John Bolton and the Nature of Discrete Radio Sources

Thesis submitted by

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Abstract

John Bolton is regarded by many to be the pre-eminent Australian astronomer of his generation. In the late 1940s he and his colleagues discovered the first discrete sources of radio emission. Born in Sheffield in 1922 and educated at Cambridge University, in 1946 Bolton joined the Radiophysics Laboratory in Sydney, part of Australia's Council for Scientific and Industrial Research. Radio astronomy was then in its infancy. Radio waves from space had been discovered by the American physicist Karl Jansky in 1932, followed by Grote Reber who mapped the emission strength across the sky, but very little was known about the origin or properties of the emission. This thesis will examine how the next major step forward was made by Bolton and colleagues Gordon Stanley and Bruce Slee. In June 1947, observing at the Dover Heights field station, they were able to show that strong radio emission from the Cygnus constellation came from a compact point-like source. By the end of 1947 the group had discovered a further five of these discrete radio sources, or 'radio stars' as they were known, revealing a new class of previously-unknown astronomical objects.

By early 1949 the Dover Heights group had measured celestial positions for the sources accurately enough to identify three of them with known optical objects. One coincided with an unusual object in the local Galaxy and two coincided with peculiar extragalactic objects. As I will show, the optical identifications built a bridge between traditional astronomy and the fledgling radio astronomy. The identifications also marked the birth of extragalactic radio astronomy, which was to have a major impact on the development of astronomy in the second half of the twentieth century.

In the early 1950s, with improved instrumentation, the Dover Heights group carried out a sky survey that revealed over 100 radio sources, consolidating its position as the world's leading group for 'cosmic' radio astronomy. To conclude, I will briefly survey Bolton's career after the closure of Dover Heights in 1954. Bolton had the unusual distinction of being the inaugural director of two major observatories, first at the California Institute of Technology (1955–60) and then at the Parkes Observatory (1961–81) in central NSW. No astronomer did more over his career to establish radio astronomy as a mature and powerful branch of astronomy.

Certification of Dissertation

I hereby certify that the work contained in this dissertation is the bonafide work of my own, that the work has not been previously submitted for an award, and that, to the best of my knowledge and belief, the dissertation contains no material previously published or written by another person except where due acknowledgement and reference is made in the dissertation to that work.

Signature of Candidate Date

ENDORSEMENT

Signature of Principal Supervisor Date

Signature of Associate Supervisor Date

Acknowledgments

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The research for this thesis has been carried out in conjunction with the preparation of a full-length biography of John Bolton to be published as a book. I would especially like to thank Mrs Letty Bolton and Professor Ron Ekers for their continued support of this project.

My research has drawn on three principal sources of archival material: the personal papers of John Bolton held in the National Library of Australia (Canberra); the official correspondence files of the Radiophysics Lab held in the National Archives of Australia (Chester Hill, NSW); and the Radio Astronomy Image Archive administered by the Australia Telescope National Facility (Marsfield, NSW). I am grateful to the staff at these three institutions for their assistance in accessing this material.

I would like to thank the National Library of Australia for providing a Harold White Fellowship to support my study of the Bolton papers in 2008 and to Manning Clark House in Canberra for providing a Residential Fellowship in 2009.

I am also grateful to three Examiners for their helpful and constructive comments on an earlier draft. Their comments have resulted in a significant improvement to the historical accuracy and interpretation of this final version.

Finally, I am pleased to dedicate this thesis to my amazing, talented daughters, Katie and Laura.

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Chapter 1

Introduction

John Bolton is regarded by many to be the pre-eminent Australian astronomer of his generation. His career consisted of three distinct periods: the years 1946–53 at the Dover Heights field station in Sydney; the years 1955–60 at the California Institute of Technology (Caltech) in Pasadena; and the years 1961–81 at the Parkes telescope in central New South Wales. This thesis will focus almost entirely on the Dover Heights period. It was during this time that Bolton, together with colleagues Gordon Stanley and Bruce Slee, discovered and identified the first discrete radio sources, or radio ‘stars’ as they were known, one of the most important discoveries in twentieth century astronomy.

The research for this thesis has been carried out in parallel with the first full-length biography of Bolton, which is currently in preparation. The Dover Heights period will be covered in three chapters of the biography. The thesis will be a far more detailed and rigorous study of this period than is possible in the book. In the present chapter, we will review the relevant published sources, discuss the unpublished sources, and conclude with a brief outline of each of the other seven chapters.

1.1 Literature Review

The origins and early development of radio astronomy in Australia is possibly the most intensively-studied chapter in the history of Australian science. Radio astronomy began immediately after the end of World War II in the Radiophysics Laboratory in Sydney, a division of the Council for Scientific and Industrial Research (the forerunner of the Commonwealth Scientific and Industrial Research Organisation – CSIRO). In the late 1940s and early 1950s the Radiophysics Lab operated up to eight field stations in and around Sydney. The radio observations at each site were under the general supervision of the head of the radio astronomy group, Joseph Lade Pawsey (1908–62). The early radio observations at a number of these field stations have been the focus of two recent PhD theses. Ron Stewart (2010) has examined the solar radio astronomy carried out at the Penrith and Dapto field stations, while Harry

Wendt (2009) has examined the contributions of the Potts Hill and Murraybank field stations to international radio astronomy. The current thesis will focus on the research program carried out at the cliff-top field station at Dover Heights, 5 km south of the entrance to Sydney Harbour.

