision in August 1959 to proceed with the Radiotelescope at the expense of the SuperCross meant that Bernie Mills had to quickly assess his future. He did not have to look far. In May 1960 the offer of a position came from charismatic Canadian-born Harry Messel in the School of Physics at the University of Sydney, virtually next door to the RP Lab (Mills, 2006; Frater et al., 2017: Chapter 3). After his appointment as Head of the School, Messel had begun a vigorous campaign to recruit new staff with the aim of transforming what was then a scientifically moribund department into a research centre of world class. To broaden the scope of the School, Messel announced he would establish a new centre for radio astronomy with Mills as his star recruit. Messel's timing was perfect. The National Science Foundation (NSF) in Washington announced that it would, for the first time, consider making grants to scientists outside the United States. Mills submitted a detailed funding application and, in 1962, the NSF announced that it would fund the SuperCross with a sum of \$US746,000 spread over five years. This grant was the largest made to any project outside the United States by the NSF, a body which until then had focused almost exclusively on funding research in American universities and laboratories. Following the Parkes dish and the Radiotelescope, the SuperCross became the third major Australian radio telescope to be partly or wholly funded by the United States (Fig. 5.5).

The SuperCross is notable for being the project that finally broke the near monopoly held by Radiophysics on radio astronomy in Australia. Some radio astronomy research areas had been initiated in Australian universities, but these programs were not genuine competitors to Radiophysics. As undoubtedly the most

Fig. 5.5 A view along the east–west arm of the SuperCross at Hoskinstown, near Canberra. Bernie Mills with Australian Prime Minister Sir Robert Menzies at the inauguration of the SuperCross in November 1965 (courtesy: University of Sydney Archives)

outstanding example, a group led by Bill Ellis at the University of Tasmania in Hobart carried out observations of radio emission at low frequencies between about 1 and 30 MHz, a program boosted by the arrival of the American pioneer Grote Reber in 1954 (e.g. see George et al., 2015, 2017). Reber had been attracted by an unusual hole or ‘window’ in the ionosphere that makes Tasmania a particularly good location for radio astronomy at very low frequencies. Characteristically, using his own resources, Reber constructed a radio telescope at Bothwell, north of Hobart, a vast array of wooden poles and wire (see Fig. 1.42). In terms of its physical dimensions, it was the world’s largest telescope – the first ‘Square Kilometre Array’. Working largely alone, Reber carried out a survey of radio emission from the Milky Way at 2 MHz, a frequency much lower than anything attempted at Radiophysics. While the resources available to Reber and the University of Tasmania group were small compared to the RP radio astronomers, Tasmania quickly established itself as the world leader in very low frequency radio astronomy. Reber and Ellis’ group were never viewed as competitors by RP – rather their programs complemented those of RP and helped maintain Australia’s world supremacy in radio astronomy during the 1950s and through into the 1970s.

As we have seen in previous chapters, a major part of the radio astronomy program at Radiophysics in the 1950s had used instruments based on variations of the same principle. The Mills Cross had been used for surveys of Galactic and extragalactic sources, the Shain Cross for a survey of the Galaxy at low frequency and the Chris Cross for studies of the Sun. In 1960, in a period of just a few months, each of these three programs came to an abrupt halt. In February Alex Shain died, aged only 38, and the RP group lost one of its foundation members. Three months later, both Mills and Chris Christiansen joined the University of Sydney. In contrast to Mills,

however, who left because of much better research prospects, Christiansen chose to leave because of his fundamental objection to the direction radio astronomy had taken at Radiophysics (Frater et al., 2017: Chapter 4). Paradoxically, Christiansen had contributed solidly to the planning of the Parkes telescope and he was the one who found the Goobang Valley site near Parkes. And yet, throughout the project he was the telescope's most vocal critic. Christiansen had achieved outstanding success in developing new radio telescopes, beginning with the grating interferometers at Potts Hill in the early 1950s. Given the brilliant record by Radiophysics in devising and building new types of telescopes, Christiansen believed the new Parkes dish to be too conventional and, indeed, too old fashioned. He mockingly referred to it as 'the last of the Windjammers' (Christiansen, 1990).

Christiansen's outspokenness put him on a collision course with his chief. The matter came to a head when Taffy Bowen learnt that Christiansen had been openly critical of Bowen's ability as a scientist. Christiansen had no option but to resign. Earlier in 1960, Christiansen had been invited to apply for the Chair in Electrical Engineering at the University of Sydney, but had turned down the offer. However, in view of his clash with Bowen and also the fact that the engineering department would be closely associated with the new radio astronomy centre, Christiansen put in a late application which was accepted immediately.

Christiansen then faced the daunting task of starting his new university position with no radio telescope and no ready source of funds. He then learnt of a plan to demolish his abandoned Chris Cross at the Fleurs field station. Following some swift negotiations, CSIRO agreed to transfer ownership of the Fleurs site to the University of Sydney. Over the next decade Christiansen revamped the old cross by adding several medium-size parabolic dishes to the array to form the Fleurs Synthesis Telescope (see Section 5.4 below). After the Parkes dish, the Radioheliograph and the SuperCross, the Fleurs Synthesis Telescope became the fourth major Australian radio telescope built in the 1960s. The Fleurs instrument would take much longer to complete than the other three, but it could be funded within the university budget and did not rely on American philanthropy.

Both Christiansen and Mills, then in their forties at the time of their controversial departure from Radiophysics, were able to re-establish themselves and carve out successful new careers in radio astronomy. For Joe Pawsey, the future did not hold the same good fortune. Since the beginning of the radio astronomy group in 1945, Pawsey had provided leadership and cohesiveness to a loose federation of small research teams; his wisdom, intellect, modesty and international stature as a scientist had won him the admiration and, in most cases, fierce loyalty of his staff. By 1960 circumstances had changed radically. With the formation of the two largely independent Parkes and Culgoora groups, Pawsey's position no longer had the same relevance.

The changing of the guard had been signalled by the appointment of John Bolton to take charge of the Parkes Radio Telescope, a post which later was given the title of Director of the Australian National Radio Observatory (ANRAO). Bolton had outstanding credentials for the position, not least his illustrious start in the late 1940s with the discovery and identification of the first discrete radio sources (see

Chapter 4). As noted above, in 1955 he and Gordon Stanley were recruited by Caltech to be the founders of the Owens Valley Radio Observatory in northern California, the first major centre for radio astronomy in the United States. A further point in Bolton's favour was that, from the outset, he had been a strong supporter of building the giant Australian dish. His support for the project, combined with a special rapport he had developed with Taffy Bowen, made him the leading candidate for the director's position. In June 1960 Bolton informed Caltech that he would be returning to Australia and, by the time the position was advertised several months later, the outcome was a foregone conclusion.