Among the first to write about the history of Australian radio astronomy were the early practitioners, the radio astronomers themselves. The overview by Pawsey (1953) appears to be the earliest – see also Pawsey (1961). Other personal reminiscences have been given by Bolton (1982), Bowen (1988), Mills (2006), Slee (2005) and Wild (1972). Early Australian radio astronomy has also attracted the interest of historians of science, both amateur and professional. The books by Robertson (1992) on the history of the Parkes radio telescope and by Haynes *et al.* (1996) on the history of Australian astronomy both devote lengthy sections to the early years of radio astronomy.

The first professional historian to research the early history was Woodruff Sullivan at the University of Washington, Seattle. His landmark publication (Sullivan 1984) contained historical chapters by five Australian pioneers (Bowen, Bracewell, Christiansen, Kerr and Mills). In 1988 Sullivan published the first detailed history of early Australian radio astronomy in the book ‘Australian Science in the Making’, a volume marking the bicentenary of Australian science. More recently Sullivan (2009) has published the study ‘Cosmic Noise: A History of Early Radio Astronomy’, widely regarded as the most comprehensive and definitive book on the subject. The book devotes well over a chapter to the Radiophysics Lab during the period 1945–52 and is based on his earlier study on the beginnings of Australian radio astronomy (Sullivan 2005).

By far the most prolific writer on the early history of Australian radio astronomy has been the Australian historian of science Wayne Orchiston. Over the past twenty years he has edited several books and written numerous book chapters and journal articles, many of them coauthored by Bruce Slee, one of Bolton’s principal colleagues at the Dover Heights field station (see e.g. Orchiston 2004, 2005a, 2005b; Orchiston and Slee 2002, 2005; Robertson *et al.* 2014). This thesis will attempt to build on this existing body of work and provide a deeper insight into the discoveries at Dover Heights.

Another valuable source of information is Goddard and Haynes (1994), a special issue of the *Australian Journal of Physics* (at this time the present author was the managing editor of the *AJP*). The issue consists of papers presented at a symposium in memory of Bolton held at the Parkes telescope in December 1993. Papers by Bruce Slee, Gordon Stanley and Kevin Westfold are devoted to the Dover Heights years, while another paper by Wayne Orchiston describes the expedition to New Zealand by Bolton and Stanley in 1948 (see Chapter 4).

In 1965 Bolton was elected a fellow of the Australian Academy of Science. In 1973 he was elected a fellow of the Royal Society of London, becoming the fourth Australian radio astronomer to receive the honour following Joe Pawsey (1954), Bernard Mills (1963) and Paul Wild (1970). As is customary for fellows, Bolton prepared lengthy autobiographical notes which would be used as the basis of his official memoir by Wild and Radhakrishnan (1995), published by both the Australian Academy and the Royal Society. Three other biographical memoirs have been published by Radhakrishnan (1993), Kellermann (1996) and Kellermann and Orchiston (2008). Biographical articles have also been published for Bolton’s two principal collaborators at Dover Heights – Gordon Stanley (Kellermann *et al.* 2005) and Bruce Slee (Orchiston 2004, 2005a).

Finally, there were 23 research papers produced by the Dover Heights group and published over the period 1947–57 (see the Appendix). Bolton was the sole author or co-author on all but four. Seven of the papers were short communications in the prestigious British journal *Nature*, while 12 papers were published in the *Australian Journal of Scientific Research (Series A)* (commenced 1948) or its successor the *Australian Journal of Physics* (commenced 1953).

1.2 Discussion of Unpublished Sources

After Bolton died in July 1993 his family arranged for his personal papers to be deposited in the National Library of Australia in Canberra where they could be properly sorted and catalogued. The collection is arranged into five series: Series 1 –

correspondence (1940–93); Series 2 – published articles and papers (1947–93); Series 3 – newspaper cuttings (1948–93); Series 4 – photographs (1951–89); and Series 5 – general papers (1968–91).

In 2008 I spent two extended periods in Canberra studying the Bolton papers, supported by a Harold White Fellowship awarded by the National Library. The following year I spent a third extended period in Canberra, supported by a residential fellowship at Manning Clark House, and completed my examination of the Bolton papers. My research has involved a number of visits to Sydney where most of Bolton's family and former colleagues currently live. The Radiophysics Lab correspondence files relevant to the Dover Heights period are held in the NSW branch of the National Archives of Australia in the Sydney suburb of Chester Hill.

Correspondence

There is very little correspondence relevant to this thesis among Bolton's personal papers in the National Library, but this was anticipated. In 1984 Bolton told me that his personal papers from the Dover Heights years had been lost. He could not recall exactly when, but it may have been during one of the several occasions he moved house in California. There are a few documents relating to his Cambridge degree and his discharge from the Royal Navy, but nothing else of relevance.

In complete contrast, the Radiophysics Lab correspondence files held in the National Archives provide a wealth of relevant material. Whenever a research officer corresponded with a person or institution outside the Lab, or with a Radiophysics colleague overseas, it was considered official business. The research officer was obliged to have the letter typed by the Lab's pool of secretaries and arrange for a carbon copy to be added to the relevant file. The result was a remarkably complete and comprehensive coverage of the Lab's activities during the postwar years. Most of the files were transferred from Radiophysics to the National Archives in the mid-1990s. Since then many of the files have been digitised and are available online. The existence of this excellent resource has been a significant reason behind the surge in interest by historians in the early history of Australian radio astronomy, as discussed above.

Illustrations

The majority of photographs reproduced in this thesis are previously unpublished and have been obtained from a variety of sources. The major source is the Radio Astronomy Image Archive (RAIA) managed by the Australia Telescope National Facility (successor to the Radiophysics Lab) (see https://imagearchive.atnf.csiro.au). Other significant sources include the Bolton and Stanley families and the Bolton papers in the National Library.