Bolton's responsibilities were to be wide ranging. Aside from pursuing his own research interests, he would oversee the allotment of observing time on the telescope, supervise a procession of postgraduate students from Australian and overseas universities, and vet all research papers before they went out for publication – duties which in practice made him leader of the Cosmic Radio Astronomy Group. In terms of professional classifications within CSIRO, Bolton was appointed at the level of Chief Research Scientist. Earlier, Paul Wild had also been elevated to the same classification after being offered a new chair in astronomy at Cornell University, at more than three times his CSIRO salary. Although CSIRO could not match the American offer in monetary terms, the promise of promotion and support to build the Radioheliograph had persuaded Wild to stay in Australia. In practice, Wild was now leader of the Solar Radio Astronomy Group. Pawsey too was classified as a Chief Research Scientist. Although he was not outranked by his two former protégés, his position had basically become redundant.

Pawsey was not to be stranded. In December 1961 he accepted an offer to succeed Otto Struve as Director of the National Radio Astronomy Observatory, recognised as the top-ranking post in radio astronomy in the United States (Fig. 5.6). Since its foundation four years earlier, the NRAO had worked towards its goal of establishing a national facility with state-of-the-art equipment, shared by radio astronomy groups across the country, as well as its own permanent research staff. A 26 m telescope had been completed in 1958 at the Green Bank site in West Virginia and a 91 m dish, steerable in elevation only, was nearing completion. In March 1962 Pawsey arrived at Green Bank for an initial six-week visit, but a few days later suffered paralysis of the left arm and leg. After several weeks in hospital he was operated on for the removal of a brain tumour. He recovered sufficiently to return to Sydney and he was able to visit the Lab a few times a week. However, his condition continued to deteriorate and he went into hospital for the last time in October 1962. One of Pawsey's last visitors was Fred Hoyle, who presented him with the prestigious Hughes Medal on behalf of the Royal Society of London (Lovell, 1964).

Pawsey's death marked the end of a golden era in Australian radio astronomy (Fig. 5.7). It also marked the end of the period of upheaval begun several years earlier, triggered by the decision to wind down support for the research programs of the 1950s and to direct the resources into the two giant instruments at Parkes and Culgoora. Several factors contributed to this turbulent period of transition. Paradoxically, one factor was the very success of the RP group. Although the size of the group had undergone a steady growth since the early post-war years, its key

Fig. 5.6 Joe Pawsey at the Vermilion River Observatory, Illinois, in September 1961, shortly before he was offered the position of Director of the US National Radio Astronomy Observatory (courtesy: CRAIA)

Fig. 5.7 A letter sent to Joe Pawsey, shortly before his death, by the radio astronomy group he had founded (courtesy: CRAIA)

personnel had changed remarkably little. With the group's growing international prestige and, until about 1960, its comfortable level of funding, there had been no incentive for its members to leave. The success of the group had given it a certain stability and cohesiveness. One measure of this success is that eight members of the group (Bolton, Christiansen, Mills, Minnett, Pawsey, Piddington, Robinson and Wild) were elected Fellows of the Australian Academy of Science, recognised as the highest honour Australia can bestow on its scientists. This success in many cases led to accelerated promotion through the ranks faster than most scientists in CSIRO and for some, at a relatively young age, to an eventual promotion barrier. The best prospects for advancement were then to be found beyond the doors of Radiophysics.

5.4 Pulsars – Cosmic Lighthouses at Radio Wavelengths

It is beyond the scope of this book to provide an overview of Australia's contributions to radio astronomy over the sixty-plus years since the Parkes Radio Telescope opened in 1961. However, the discovery and study of pulsars provides a good case study of how Australia has excelled in one particular branch of radio astronomy. Pulsars are also a good example of how Australia, with its clear view along the plane of the Milky Way, has had a significant advantage over the northern observatories. As former RP physicist Neville Fletcher once joked: "In astronomy circles it is often remarked – mostly by envious northerners – that God, in creating the Universe, perversely located the most interesting regions of our Galaxy in the southern hemisphere, but most of the astronomers in the north." (Robertson, 1992: 277).

In February 1968 the Cambridge group stunned the astronomical world by announcing it had discovered a completely new type of radio source. Inspired by the term quasar, the word 'pulsar' was coined for the new objects. Similar to other landmark discoveries in radio astronomy, the pulsar discovery was made by serendipity, not by design. Early in 1967 Antony Hewish and his graduate student Jocelyn Bell were observing quasars and other compact objects when Bell noticed a new type of radio source with fluctuations in its strength apparently unrelated to any type of local electrical interference. Further observations by Bell and Hewish established that the source lay in the plane of the Milky Way with signals consisting of a succession of regular pulses. The signal varied erratically in intensity, but the astonishing feature was the extraordinarily precise timing between individual pulses – exactly 1.3372795 seconds.

Within weeks three other sources had been discovered, each with a different pulsation period but each with the same incredible regularity. The Cambridge group thought it might have stumbled across signals sent by extra-terrestrial civilisations. The observations continued in secret for several months as Bell and Hewish worked to establish a natural, physical origin for the signals. Finally, convinced that the signals were not the creation of unknown alien life, Hewish announced the discovery (see Bell Burnell, 1977).

Fig. 5.8 In 1973 the Australian Government issued a new \$50 note celebrating Australian science. One side featured the physiologist and Nobel Laureate Howard Florey and the other Ian Clunies Ross (above), the former Chairman of CSIRO (1949–59). The Parkes dish is at centre and above it is a contour map of the Large Magellanic Cloud and a solar burst recorded by the Radioheliograph at Culgoora. At far left is the signal from the pulsar CP 1919 recorded at Parkes in March 1968 (courtesy: Robertson collection)

Pulsar observations began at Parkes two weeks after the announcement of the discovery, principally by Max Komesaroff, Brian Robinson and visiting Indian astrophysicist Radhakrishnan. They began by correcting a small timing error in the pulse period of CP 1919, the first of the Cambridge pulsars (Robinson et al., 1968; see Fig. 5.8). In a study of the Vela pulsar (see below) they were able to measure a very small slowing down in its pulse period of 10 nanoseconds per day and also to show that each pulse was strongly polarised. Both these results provided evidence in favour of a ‘lighthouse’ theory put forward by Tom Gold at Cornell University. According to Gold, a pulsar consists of a neutron star spinning extremely rapidly and with its magnetic axis inclined at a large angle to the rotation axis (Gold, 1968; see Fig. 5.9). Another peculiar property of pulsars was also revealed by the Parkes observations on Vela. On occasions the pulse period of the pulsar would suddenly speed up. The word ‘glitch’ was coined to describe the abrupt change. After each glitch, the pulsar enters another long phase of gradual slowdown until the next glitch. The glitch is thought to be caused by a sudden change to the internal structure of the pulsar.

In the hunt for new pulsars Parkes was no match for the Molonglo SuperCross with its much larger collecting area at low frequencies. The Molonglo group lead by Michael Large discovered the first southern pulsars, including one which was shown to coincide with the position of the supernova remnant Vela X. A similar discovery by an American group of a pulsar at the centre of the famous Crab Nebula provided further evidence that some pulsars are created in supernova explosions of stars with masses much greater than the Sun. By the end of 1971 the Molonglo group, with a tally of 31, were the world leaders in pulsar discovery, while Jodrell Bank in

Fig. 5.9 A pulsar has its magnetic axis inclined to its spin axis. The intense magnetic field produces enormous forces that strip plasma material from the surface of the pulsar. The plasma is accelerated to nearly the speed of light causing it to emit intense radiation. Most of the radiation is beamed out along the north and south poles where the magnetic field is strongest. If the pulsar is suitably aligned in space, a pulse of radiation will be observed every time the beam sweeps across the Earth. The effect is the same as the flashing signal seen from a distant lighthouse (after Robertson, 1992: 311)

Cheshire, Green Bank in West Virginia and Arecibo in Puerto Rico were the most prominent groups in the northern hemisphere.

The Molonglo Cross was ideal for discovering pulsars, but not for studying them in detail. Observations of a particular pulsar required an instrument which could track the object for long periods of time. Here the Parkes dish came into its own in terms of actually learning what makes a pulsar tick. In 1976 Dick Manchester (Fig. 5.10) at Radiophysics led a collaboration between the Parkes and Molonglo groups in a survey of the southern sky. The great majority of pulsars were found to lie roughly along the Galactic Plane. In 1978 the collaboration published a catalogue of 155 pulsars, more than doubling the number of pulsars then known (Manchester et al., 1978).

In most branches of radio astronomy, advances in instrumentation usually lead to the next major breakthrough in the field. In 1997 a new multibeam receiver was fitted to the Parkes dish which allowed the simultaneous observation of 13 separate patches of sky and which lead to the discovery of over 1200 pulsars (Manchester et al., 2001). Among them was the discovery of what remains the only known ‘double’ pulsar – two pulsars bound in tight orbit around each other. The system radiates gravitational waves and is an ideal laboratory for carrying out precision tests of Einstein’s general theory of relativity and other theories of gravity. In 2004 *Science* magazine voted the discovery as one of the top ten scientific breakthroughs of the year.

Fig. 5.10 Dick Manchester is a world authority on pulsars. During his career he has led teams that have discovered about sixty per cent of all known pulsars. In 2019 Dick was awarded the prestigious Matthew Flinders Medal by the Australian Academy of Science (courtesy: CRAIA; credit: Kristen Clarke)

Currently there are over 2700 known pulsars – with more than half discovered at Parkes – with pulse periods ranging from 1.4 milliseconds up to 23 seconds. Two major goals of pulsar researchers are to find the first sub-millisecond pulsar and to find a pulsar orbiting a black hole. The next chapter in the pulsar story is likely to be when the Square Kilometre Array (SKA) comes into operation in the late-2020s. With its exceptional sensitivity, it is expected that the SKA will be able to detect pulsars even in distant galaxies (see Section 5.7).

5.5 A Birthday Present for the Nation

In broad terms, the evolution of Australian radio astronomy can be divided into four phases or periods. The first period – the subject of this book – covered the years 1945–60 when the Radiophysics Lab not only dominated Australian radio astronomy, but became a global leader in the new field. It was characterised by small, relatively independent groups working at a variety of field stations in and around Sydney. In most cases these groups devised and built their own radio telescopes, all of which could be funded within the annual RP budget. As we saw earlier in this chapter, the second period of Australian radio astronomy came in the 1960s when Big Science arrived in Australia, with the Parkes dish, the Radioheliograph and the Molonglo SuperCross all funded by American philanthropy. For the first time the groups lead by Bernie Mills and Chris Christiansen at the University of Sydney challenged RP's leadership in the field. The third period in Australian radio astronomy began when 'aperture synthesis' became the dominant way of doing radio astronomy – the technique that uses the Earth's rotation and a number of radio antennas in an array to simulate or 'synthesise' the effect of observing with a very large single telescope. (We discuss the fourth period below.)

The first Australian synthesis telescope was brought into operation in the early 1970s at the Fleurs field station. As noted earlier, Chris Christiansen had managed to save his old 'Chris Cross' from the bulldozers by persuading Radiophysics to

transfer ownership of the field station to the University of Sydney. The Chris Cross consisted of north–south and east–west arms, each comprising 32 dishes 5.8 m in diameter (see Orchiston and Mathewson, 2009). Christiansen added two larger (13.7 m) dishes to each arm to convert the grating cross into a very sensitive synthesis telescope with a 20 arcsec beam, the narrowest of any single radio telescope in the southern hemisphere. The Fleurs Synthesis Telescope (FST) was used during the 1970s to study the structure of large radio galaxies, supernova remnants and emission nebulae, and for a while it also continued to produce the daily 21 cm maps of the Sun. Although further upgrades were made in the 1980s, the retirement of Christiansen led to a winding back of the research program. The FST was shut down in 1988 on the very same day as the inauguration of the Australia Telescope (AT – see below).

The second Australian synthesis telescope was also developed at the University of Sydney. Similar to the first full-scale cross built at Fleurs in 1954, Bernie Mills knew that the SuperCross at Molonglo would only have a limited lifetime. As a transit instrument operating at the single frequency of 408 MHz, once the whole sky had been surveyed the scientific returns would diminish rapidly. The ‘Molonglo Reference Catalogue’ of over 12,000 strong sources and several catalogues of weaker sources was completed in 1978. (In comparison, the Parkes survey at 408 MHz carried out in the 1960s and followed by the survey at 2.7 GHz in the 1970s catalogued just over 8000 sources.) Mills then decided to transform the SuperCross from a transit telescope to a state-of-the-art synthesis telescope at the higher frequency of 843 MHz. The north–south arm was closed down and by 1981 the east–west arm, 1.6 km (one mile) in length, had been converted into a new steerable instrument, the Molonglo Observatory Synthesis Telescope (MOST), named after the nearby Molonglo River. The large collecting area and the long observing times ensured that, for most of the 1980s, MOST was the most sensitive radio telescope south of the equator. After several upgrades, MOST is still in operation today.

The success by Christiansen with the FST and by Mills with the MOST once again displayed their talent for developing innovative radio telescopes and techniques. It also called into question once again the wisdom of concentrating the resources at Radiophysics into a single multipurpose dish. However, by the mid-70s, after 15 years of operation, the Parkes Radio Telescope was undoubtedly an outstanding success. Each year increasing numbers of radio astronomers from Australian universities and from overseas competed for observing time. And yet there was a growing realisation that Parkes was falling behind the new generation of synthesis telescopes coming into operation in the northern hemisphere: the Westerbork Synthesis Radio Telescope built by the Dutch group had begun observations; the 5-km telescope built by Martin Ryle’s group at Cambridge was operational; and the Very Large Array (VLA) was under construction in New Mexico by the National Radio Astronomy Observatory. With the development of computer technology, these instruments could produce images of radio sources of exceptionally high resolution, which were not possible with single dish instruments. At the same time, these arrays were able to operate at multiple frequencies and achieve high sensitivity through large collecting areas.

In 1975 a committee was formed to investigate the options for an Australian Synthesis Telescope (AST) (see Fig. 5.11), chaired by Paul Wild who had been appointed Chief of Radiophysics following the retirement of Taffy Bowen in 1971. The formation of the committee was an achievement in itself given the previous animosity between Radiophysics and the University of Sydney groups. Bolton wanted to add another large dish to the 64 m Parkes dish to form an instrument similar to the one he had designed at Owens Valley in California, while Christiansen was in favour of an array consisting of many small dishes. A compromise was eventually reached with the Parkes dish linked to a number of medium-sized dishes which could be moved along rail tracks (Fig. 5.12). There were, however, critics of the proposal who believed the AST design was only an incremental improvement on Australia's existing instruments. Others argued that a government funding cap of \$A5.8 million for the AST was grossly inadequate for the project to succeed. With the astronomical community divided, the government decided not to fund the project.