Most of the line diagrams are reproduced from various Dover Heights research papers and credit is given to the relevant publisher.

Interviews

Bolton carried out three major interviews later in his career and transcripts are available for each:

- Interview by Lennard Bickel at University House, Canberra, in January 1975. The interview was conducted on behalf of the Oral History Section of the National Library as part of its ongoing project to interview prominent Australians. At the time Bickel was science correspondent for *The Australian* newspaper

- Interview by Woody Sullivan at Jodrell Bank, UK, in August 1976, and at Parkes, NSW, in March 1978. The interview was part of Sullivan's research into the early history of radio astronomy and led to the publications cited above (Sullivan 1988, 2005, 2009). Sullivan has also provided me with transcripts of interviews he conducted with Gordon Stanley (Owens Valley, California, June 1974) and Bruce Slee (Marsfield, NSW, March 1978)

- Interview by the author at Buderim, Qld, in April 1984. This interview was part of my research on the history of the Parkes telescope (Robertson 1984, 1992)

In addition to Bolton himself, I have interviewed various family members including his wife Letty Bolton (Round Corner, NSW, November 2006 and July 2007) and his son Brian Bolton (Melbourne, April 2007). I have also interviewed three of the five members of the Dover Heights group: Richard ('Dick') McGee (Eastwood, NSW, November 2006), Bruce Slee (Marsfield, NSW, November 2006) and Kevin Westfold (Monash University, Vic., March 1984). I did not have an opportunity to interview Gordon Stanley who died in 2001. I did however have the opportunity in May 2010 to examine his personal papers, held by one of his daughters at her home in northern California. These papers were recently donated to the archives of the California Institute of Technology, where Stanley spent most of his career after the closure of the Dover Heights field station in 1954.

1.3 Summary of Chapters

The thesis will consist of eight chapters. Chapter 2 will set the scene up to when Bolton joined the Radiophysics Lab in 1946, while Chapters 3–6 will cover the Dover Heights years 1946 –53. Chapter 7 will consist of an overview of the remainder of Bolton's career, while the final chapter will present my concluding remarks.

Chapter 2 – From Radar to Radio Astronomy

John Gatenby Bolton was born in Sheffield in 1922 and both his parents were teachers. He attended the leading secondary school in Sheffield and won a scholarship to study science at Trinity College, Cambridge. After graduating in 1942 he enlisted in the Royal Navy and spent two years carrying out research in airborne radar, before being appointed the radio officer on a British aircraft carrier.

The Radiophysics Laboratory in Sydney was formed in 1940 to carry out secret wartime research in radar. At the end of the war the Lab investigated a wide range of peacetime applications of radar. Radio astronomy turned out to be the wild card in the pack. By 1950 approximately half the resources of the Lab were devoted to radio astronomy.

In this chapter we also look at the origins of radio astronomy itself, beginning with the discovery of radio waves from space by Karl Jansky, a physicist at the Bell Telephone Laboratories in New Jersey. Jansky's discovery was followed up by a radio engineer, Grote Reber, who built his own radio telescope in his hometown near Chicago. Reber produced the first maps showing the intensity of radio emission across the sky.

Chapter 3 – Discovery of the First 'Radio Stars'

When Bolton joined the Radiophysics Lab in September 1946 he was stationed at a field station at Dover Heights, a short distance south of the entrance to Sydney Harbour. Bolton was assigned the task of observing and analysing the radio emission from the Sun. With colleague Bruce Slee, he tried to detect radio emission from other astronomical objects such as the Moon and the planets, but the attempt failed.

Several months later Bolton decided to investigate a report by an English group that there is unusually strong radio emission coming from the constellation of Cygnus. With colleague Gordon Stanley, Bolton used a technique known as sea interferometry which uses a simple aerial similar to a TV antenna. The aerial is pointed out to sea where it picks up the direct radio signal from above the horizon and the signal reflected from the sea surface to create an interference pattern. In June 1947 they succeeded in detecting the emission from Cygnus and, from its distinctive interference pattern, they were able to conclude that the emission came from a very compact point-like source. By the end of 1947 Bolton, Stanley and Slee had found a further five of these point-like sources. Here was evidence that the Dover group had discovered a new class of astronomical object previously unknown to astronomers.

Chapter 4 – Identification of the First Radio Sources

The celestial positions of these first few sources were known only approximately and so it was not possible to identify them with any visible objects. Bolton decided to find a better observing site than Dover Heights. He needed a site where the cliffs were much higher (and thus give better resolution) and where he could observe the sources rise above the horizon in the east and then set below the horizon in the west. Nothing suitable could be found on the eastern seaboard of Australia, so Bolton chose the north island of New Zealand where there were very high cliffs on both the east and west coasts. Gordon Stanley built a sea interferometer on a mobile trailer which was shipped to New Zealand in June 1948.

Bolton and Stanley returned to Sydney after three months of observations. It took Bolton several months to analyse the data and by the end of the year he had derived accurate positions for four sources. The Cygnus position was still not accurate enough to make a positive identification, but the other three all coincided with very unusual objects. One coincided with the Galactic object known as the Crab Nebula, a supernova remnant which had been studied intensely by astronomers. The other two coincided with extragalactic objects which provided an even bigger surprise – how could objects at such vast distances radiate so much radio energy? Bolton, Stanley and Slee published their first three identifications in a short note to *Nature*. They had now established a bridge between traditional optical astronomy and the fledgling new radio astronomy.

Chapter 5 – The Emergence of Radio Astronomy in Australia and England

By 1950 the Dover Heights group was only one of a number of Radiophysics groups involved in radio astronomy at field stations in and around Sydney. Approximately one-half of radio astronomy resources were devoted to radio studies of the Sun. Collectively, the Radiophysics radio astronomy group under Joe Pawsey's leadership was the largest in the world. The two main rivals to Radiophysics were the group at the University of Cambridge led by Martin Ryle and the group at the University of Manchester led by Bernard Lovell. Both these groups were however relatively small and during the postwar austerity in England could not match the resources available at Radiophysics.

Bolton spent most of 1950 touring the major astronomical observatories and the emerging radio astronomy centres in England, Europe and the United States. He lectured extensively on the research at Dover Heights and helped to publicise the work at Radiophysics. On his return to Sydney, Bolton was undoubtedly one of the best connected and most knowledgeable of the growing band of scientists referring to themselves as 'radio astronomers'.

Chapter 6 – Consolidation and Competition: The Dover Heights Years 1951–54

In the early 1950s the Dover Heights group built a series of new instruments culminating in the so-called 12-yagi sea interferometer. This instrument was used to carry out a sky survey that detected and catalogued over 100 new radio sources. Another major instrument was a parabolic dish dug out of the ground known as the hole-in-the-ground telescope. With new recruit Dick McGee, Bolton used this instrument to carry out a survey of radio emission along the plane of the Milky Way and this led to the discovery of the nucleus of the Galaxy.

Bolton wanted to build an even larger instrument at Dover Heights in 1953 but was unsuccessful. Joe Pawsey and the Radiophysics group decided instead to build a new cross-type instrument devised by Bernard Mills. Bolton decided to temporarily leave radio astronomy and move into the other major research activity at Radiophysics – the cloud physics and rainmaking group.

Chapter 7 – Beyond Dover Heights: An Overview of Bolton's Career 1955–81

Bolton had the unusual distinction of being the foundation director of not one but two major radio astronomy observatories. Although the Americans Karl Jansky and Grote Reber pioneered radio astronomy in the 1930s, the US did not build on its lead after the war. This changed in 1955 when the California Institute of Technology (Caltech) invited Bolton and Gordon Stanley to build a new radio astronomy observatory. They chose a site at Owens Valley near the Sierra Nevada Mountains and designed an interferometer consisting of two large parabolic dishes. In 1960 Bolton returned to Australia to become the inaugural director of the Parkes telescope in central NSW.

This chapter will show that the remainder of Bolton's career did not deviate too far from the original program at Dover Heights. During the 1970s he led a sky survey at Parkes that discovered and catalogued over 8000 radio sources, many of which were a new class of object known as quasars. Over his career no one had done more to establish radio astronomy as a mature new science.

Chapter 8 – Concluding Remarks

In the final chapter I will attempt to draw together the main points and conclusions of John Bolton's career during the Dover Heights years 1946–53. In a series of bullet points I will summarise Bolton's personal achievements, the significance of the research by the Dover Heights group, and the contribution of the Radiophysics Lab to the development of radio astronomy. Next, I will suggest a few topics related to this thesis which might prove fruitful areas to investigate by future researchers. Finally, I will make a few remarks about Bolton's later years, showing that the Dover Heights period was just the first stage of what turned out to be a remarkable and influential career in astronomy – both radio and optical.

Chapter 2

From Radar to Radio Astronomy

In 1983 the pioneer radio astronomer Robert Hanbury Brown wrote a brief article that discussed the role of serendipity in science. He concluded with the amusing observation: ‘How can you plan serendipity? I think that you need the right man in the right place at the right time, but he must be a man who doesn’t know too much!’ [1]. In retrospect we can see that John Bolton makes an excellent case study of Hanbury Brown’s aphorism.

In terms of his background and training, Bolton qualified as the *right man* to be a pioneer of radio astronomy. Bolton did not begin school until grade 6 in primary school. His mother, a former teacher, taught him the basics, but otherwise Bolton was self-taught and independent in his thinking. He showed his academic talent at secondary school and in his final year won two scholarships to study at Trinity College, Cambridge. He majored in mathematics and physics in his Bachelor of Science degree which provided a solid theoretical foundation for his career ahead. Bolton enlisted in the Royal Navy in 1942 and spent two years developing airborne radar equipment and then a further two years as a radio officer onboard an aircraft carrier. He became an expert in getting radio and electronic equipment to operate correctly, often in difficult physical conditions and often under the urgency of wartime deadlines. Bolton once remarked that his four years in the navy were far better preparation for a career in radio astronomy than any postgraduate training at a university [2].

Bolton was also in the *right place*. In 1946 he joined the Radiophysics Laboratory in Sydney, part of the Council for Scientific and Industrial Research (the forerunner of CSIRO). The Radiophysics Lab had been formed in 1940 to carry out secret wartime research on radar for the armed forces. By the end of the war the Lab had a highly skilled staff and was the best-equipped laboratory of any in Australia. The Lab investigated a wide range of possible peacetime applications of radar. Radio astronomy proved to be the wild card in the pack. By 1950 half the resources of the Lab were devoted to radio astronomy. If Bolton had joined a government research lab with a rigid research program it seems unlikely that radio astronomy would have emerged to become one of the great success stories of Australian science.