Scientific proposals are often turned down because they are seen to be too ambitious or because they cost too much for the likely scientific returns. Oddly, the proposal for the AST failed because it was not ambitious enough and because it was hampered by the government's penny-pinching attitude. The turning point came in

Fig. 5.11 A meeting of the Australian Synthesis Steering Committee in 1977: (back) John Bolton (Parkes Observatory), Jon Ables (Radiophysics), Don Mathewson (Mt Stromlo and Siding Spring Observatories), Dick Manchester (RP), Bob Frater (U Sydney), Brian Robinson (RP), Paul Wild (chair, RP), Bernie Mills (U Sydney), Don Morton (Anglo-Australian Observatory), Ron Brown (Monash U) and Kel Wellington (RP). (front) Harry Minnett (RP), Robert Hanbury Brown (U Sydney), Chris Christiansen (U Sydney) and Kevin Westfold (Monash U) (courtesy: CRAIA)

Fig. 5.12 Sketch of the proposed Australian Synthesis Telescope (AST) which linked the Parkes dish with several medium-sized dishes mounted on rail tracks. Although the proposal was not funded, the idea evolved into plans for the Australia Telescope (courtesy: CRAIA)

Fig. 5.13 Bob Frater (left) was the driving force behind the Australia Telescope. In 1982 he was appointed Chief of the Radiophysics Lab, following David Martyn (1940), Fred White (1942), Taffy Bowen (1946), Paul Wild (1971) and Harry Minnett (1978). John Brooks (right) was appointed Project Manager during the construction of the AT and later became the Assistant Director of the Australia Telescope National Facility (courtesy: CRAIA)

1981 with the appointment of Robert (Bob) Frater as the new Radiophysics chief (Fig. 5.13). As the first chief recruited from outside CSIRO, Frater came from Christiansen's Electrical Engineering Department, where he had been part of the design teams for both the Molonglo SuperCross and the Fleurs Synthesis Telescope. Shortly before Frater's appointment, a mining company had announced plans for a new copper and gold mine less than 20 km away from the Parkes Observatory,

raising the prospect of radio interference from its machinery seriously degrading the quality of the Parkes site (thankfully, the company later cancelled its plan). Following discussions between Frater and Brian Robinson, the head of the RP Radio Astronomy Group, the two realised that by moving any planned synthesis array away from Parkes would allow a much superior array of dishes to be built. The obvious place for a new site was Culgoora in northern New South Wales where Radiophysics operated the Radioheliograph and where much of the required infrastructure was already in place.

Over the following year the design of the new array evolved into one radically different to the AST. The main array at Culgoora would consist of five 22 m dishes mounted on a 3 km long east–west rail track and these dishes could be positioned at any one of 35 different stations along the track. A sixth dish, a further 3 km to the west, could also be moved along a short east–west track. A seventh stand-alone dish was positioned at Mopra Rock near Siding Spring Mountain, 130 km south from Culgoora, while a further 220 km south was the 64 m Parkes dish. Importantly, the three sites formed an almost perfect three-element array, since the separations between the sites were in the right ratio to produce excellent radio images.

The new design had a number of distinct advantages over the AST. First, it could accommodate the diverse objectives of the various Australian astronomy groups, such as those interested in wide-field mapping or very long baseline interferometry, and like the arrays in the northern hemisphere it could operate over a wide range of wavelengths (from 3 mm to 1 m). The single dish at Mopra Rock could also be used as a stand-alone instrument for millimetre wavelength observations of molecules in interstellar space, where previously radio astronomers had been reliant on the Parkes dish which could not operate below about 3 cm. The new design was in the same league as the new synthesis telescopes in the northern hemisphere and clearly capable of front-line research well into the twenty-first century. Not surprisingly, the new design won the strong support of Australia's astronomical community.

Funding the new telescope was another matter. Unlike the American philanthropic support for the Australian radio telescopes of the 1960s, the new array would be totally reliant on Federal Government funding. To help sell the project to Canberra, Bob Frater decided that at least 80% of the telescope would be built by Australian industry, and so stimulate the economy by promoting new and innovative technologies. A master stroke was the suggestion by David Jauncey to name the project the 'Australia Telescope', so that any serious opposition from politicians would seem almost unpatriotic.

An even better idea was to nominate the Australia Telescope (AT) to be a Bicentennial project in 1988. Canberra was organising the celebrations for the Bicentenary of European settlement in 1788 and wanted to support high profile projects to mark the occasion. The appeal of the AT was that not only would it consolidate Australia's position as a world leader in astronomy, but would also be a fine tribute to its astronomical heritage. After all, Captain James Cook and his crew were sent to the South Pacific in 1768 to observe the transit of Venus (see our Frontispiece on page v and Orchiston, 2017) and then to chart the east coast of the fabled southern land, not to mention Aboriginal astronomy stretching back tens of thousands of

years (for a primer see Norris and Norris, 2009). In August 1982 the Federal Government approved funding of up to \$25 million for the construction of the AT, over four times the earlier miserly allocation for the AST. Fortunately, the funds were indexed to inflation which ran high throughout the 1980s. The final cost of the AT was just over \$50 million in 1988 dollars (for detailed accounts of the planning and construction see Frater, 2019; Haynes et al., 1996; see also Sim, 2013).

To free up operational funding for the AT, Frater made the difficult decision in 1982 to close down the Radioheliograph at Culgoora. It was a controversial decision, but even its founder Paul Wild agreed that after 15 years of successful operation the instrument was coming to the end of its scientific life (the Culgoora site was later renamed the Paul Wild Observatory). Site preparation work for the AT began in September 1984 and rapid progress was made in laying the wide-gauge (9.6 m) rail track to support the six movable dishes (Fig. 5.14). Despite careful planning, there were some unforeseen environmental problems associated with this rural site, ranging from kangaroos bounding over the metre-high perimeter fence to sulphur-crested cockatoos chewing holes through the fibreglass insulation and aluminium foil used on each of the dishes.

By December 1985 all civil works at Culgoora were complete and work began on the construction of the 22 m dishes. The inner 15 m surface of each dish was solid aluminium with the outer section perforated aluminium to reduce weight and

Fig. 5.14 The Australia Telescope Compact Array (ATCA) under construction at Culgoora in 1987. The extraordinary surface accuracy of each 22 m dish enables the array to operate at wavelengths as short as 3 mm (courtesy: CRAIA)

wind loading. To operate at wavelengths as short as 3 mm (100 GHz) required surface accuracies of 0.15 mm for the inner panels and 0.25 mm for the exterior ones. To get this level of precision RP staff developed an innovative technique for forming the parabolic surface that was over ten times cheaper to manufacture than the conventional and expensive method of using machined moulds. Later, Radiophysics and Macdonald Wagner, the consulting engineers building the AT, formed a consortium to commercialise the RP technique and it was used in a variety of satellite and telecommunications dishes elsewhere in Australia and in countries such as Cambodia and Vietnam. The total value of these commercial contracts was estimated to exceed the total cost of the Australia Telescope. In all, over 30 companies were involved in the construction and the project was able to comfortably meet Bob Frater's pledge of at least 80% Australian content.

In the lead up to the inauguration, a major organisational change came with the formation of the Australia Telescope National Facility (ATNF) which would manage the Australia Telescope operations, including the Parkes Observatory. The ATNF was to have essentially the same status as other CSIRO Divisions and, in effect, it meant that radio astronomy would be removed from Radiophysics where it had been the major research program since the late 1940s. In practice, there was relatively little impact on the Radio Astronomy Group itself, as Radiophysics and the ATNF were to be co-located on the same site in the suburb of Marsfield in north-west Sydney (in 1968 the Radiophysics Lab had moved from its original building in the grounds of the University of Sydney to this six-hectare greenfield site). After a worldwide search Professor Ron Ekers (Fig. 5.15) was appointed the Foundation Director of the Australia Telescope. After completing his PhD in 1967 at the Australian National University (co-supervised by John Bolton), Ekers held positions at Caltech, Cambridge and the Kapteyn Observatory in the Netherlands. In 1980 Ron was appointed the inaugural Director of the Very Large Array in New Mexico, built and operated by the National Radio Astronomy Observatory. Ekers brought a wealth of experience in image processing and had been a leading advocate of building a major synthesis telescope in the Southern Hemisphere.

Fig. 5.15 Professor Ron Ekers (AO) was the Foundation Director (1988–2003) of the Australia Telescope National Facility. Ron is the only Australian-born astronomer to be elected President of the International Astronomical Union (2003–2006) (courtesy: CRAIA)

Fig. 5.16 (above) Five of the six 22 m dishes making up the ATCA. The sixth dish is 3 km to the west. (below) The Australia Telescope was officially opened by Prime Minister Bob Hawke in September 1988, as part of Australia's Bicentennial celebrations. At left are Hazel Hawke and science minister Barry Jones (courtesy: CRAIA)

The official opening ceremony of the Australia Telescope was held on a very windy day in September 1988. Although the main construction was complete, the project was in fact about 12 months behind the original schedule with much work remaining to get the telescope fully operational. Grote Reber and a Who's Who of

Australian astronomy were among the 800 guests. The Prime Minister Bob Hawke and wife Hazel were ‘driven’ to the official dais on one of the 22 m dishes (Fig. 5.16). After the speeches, Hawke declared the Australia Telescope open and then pressed a button causing three of the dishes to tilt down towards the guests and release a swarm of green and gold balloons.

A brief interlude. As we saw in Chapter 4, the Radiophysics group of John Bolton, Gordon Stanley and Bruce Slee at the Dover Heights field station were able to show that the intense radiation from the northern Cygnus constellation came from a compact, point-like source. In June 1947 the group thought that they had found a second source in the southern constellation of Centaurus, but repeated attempts to confirm the detection proved a frustrating failure. The sensitivity of their equipment was simply not good enough to detect sources any fainter than the strong Cygnus source. Gordon Stanley made the crucial breakthrough in October 1947 when he was able to eliminate most of the noise variations in the receivers, so that much fainter signals could be detected. Early in November, the Dover Heights team was rewarded by the detection of a second source in the Taurus constellation, followed by a third in Virgo and then – the one that had eluded them – a fourth in Centaurus. The striking images of Cygnus A and Centaurus A in Fig. 5.17 are a powerful illustration of just how far radio astronomy has come in such a short period of time.

5.6 A Radio Telescope as Wide as Australia

The technique of interferometry has been an integral part of Australian radio astronomy from the very beginning. As we saw in Chapter 2, in 1946 Joe Pawsey, Lindsay McCready and Ruby Payne-Scott used a sea interferometer at Collaroy to show that sunspots are an intense source of radio emission. Similarly, in 1949 Bernie Mills at the Badgery’s Creek field station constructed an interferometer consisting of three broadside antennas to study the strongest discrete radio sources (Fig. 2.53). The antennas were connected to each other using underground cables and their signals were sent to a receiver hut where they were combined to produce the distinctive interference patterns. Later, in a world first, Mills used a microwave link to connect one of the broadside antennas to another movable antenna mounted on a trailer (Fig. 2.55). The distance between the two antennas, known as the baseline, could be varied by up to 10 km.

A major breakthrough in interferometry took place in the late 1960s in Canada and the US with the introduction of atomic clocks as time and frequency standards, with a precision better than one part in 10^{12} . Rather than rely on cables or microwave links between the antennas in an interferometer, atomic clocks could be used to precisely synchronise the signals received at each antenna. The received signals could be recorded on magnetic tape and then the tapes from each antenna later combined (‘correlated’) at a central processing station. The interference patterns were

Fig. 5.17 Two old favourites in a new light: (above) A multi-wavelength view of the spectacular active galaxy Cygnus A, featuring X-ray data (blue), radio emission (red) and optical observations

Fig. 5.18 David Jauncey at the ATNF pioneered very long baseline interferometry in Australia. He used the 64 m dish (later upgraded to 70 m and shown at centre) at the NASA tracking station at Tidbinbilla, south-west of Canberra, combined with other radio telescopes in Australia and the United States (courtesy: CRAIA)

no longer produced in real time, and in principle there was no longer a limit to the possible distances between the antennas. This marked the start of a major new branch of radio astronomy – very long baseline interferometry (VLBI).

The first step in Australia towards VLBI was in 1967 by a group at the Defence Science and Technology Organisation (DSTO) in Adelaide. The group used the 26 m NASA tracking dishes at Island Lagoon near Woomera and at Tidbinbilla near Canberra to study the internal structure of the quasar 3C273. The group also carried out a successful trans-Pacific experiment connecting a NASA dish in California with the Tidbinbilla dish, but in 1973 DSTO decided to discontinue this pioneering work in VLBI. The next step towards Australian VLBI was the appointment of David Jauncey to the Radiophysics Lab in 1974 (Fig. 5.18). After graduating from the University of Sydney, Jauncey had spent almost ten years at Cornell University where he joined a group carrying out the first VLBI experiments in the United

◀ **Fig. 5.17** (continued) by the Hubble Telescope (white). In the early 1950s, the two radio jets emanating from the central core were mistakenly thought to be two galaxies in collision (see Fig. 4.15) (courtesy: NASA and seven other US organisations). (below) A composite image showing the radio glow from the galaxy Centaurus A in comparison with the full Moon. The observations were made at 1.4 GHz by the AT Compact Array and the Parkes Radio Telescope. The huge extent of the glow dwarfs the size of its optical counterpart NGC 5128. The white dots in the sky are not stars, but represent radio sources such as quasars and radio galaxies in the distant Universe [courtesy: Ilana Feain, Tim Cornwell, Ron Ekers, Shaun Amy (CSIRO); R. Morganti (ASTRON); N. Junkes (MPIfR)]

States. On his return Jauncey moved to Canberra, rather than Sydney, to take advantage of a new 64 m antenna NASA had constructed at Tidbinbilla as part of its Deep Space Network (DSN) for tracking spacecraft. Under Australia's agreement with NASA, a small fraction of the antenna's time would be available to Australian astronomers. Jauncey began a collaboration with a group led by Robert Preston at the Jet Propulsion Lab in Pasadena that used Tidbinbilla and other NASA facilities worldwide to study compact, milliarcsecond components in quasars and radio galaxies. The whole sky survey ran for almost ten years and led to a catalogue of over 900 compact radio sources with positions measured to sub-arcsecond precision (Jauncey, 2012).