It was also the *right time* to begin a career in radio astronomy. The discovery of radio waves from space was made in 1932 by the physicist Karl Jansky, who worked for the Bell Telephone Laboratories in New Jersey. Jansky was given the task of identifying the sources of interference to a new trans-Atlantic radio communication service. In a fine example of serendipity in science, Jansky found that there was a steady component in the interference that appeared to have no terrestrial origin. Jansky's discovery was followed up by a radio engineer, Grote Reber, who built his own radio telescope at his parents' home near Chicago. Reber produced sky maps of the radio emission which seemed to suggest that the emission was produced by ionised clouds of matter in interstellar space. At the end of the war, the time was ripe for other enterprising radio engineers and physicists to take the next step.

Bolton also qualified for Hanbury Brown's final criterion of being *a man who doesn't know too much*. Like almost all of the generation of postwar radio astronomers, Bolton had no formal training in astronomy. Similar to his early self-taught years before starting school, he became a self-taught astronomer. He used the night-time observing runs to read textbooks and back issues of the research journals. His Cambridge degree made it relatively easy for him to pick up what he needed on the run.

2.1 Early Life: From Sheffield to Sydney

John Gatenby Bolton was born in Sheffield, Yorkshire, in 1922. He shared the same name as both his father and grandfather. John's father and mother both came from Yorkshire families with humble beginnings. The Bolton family can be traced back to John's great grandparents. In 1850 Thomas Bolton, a farm labourer, married Elizabeth Gatenby, a dressmaker, in a small town on the edge of the Yorkshire Dales. They are believed to have had three sons and two daughters. The second son was born in 1852 and christened John Gatenby Bolton, in keeping with a Yorkshire custom of adopting the mother's maiden name as the child's middle name. Thomas and Elizabeth seem to have done reasonably well for themselves. The Yorkshire census from 1871 records them as having a combined grocery and drapers shop [3].

In 1875 John's grandfather, the first John Gatenby Bolton, married Annie Andrew and they settled in the mining town of Skelton-in-Cleveland. They had five children, though they lost their fourth child, a two-year old girl, when a typhoid epidemic swept through the district in the early 1880s. Their fifth child, a boy and very much an afterthought, arrived ten years later and was named after his father. John's grandfather spent his entire career working for South Skelton Mines as a cashier, making up the pay packets of the miners. He was also on call night and day to organise rescue missions whenever there had been an accident at the mine, not an infrequent occurrence in those times. Known for his financial skills, grandfather Bolton was the founder of the Skelton branch of the Yorkshire Penny Bank, one of dozens of branches that sprang up in Yorkshire at this time. These non-profit community banks, staffed by volunteers, introduced the practice of banking to the working class.

Similar to his father, John's mother was also an afterthought in her family. Ethel Kettlewell was born 15 years after her sister and almost 20 years after her brother. Although Kettlewell came originally from the name of a small Yorkshire village, the Kettlewell family were farmers from Lincolnshire, the county to the south of Yorkshire. It was John's maternal grandfather, Thomas Kettlewell, who made the break from rural life. He and his wife Elisabeth moved to Goole in East Yorkshire where he had ambitions to be a railway engine driver. However, an accident left him partially disabled and he had to settle for a career as a railway guard [4].

Both John's parents were schoolteachers and, most unusual for the time, both had university degrees. His mother, Ethel Kettlewell, graduated from Leeds University with an Arts degree and taught in Leeds for a short while before returning home to teach botany at the Goole Grammar School, a public co-educational school. John's father, John Bolton senior, was educated at a grammar school near Skelton-in-Cleveland. He then went to Exeter College on the south coast of England, part of the University of London, and in 1915 he was awarded a Bachelor of Science degree, with a major in mathematics, together with a Bachelor of Education. He tried to enlist but was spared the carnage of World War I when he failed the medical. John took up teaching instead and in 1916 was appointed the mathematics master at Goole Grammar. A history of Goole noted that their grammar school 'was fortunate in having the services of a brilliant mathematician, J. G. Bolton, who also played the piano for morning assembly and later married Miss Kettlewell, the botany mistress' [5].

Figure 2.1. Bolton with his mother Ethel and sister Joanne on holiday in Bridlington on the North Sea coast. [courtesy: Wheatley family]

John and Ethel married in July 1921 at the Methodist Chapel in Goole and spent their honeymoon in Exeter. Upon returning to Goole they began preparing to set up home when a letter arrived which led to a sudden change of plans. John had been offered the position of senior mathematics teacher at one of Sheffield's leading schools, an offer he accepted immediately. They moved to Sheffield in late 1921 and rented a small terrace house in a rundown area near the centre of the city. On 5 June 1922, less than a year after their marriage, Ethel gave birth to a boy, John Gatenby Bolton. Two and half years later a daughter Joanne arrived (see Figure 2.1).

When John was five the family moved to a new and more spacious house in Abbeydale, a rural area on the southern outskirts of Sheffield. Two attempts were made to start John in primary school and both failed. He seemed unable to accept the authority of his teacher or understand the need for discipline within the classroom. Fortunately, at this time there was a law in Yorkshire that, if either parent was a teacher, then it was not compulsory to send the child to primary school. After these two early failures John's parents decided to tutor him at home. His mother, who stopped teaching after her marriage, took care of his introduction to the three R's. John read widely and was largely self-taught. He spent much of his time roaming around the surrounding farms. Although he made friends in the neighbourhood, John's primary school years were a lonely time, a time when most children are being thoroughly socialised at school [6].