By about 1980 it became clear to the growing band of radio astronomers involved in VLBI that Australia needed its own VLBI imaging capability. This led to the formation the Southern HEMisphere VLBI Experiment (SHEVE) consisting of five antennas at Parkes, Fleurs, Tidbinbilla, Hobart and Alice Springs, with a sixth at Hartebeesthoek in South Africa. SHEVE was a cooperative effort involving both astronomers and scientists involved in geodesy – the study of the precise size and shape of the Earth. The time synchronisation was done with a rubidium atomic clock supplied by Geoscience Australia, the recording equipment was on loan from the Jet Propulsion Lab, and the correlation of the data tapes was carried out at a joint Caltech–JPL facility in Pasadena. As an indication of the increasingly international and cooperative nature of radio astronomy, especially VLBI, the first series of publications by the SHEVE collaboration, reporting observations made in April 1982, numbered 29 authors from 14 institutions (see e.g. Jauncey et al., 1983).

The next major step in Australian VLBI came in 1984 with the proposal by Ray Norris (Fig. 5.19) to use the existing radio link between the 64 m dishes at Parkes and Tidbinbilla to form a new interferometer. Before the 64 m Tidbinbilla dish came into operation in 1973, NASA relied on 26 m dishes at Tidbinbilla and at Honeysuckle Creek (also near Canberra) to communicate with the Apollo 11 spacecraft in 1969

Fig 5.19 Three of the main players in the development of Australian VLBI (from left): Ray Norris, John Reynolds and Tasso Tzioumis (courtesy: CRAIA; credit: John Sarkissian)

through to Apollo 17 in 1972. NASA contracted the Parkes dish during each Apollo mission in order to use its much larger collecting area to receive the TV signals from the lunar surface (in fact, the world saw the first moon walk by Neil Armstrong and Buzz Aldrin from signals received by both Honeysuckle Creek and Parkes). Norris and Mike Kesteven were able to use the Apollo radio link (and not atomic clocks), along with new electronics and software, to form the Parkes–Tidbinbilla Interferometer (PTI). With a baseline of 275 km the PTI became the world's longest baseline interferometer operating in real time and was especially well-suited for studying rapidly varying and transient radio sources (Norris and Kesteven, 2013).

Australian interferometers were involved in two of the most exciting discoveries of the 1980s. During the 1960s several Parkes radio sources held the record for the most distant known object in the Universe, including the quasar PKS 0237–23 with a redshift of 2.22. By 1973 the record had passed to two sources observed by John Kraus and his group at Ohio State University, with redshifts of first 3.40 and then 3.53. Almost a decade passed without the record being broken and many astronomers thought this indicated that the Ohio sources marked the edge of the observable Universe.

The identification and redshift measurement of PKS 2000–330 in March 1982 by Bruce Peterson, Ann Savage, David Jauncey and Alan Wright involved a series of observations with four telescopes, two radio and two optical. The source itself had been detected at Parkes as early as 1970, but there had been nothing to suggest anything unusual. In 1978 the radio position of the source was measured to greater accuracy with the Tidbinbilla short baseline interferometer (consisting of the 64 m and 34 m NASA dishes). Next it was possible to reliably identify the source on a photographic plate taken with the UK Schmidt telescope at Siding Spring in NSW. Finally, observations with the Anglo-Australian telescope at Siding Spring revealed a new record redshift of 3.78 for PKS 2000–330, making it not only the most distant but also the most luminous object known in the Universe (Peterson et al., 1982). The discovery received widespread media coverage internationally, including front-page headlines in several Australian newspapers.

Possibly the most important astronomical event of the 1980s was the explosion of the supernova SN1987A in February 1987. The explosion occurred in the Large Magellanic Cloud and despite the distance it became the first naked-eye supernova since Kepler's star in the year 1604. Immediately after the discovery, virtually every telescope in the Southern Hemisphere – radio, optical and infrared – focussed on the LMC. Duncan Campbell-Wilson at the Molonglo Cross was the first to detect radio emission from the supernova, at 843 MHz, two days after its discovery. Observations with high angular resolution were essential to separate the supernova emission from the crowded radio background, an ideal challenge for the Parkes–Tidbinbilla Interferometer, which had just come into operation. PTI observations at 2.29 and 8.41 GHz were underway almost immediately and four days later the radio emission peaked but then, a few days later, it faded and became undetectable (Turtle et al., 1987). Although the supernova remnant has been monitored regularly over the years (see Fig. 5.20), and most recently by the Parkes dish (Zhang et al., 2018), there is still no evidence for a pulsar. It is quite possible that the explosion created a pulsar, but with an orientation where the radio beam does not sweep across the Earth.

Fig. 5.20 The evolution of the supernova remnant 187A observed by the AT Compact Array at 9 and 18 GHz from 1992 to 2008. The remnant has grown in size and brightened significantly as the shock wave from the supernova explosion collides with material ejected in the death throes of the star (after Ng et al., 2008)

Fig. 5.21 The Australian Long Baseline Array currently consists of eleven antennas, including one at Hartebeesthoek in South Africa. Yarragadee and Katherine are part of the AuScope geodetic VLBI array, operated in partnership with Geoscience Australia. The Australia Telescope National Facility operates ATCA, Mopra, Parkes and the Australian Square Kilometre Array Pathfinder (ASKAP) in Western Australia (see next section). Tidbinbilla is operated by CSIRO on behalf of NASA. Hobart and Ceduna are operated by the University of Tasmania and Warkworth by the Auckland University of Technology. The correlation of the signals from each antenna is carried out by CSIRO at the Pawsey Supercomputing Centre in Perth, Western Australia (courtesy: Chris Phillips, ATNF)

The current VLBI facility in Australia is known as the Long Baseline Array (Fig. 5.21). Unlike the SHEVE collaboration in the 1980s, where most of the recording equipment was borrowed from the Jet Propulsion Lab, the LBA is fully funded by the Federal Government's Major National Research Facilities program. The LBA has the status of a national facility, managed by the Australia Telescope National Facility, and so potential users are granted observing time according to the scientific merit of their proposal. The LBA is also an important element in the Asia-Pacific region, linking Australia to radio telescopes in Brazil, Chile, China, India, Japan, New Zealand and South Korea. Finally, the LBA was also involved in what is known as space VLBI (SVLBI) where ground-based arrays are linked to antennas in Earth orbit to create baselines as long as several Earth diameters. Two of the main Australian SVLBI collaborations have been the Russian-led RadioAstron and the Japanese-led VLBI Space Observatory Program, involving up to fifty radio telescopes in more than twenty countries. VLBI and SVLBI have been spectacular examples of how progress in science is achieved through international collaboration.