When John was 11 his parents decided to move back closer to the centre of Sheffield. John's father taught at Central High School and the house they rented when they first moved to Sheffield was within walking distance. When the family moved out to Abbeydale it was easy enough for him to catch the bus to work. However, in 1933 the school decided to relocate from the inner city to a new campus built on the school's playing fields, south-west of the city, an area known as High Storrs near the foothills of the Peninnes. Renamed High Storrs Grammar School, John's father would spend the rest of his career at the new school. The family moved to Ecclesall, a town near the new campus and soon to become a suburb of an expanding Sheffield.

Another reason his parents decided to move is that John would need to spend at least six months at a primary school to be able to sit the entrance examination for secondary school. Towards the end of their stay at Abbeydale, John had overcome his aversion to the classroom and attended a small private school. In Ecclesall both John and sister Joanne were enrolled at nearby Greystones Primary School. As a preview of an outstanding academic career ahead, John passed the entrance examination to secondary school and won a scholarship as well.

There were two main secondary schools in Sheffield in the 1930s. One was High Storrs Grammar, where John's father taught, and which was co-educational to the extent that the boy's school and the girl's school were located on the same campus.

John's father decided that daughter Joanne would go to High Storrs, while John would attend its major rival, the boys-only King Edward VII School. Known popularly as King Ted's, the school was formed in 1905 by the merger of two smaller schools and named after the reigning monarch who had succeeded Queen Victoria in 1901. The school underwent a major growth in the 1920s when it became the school of first choice among Sheffield's growing middle class. Its reputation meant it could attract the most talented teachers. When John started in September 1933 over three-quarters of the staff were graduates from Oxford or Cambridge. Although technically King Ted's could not count itself among the elite public schools, it certainly thought itself as the equal of one [7].

In his first year John studied English, geography, history, mathematics, Latin, French and science. Latin was compulsory for the first three years and each student was required to take a heavy load of six periods a week in the subject. John found Latin with its systematic structure easy to learn and he also found that he had inherited some of his father's talent for mathematics. John's future career was very nearly nipped in the bud when he failed the first-year science subject and for the next two years he transferred to the classics stream of languages, history and mathematics [8]. After four years in middle school, John was awarded the School Certificate with credits in five subjects, but with mediocre results in Latin and Greek. At the beginning of senior school he decided to reverse the disastrous start in science in his first year by choosing physics and mathematics as his two major subjects. In July 1939 John completed the two years of Sixth Form, known rather unimaginatively as the Lower Sixth and the Upper Sixth.

As was the custom for boys planning to go to university, John then spent a year preparing for the Oxford and Cambridge Schools Examination. John's secret weapon was his father. Both King Ted's and High Storrs School had a high success rate in getting their brightest students accepted into Oxford or Cambridge, or Oxbridge as it was collectively known. At High Storrs, John's father had specialised in coaching students for the examination. At any one time he had at least one former student studying at Oxbridge and he would personally supervise John's preparation. John sat the examination at the end of both the Lower and Upper Sixth years and passed both times, but these were only practice runs for the third and final sitting in June 1940.

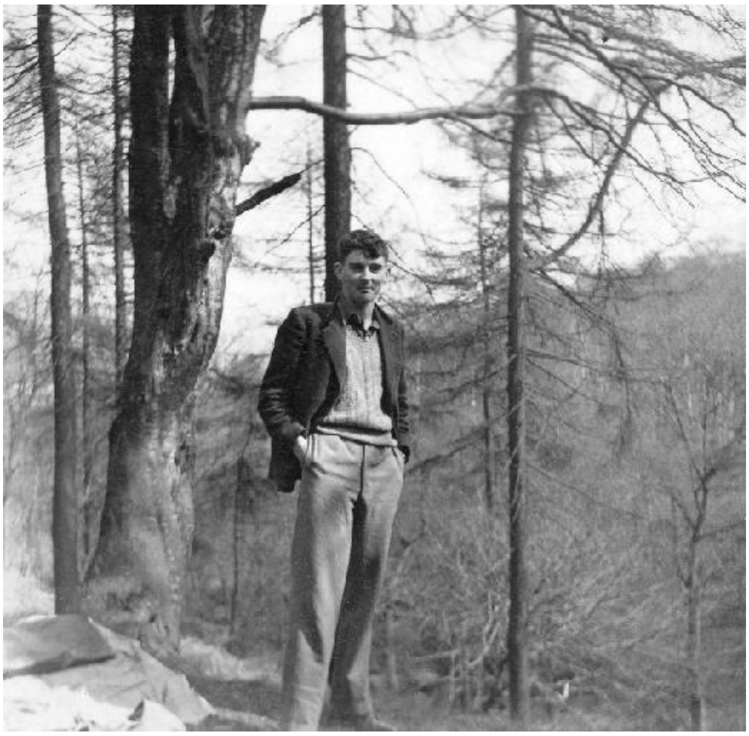


Figure 2.2. Bolton at the time he entered Trinity College, Cambridge. Because of wartime conditions his three-year Bachelor of Science degree was compressed into two years. [courtesy: Bolton family]

Bolton passed the Oxford and Cambridge Schools Examination with flying colours and won a place to study mathematics at Trinity College, Cambridge (see Figure 2.2). He was awarded not one, but two scholarships. One was the Sheffield Town Trust Scholarship worth 50 pounds a year. The other and more prestigious was known as a State Scholarship, awarded by the England Board of Education, and would pay his undergraduate fees as well as provide a living allowance of 100 pounds per year. He arrived at Trinity College in October 1940 and was assigned a room looking out onto Great Court, a large rectangular area at the centre of the college. Across Great Court John could see the first floor windows where Trinity's most famous resident once lived, the mathematician and natural philosopher Isaac Newton (1642–1727). Most of the boys at Trinity were the products of the leading public schools in southern England and many were from wealthy and privileged families. John was conscious of his Yorkshire accent and with his competitive instincts was determined to outdo them all. He was one of 136 new students entering Trinity that year, down by about a third of those who entered the year before, partly a result of students deciding to enlist in the armed services rather than study. Another reason is that, because of wartime conditions, the usual three-year bachelor's degree would be compressed into two years. There would be little opportunity for Bolton and his friends to engage in the normal social and recreational activities that are part of university life in peacetime [9].

In terms of student numbers, Trinity was the largest of all the Cambridge colleges, with a rich history dating back to its foundation in 1546. Its library, designed by Christopher Wren and completed in 1695, is an architectural marvel and, after King's College, is considered to be the most historically important building in Cambridge. Trinity is also the wealthiest of the colleges having built up an extraordinarily large portfolio of property and investments over the years. A list of Trinity alumni reads almost like a Who's Who of British history. As one example, up to 1940, the five men to have been director of the Cavendish Laboratory in Cambridge, the most famous of all physics laboratories, were all Trinity men. To date, Trinity has produced over thirty Nobel Laureates, more than all of France [10].

Mathematics was considered the jewel in the Cambridge academic crown. The mathematics faculty was undoubtedly the most talented group in any British university and it attracted the most number of students. There was no lecture room in Cambridge large enough to hold all the students enrolled in the mathematics tripos, so the lectures were given twice with students divided into a slow stream and a fast stream. John joined the fast stream which consisted of about one half of gifted students entering their first year of university. The other half consisted of students who were considerably older and who had already completed a mathematics degree at another university in Britain or in Commonwealth countries such as Australia. These mature age students came to Cambridge for a final topping up at the finest mathematics school in the world [11].

The full name of the mathematics tripos was 'pure mathematics and natural philosophy', with the latter including any branch of applied mathematics, theoretical physics, theoretical chemistry and theoretical astronomy. In John's first year he attended lectures in subjects such as algebra, mechanics, electromagnetism, statistics and geometry. One of John's lecturers was the astrophysicist Arthur Eddington, who was best known for leading an expedition to Brazil in 1919 to observe a solar eclipse.

The expedition confirmed a prediction made by Albert Einstein that light from a distant star would bend slightly as it passes through the gravitational field of the Sun. The successful prediction soon made Einstein an international celebrity. Eddington was also a renowned science writer and John had read and been inspired by several of his popular books on astronomy.

At the end of his first year John passed the examinations for Part I of the mathematics tripos with first class honours, doing well enough to be awarded a Book Prize and a Trinity College Exhibition, worth 40 pounds per annum. Added to the two scholarships he had won at King Ted's, John now had three separate sources of income, though in practice he was no better off. The England Board of Education had a firm policy on what it considered double dipping, and so John's annual allowance from his State Scholarship was cut from 100 pounds to 60 pounds, leaving him with exactly the same income.

At the end of his first year John moved from Great Court into a slightly larger room in another part of Trinity known as Whewell's Court. For his second year John chose the Physics tripos instead of Mathematics. Because his degree was compressed into two years, he had to spend the summer holidays of 1941 completing the practical laboratory classes, before the lectures commenced for Part II Natural Sciences in Physics in the Michaelmas term. In May 1942 John completed the second and final year of his abbreviated degree by passing the examinations. He finished in the top half of students awarded second class honours. This was not quite as good as the first class honours in his first year, but the reason was understandable. His mother Ethel had been diagnosed with a heart condition shortly after John was born. Her health slowly deteriorated over the years and, aged only 48, she died of a heart attack in May 1942, the same month as John's examinations [12].

Similar to most of his Cambridge friends, Bolton enlisted as soon as the final examinations were over. The navy was the logical choice. John had a love of ships that came from the holidays with his mother's family in Goole. At age 16 his ambition had been to attend Dartmouth Naval College and study to become a naval architect. One of his Kettlewell cousins was the captain of a frigate and had been presented a medal by no less than the King for sinking a German U-boat. During his second year John made contact with the novelist C. P. Snow who was the Royal Navy's recruitment man in Cambridge. Snow arranged for him to apply for a commission, which involved attending an interview at the Navy Board in London. The interview was a formality and soon after the Admiralty appointed John a Sub-Lieutenant in the Royal Navy Voluntary Reserve. As the name indicates, the RNVR consisted of volunteers, unlike the career personnel in the Royal Navy. The volunteers were distinguished from the Royal Navy regulars by having wavy gold stripes of rank on their sleeves. They were popularly known as the 'wavy navy' [13].

In June 1942, a few days after his twentieth birthday, John reported for duty at Portsmouth Naval Barracks. He was shocked by what he saw. Unlike the relatively cosy, sheltered environment of Cambridge, this port on the south coast was of major strategic importance and it had been heavily bombed. Large sections of the city had been completely destroyed. John spent the first week at the college learning how to become 'an officer and a gentleman' and then a month completing a crash course in naval electronics and radar. He came top of the class which meant he was given first choice for his next assignment. John chose to do research and development of airborne radar.

The word radar was an acronym coined by the Americans in 1940 to describe what for many years had been known as radio direction finding. As early as 1922 Guglielmo Marconi and others had suggested that it might be possible to locate ships at sea by means of reflected radio waves. In 1931 engineers at the British Post Office built a workable system for detecting nearby ships. At about the same time radio operators reported radio interference apparently caused by planes flying in the vicinity, leading to speculation that this effect might be used as a way of detecting aircraft. In January 1935 Robert Watson Watt wrote a confidential report arguing that this effect should be developed into a major part of Britain's system of air defence. Against scepticism in official circles, an air ministry committee chaired by Henry Tizard decided to provide financial backing to test the idea. A secret research station was established near the small village of Bawdsey on the English Channel. An encouraging start was made in June 1935 when echoes were detected bouncing off an aircraft at a distance of 30 km. Three months later the detection range of the equipment had been extended to 150 km. After intensive development this radar equipment formed the basis of the air warning system which proved crucial to eventual success in the Battle of Britain [14].