5.7 Simply Astronomical – the Square Kilometre Array

Until recently, with the exception of the small group at the University of Tasmania (Fig. 5.22), Australian radio astronomy has really been New South Wales radio astronomy. Every major Australian radio telescope was located in NSW, lying roughly on a north-south line running down the centre of the state, west of the Great Dividing Range of mountains. Towards the north near Narrabri were first the Radioheliograph followed by the Australia Telescope Compact Array, and then to the south was the small precision dish near Siding Spring. Further south was the Parkes dish and then another four-hour drive to the Molonglo Cross near Canberra. The one exception to the north-south line was the Fleurs Synthesis Telescope near Sydney, operated by Chris Christiansen and his group. Australia's optical astronomers were also concentrated in NSW. The intensity interferometer built by Robert Hanbury Brown, and used for measuring the diameter of stars, was located at Narrabri, while Siding Spring mountain was host to a suite of instruments operated by the Australian National University, as well as the UK 1.2 m Schmidt Telescope (opened in 1973) and the Anglo-Australian 3.9 m Telescope (opened in 1974).

Early in the new millennium the focus of Australian radio astronomy began to shift from NSW to a remote site in outback Western Australia. The site in Murchison Shire north of Perth had been shortlisted as a possible host for the largest, the most complex, and by far the most costly radio telescope ever planned – the Square Kilometre Array.

But first a brief diversion. Much of this chapter has been devoted to the evolution of Australian radio telescopes over the past fifty or so years and very little has been said about the more general development of Australian astronomy as a profession. In the 1950s there was no national association of astronomers and so if any of the

Fig. 5.22 The Physics Department at the University of Tasmania currently maintains two radio observatories, one at Mt Pleasant near Hobart (shown here), and the other at Ceduna on the Nullabor Plain (Fig. 5.21). At both stations, former US satellite-tracking 23 m dishes are the main antennas (courtesy: University of Tasmania and Martin George)

radio astronomers at Radiophysics did feel part of a particular professional discipline it was more likely to be physics or radio engineering. This changed in 1966 when a small group of astronomers in Sydney formed the Astronomical Society of Australia (ASA), with Harley Wood, Director of Sydney Observatory, elected the inaugural president (see Fig. 1.17). The initial membership was about 90 and the great majority were either radio astronomers from Radiophysics and the University of Sydney or optical astronomers from the Mt Stromlo Observatory (a department of the Australian National University) (Lomb, 2015).

The membership of the ASA grew steadily to about 350 by the year 2000 and since then it has doubled to over 700 in 2019. This growth is impressive when compared with other Australian professional bodies in the physical sciences which have only shown modest growth, or indeed flat-lined, over the same period of time. Also impressive is that the number of women ASA members has grown from a handful in 1966 to 30% of the current membership (Wyithe, 2019). This expansion also reflects the growth and diversification of Australian astronomy with significant new groups at universities and institutions across the country: the Australian Astronomical

Observatory (formerly the Anglo-Australian Observatory), University of NSW, Macquarie University, Western Sydney University (NSW); University of Queensland, University of Southern Queensland (QLD); University of Adelaide (SA); Monash University, Swinburne University, University of Melbourne (VIC); and Curtin University, International Centre for Radio Astronomy Research, University of Western Australia (WA).

The Square Kilometre Array (SKA) is the astronomical equivalent of the Large Hadron Collider, the particle accelerator operated by the European Organisation for Nuclear Research (CERN) in Switzerland, the most expensive scientific instrument on the planet. The SKA will be too complex and too costly to be built by any one country. Instead, similar to CERN which is a consortium of mainly European countries, the SKA will be built by an international consortium of countries, consisting of (at the time of writing) Australia and fifteen other countries. The origins of the SKA go back to about 1990 when radio astronomers debated what type of radio telescope would be needed to investigate the leading astronomical questions of the new millennium. The consensus was that a new telescope would need to have 50 times the sensitivity of any existing telescope and with a total collecting area of one square kilometre (Ekers, 2013). An international working group was established in 1993, followed by the International SKA Project Office in 2003. Next came the SKA Program Development Office, which oversaw much of the development work up to the establishment of the SKA project as a legal entity in 2011 (Fig. 5.23). Four bids to host the SKA were short-listed – Australia, China, South Africa and a joint Argentina–Brazil bid – and in 2008 the list was whittled back to just Australia and South Africa.

Most commentators thought Australia's bid to host the SKA was much stronger than South Africa's. South Africa planned to locate most of the SKA in the semi-arid Karoo region of the country, but to achieve long baselines parts of the giant array would need to be located in eight other countries in southern Africa, including

Fig. 5.23 Richard Schilizzi was the inaugural Director (2003–2011) of the International SKA Project Office, based initially in the Netherlands and from 2008 at the University of Manchester. Richard completed a PhD on the structure of extragalactic radio sources at the University of Sydney in 1973 (courtesy: Richard Schilizzi)

Botswana, Namibia and Zambia. In contrast, Australia was large enough geographically to accommodate all of the SKA (with the possible inclusion of New Zealand) and so the logistics of establishing and operating the telescope would be much easier. Australia offered political stability with much of the infrastructure in place and, not least, was already firmly established as a leader in radio astronomy. It therefore came as a great surprise in May 2012 when it was announced that the SKA would not be awarded to just one country, but be shared between Australia and the consortium of southern African countries. Rather than one country or region, there would be two. Australia would host an array operating at low frequencies (50 to 350 MHz) – known for short as SKA-low – while southern Africa would host a completely different array operating at frequencies from 350 MHz to 14 GHz – known as SKA-mid.

The site chosen to host SKA-low is a flat semi-arid plain in Murchison Shire, approximately 800 kilometres north of Perth in central Western Australia. In 2009 CSIRO bought the pastoral lease to Boolardy Station in the middle of the shire, relocated the cattle and fenced off the site. Although the shire itself is about the size of the Netherlands, there are only about 110 permanent residents most of whom belong to the Wajarri Yamatji nation. The site has exceptionally low levels of man-made radio interference and to preserve the quietness a 520 kilometre exclusion zone has been established that bans any possible sources of radio interference (apart from satellite emissions – see Fig. 5.24).

Fig. 5.24 The Project Scientist for the ASKAP, Lisa Harvey-Smith, at the entrance to the observatory. A visit to the Murchison Radio-astronomy Observatory (MRO) from Sydney involves two full days of travel. First is a four-hour flight to Perth, followed by a one-hour flight north to the coastal town of Geraldton. Next day a 4WD vehicle, loaded with supplies, is required to drive north-east along a 300 km stretch of dirt road to the observatory site (courtesy: Lisa Harvey-Smith)

In the lead up to the construction of the SKA, three so-called ‘precursor’ arrays have been built, one in South Africa and two at the Murchison Radio-astronomy Observatory (MRO). These arrays are exceptionally powerful telescopes in their own right, but have the dual role of being test-beds to perfect the technology and techniques required by the SKA. MeerKAT at the Karoo site in South Africa consists of sixty-four 13.5 m dishes, covering the frequency range 580 MHz to 14 GHz, and came into operation in 2018. The Australian Square Kilometre Array Pathfinder (ASKAP) consists of thirty-six 12 m dishes and includes innovative technologies such as phased array feeds to give a wide field of view (30 square degrees). ASKAP was designed and built by CSIRO and officially opened in October 2012 (though it took several years for ASKAP to become fully operational – see Figs 5.25 and 5.26).

Fig. 5.25 Some of the thirty-six dishes forming the Australian Square Kilometre Array Pathfinder. The full array is spread over an area 6 km wide. ASKAP was designed and built by CSIRO at a cost of \$A188 million (courtesy: CRAIA and CSIRO/Alex Cherny; all rights reserved)

Fig. 5.26 The Murchison Radio-astronomy Observatory and ASKAP were officially opened in October 2012. A highlight were dances performed by the traditional owners of the land (courtesy: CRAIA; credit: Carole Jackson)

A wide range of observations have now been completed, mainly high-speed large-scale surveys of the southern sky, where it seems almost obligatory to name the project so that its acronym corresponds to an Australian animal: Evolutionary Map of the Universe (EMU), Deep Investigations of Neutral Gas Origins (DINGO), and we'll let our readers puzzle over what the projects POSSUM and WALLABY could possibly be.

The second Australian SKA precursor is the Murchison Widefield Array (MWA), a low frequency (80–300 MHz) interferometer which came into operation in 2013 (Fig. 5.27). In contrast to ASKAP, the MWA project is an international collaboration currently consisting of 21 institutions in six countries (Australia, Canada, China, Japan, the United Arab Emirates and the United States), with funding for the MWA provided by the partner institutions and a number of national funding agencies. Eight of the 21 partner institutions are Australian with the leading roles played by Curtin University and the International Centre for Radio Astronomy Research in Perth. ICRAR was formed in 2009 with the specific purpose of supporting Australia's bid to host the SKA and currently consists of over 100 staff and post-graduate students (Fig. 5.28). The historical concentration of Australian radio

Fig. 5.27 The Murchison Widefield Array consists of thousands of ‘bowtie’ dipoles arranged in groups of sixteen, known as tiles. The tiles are scattered throughout the observatory. The MWA has carried out a full survey of the southern sky over the frequency range 72–231 MHz, producing a catalogue of 300,000 radio sources (courtesy: ICRAR/Curtin University)

astronomy in Sydney at Radiophysics, the University of Sydney, and then the Australia Telescope National Facility, has now shifted to a quite significant degree to ICRAR and Curtin University in Perth.

The construction of SKA-Low – or the Low Frequency Aperture Array (LFAA) as it is now known – is expected to begin in early 2022. Phase 1 of the construction will see the deployment of over 130,000 identical antennas to create what has been

Fig. 5.28 Rachel Webster (left) at the University of Melbourne initiated and guided plans for the Murchison Widefield Array. The current MWA Director Steven Tingay is based at the International Centre for Radio Astronomy Research in Perth (courtesy: Rachel Webster and ICRAR; credit: MCB Photographics)

described as ‘a forest of steel Christmas trees’ (Mannix, 2018) (see Figs 5.29 and 5.30). The core of the array will be tightly packed with about three-quarters of the antennas located within a 2 km radius. The remaining antennas will form spiral arms spanning about 50 km to further enhance the image detail. The torrent of data produced by LFAA will be sent by fibre-optic cables to Geraldton on the coast and then south to the Pawsey Supercomputer Centre in Perth, named in honour of the founding father of Australian radio astronomy. Processing and storing the extraordinary amounts of data generated will require colossal computer power – at peak operation it is estimated that the LFAA could generate more data in one day than the entire current global internet.

In the meantime, at the SKA headquarters at Jodrell Bank in England (Fig. 5.31) attempts are being made to finalise the membership of the SKA Organisation, which coordinates about 100 organisations across twenty countries involved in the design and development of the SKA. Currently there are the three host countries Australia, South Africa and the UK, and another thirteen full-member countries Canada, China, France, Germany, India, Italy, Japan, the Netherlands, Portugal, South Korea, Spain, Sweden and Switzerland, with further full-member countries expected to join in the future. One setback has been the announcement by New Zealand in July 2019 that it was quitting the SKA, arguing that the cost of its membership would not directly benefit enough of its radio astronomers (Cartlidge, 2018). Originally, there were plans for both Australia and New Zealand to host the SKA, but this fell through in 2012 with the decision to divide the project between Australia and South Africa. However, with at least eight other countries expressing an interest in joining the SKA Organisation, there may be enough funding to cover the projected price tag of about two billion euros, so that the first phase of the SKA can be completed by the end of the 2020s.

Earlier in this chapter we noted that, in broad terms, the evolution of Australian radio astronomy can be divided into four phases or periods. The first period covered the years 1945–60 when the Radiophysics Lab emerged as a global leader in the new field. It was characterised by small, relatively independent groups working at a variety of field stations in and around Sydney. In most cases these groups devised and built their own radio

Fig. 5.29 (above) The Aperture Array Verification System (AAVS) is a testbed for optimising the design of the SKA-Low antennas. (below) SKA-Low engineer Maria Grazia Labate inspects one of the 256 ‘Christmas tree’ antennas making up the AAVS. The antennas have been designed to minimise cost and to maximise reliability in their harsh climate (courtesy: ICRAR/Curtin University)

telescopes, all of which could be funded within the annual RP budget. The second period of Australian radio astronomy came in the 1960s when Big Science arrived in Australia, with the Parkes dish, the Radioheliograph and the Molonglo Cross all funded by American philanthropy. For the first time the groups lead by Bernie Mills and Chris Christiansen at the University of Sydney challenged RP’s dominance in the field. The third period began in the 1980s when the Australia Telescope bicentennial project revitalised Australian radio astronomy. The development of Australian very long baseline interferometry in the 1980s also belongs to this third period.

Fig. 5.30 Computer image showing how the LFAA might appear after the full deployment of the 130,000 tree antennas in Phase 1. Eventually, provided Phase 2 is fully funded, the number of antennas will be increased to about one million during the 2030s (courtesy: SKA Observatory)

Fig. 5.31 The SKA Organisation is housed in a new building at Jodrell Bank. The organisation planning the world's largest radio telescope is next door to the very first giant radio telescope, completed in 1957. In 1987 the 250 ft dish was renamed the Lovell Telescope in honour of Sir Bernard. In February 2021, the SKA Organisation was superseded by the SKA Observatory, with Philip Diamond as the inaugural Director-General. The SKA Observatory is the intergovernmental organisation that will build and operate the SKA telescopes (courtesy: SKA Observatory)

We are now very much in the fourth period where Australia will play host to a gigantic multinational array, where both the cost and the sensitivity of the SKA will be up to two orders of magnitude greater than the Australia Telescope Compact Array. Will there ever be a fifth period of Australian radio astronomy? With the SKA projected to have a lifespan of fifty years or more, it is difficult to say. If there is to be a fifth period, then almost certainly it will be the result of major advances in the technology of radio telescopes.

Over sixty years after its inauguration in 1961, the Parkes Observatory holds the current Australian record for longevity. Perhaps one day that record will pass to the Murchison Radio-astronomy Observatory.

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