Bolton's first posting after the Portsmouth Naval Barracks was at the coastal town of Dram, on the Firth of Forth in Scotland, where the navy had established a night fighter squadron and training school. He was placed in charge of two coastal radar stations, either side of the Firth, and took part in fitting out and testing the latest radar sets in night fighters. At the end of 1942 Bolton was transferred to the Telecommunications Research Establishment, the headquarters of Britain's radar research and development. The TRE was located at Malvern in Worcester, a county far enough west to be out of range of German bombers, but still flat enough to provide operational airfields. It was housed in a boy's boarding school and staffed by hundreds of Britain's most talented scientists and engineers. Some of the people John met – Robert Hanbury Brown, Bernard Lovell and Martin Ryle – would become leaders in the emerging field of radio astronomy in postwar Britain.

Bolton joined the group developing a new airborne radar system operating at 3 centimetres. The first few months were spent at a lab bench, but then flight testing became an increasing part of his work. This involved making running repairs, changing parts, diagnosing problems and getting the equipment to work in a hurry. It was demanding and at times dangerous. He was becoming an expert in getting temperamental electronic systems to perform in physically demanding conditions, at top speed. John could not know it then, but he was getting a first-class training for a future career as a radio astronomer [15].

The D-Day invasion of France by Allied forces in June 1944 marked the beginning of the end of the European war. It also marked the end of two years active service for Bolton. By then he had grown tired of flight testing radar and needed a change. The hundreds of hours of flying, the rapid ascents and descents, had left him partially deaf in his right ear. Through a contact in the Admiralty, John was offered a position as radio officer on the British aircraft carrier, HMS *Unicorn*, stationed at the time in Sri Lanka. He would be one of the 50 officers among a complement of over 1100 men (see e.g. Figure 2.3). He would be responsible for all airborne electronics, ship-to-aircraft communication and navigational aids. John was given a berth on a troop ship

Figure 2.3. The chaplain of HMS *Unicorn*, John Tyrrel (seated with pipe), organised a weekly discussion group for the crew. Bolton is standing at far left. He and Tyrrel became good friends after the war. [courtesy: Tyrrel family]

heading to the Far East. Not all British forces were required for the D-Day invasion and his ship was part of a large convoy being sent to fight the Japanese.

Early in 1945 the *Unicorn* loaded up a hundred US aircraft in Bombay and set sail for Australia where she would join the British Pacific Fleet. The first port of call was Fremantle, where Bolton set foot on Australian soil for the first time. Upon arrival in Sydney Harbour, thousands turned out to see the largest ship in the British Navy and there was much speculation about whether the tall mast would fit under the Harbour Bridge. The British Pacific Fleet joined forces with the much larger American fleet in the island hopping campaign that pushed the Japanese back to the north. The role of the *Unicorn* was to provide support for the four British carriers on the front line and to urgently repair aircraft damaged in battle. The ship was stationed in the Admiralty Islands north of New Guinea for several months and, as the Japanese retreated, home base was then moved further north to the Philippines. The *Unicorn* had a charmed life, a very lucky war, partly because she was away from the front line, but there had been plenty of other non-combat ships that were attacked and sunk by kamikaze planes. The most serious incident came while at anchor when a ship on the other side of the harbour accidentally fired a torpedo that narrowly missed the *Unicorn* and sank the ship next to her [16].

The decisive victory at Okinawa saw the Allied forces ready to launch an invasion of the Japanese mainland. However, the invasion proved unnecessary when the two atomic bombs dropped on Japan in August 1945 brought a sudden, unexpected end to the war. VJ Day marked the end of the war for the *Unicorn*, but not the end of the campaign. The cavernous hangars and flight deck made her the ideal vessel for the task of ferrying men, aircraft and cargo back to Sydney and Brisbane. After three trips back and forth to the Admiralty Islands, John transferred to an airbase in the western suburbs of Sydney. The final task at the airbase was to dispose of all the unwanted equipment. Items of value such as clocks and altimeters were unofficially stripped and ended up as private property. Equipment still on the secret list was destroyed in high temperature ovens and anything that might have a future use, such as motors, instruments, pumps and gearboxes, was trucked to the government stores at Botany Bay. Hundreds of gutted aircraft were taken out beyond Sydney Heads and dumped at sea [17].

When the *Unicorn* set sail for England in December 1945 Bolton decided to stay behind in Sydney. There were several reasons for his decision and one of them was his health. He found that the climate of Sydney had cured him of the asthma that at times had made his childhood miserable. With the outdoor life and a fair share of physical work, he had never felt physically fitter. Another less pleasant reason was a letter he received from the Cavendish Laboratory in Cambridge. Earlier John had written to the Cavendish asking whether he could be accepted as a post-graduate student in physics after the war was over. The letter was a polite but firm no. It stated that the head of the Cavendish, Lawrence Bragg, had personally considered John's request and decided that his abbreviated wartime degree did not provide adequate training for post-graduate study. The various scholarships he had won and his first and second class honours as an undergraduate were apparently not good enough. John was deeply disappointed and no doubt wondered whether he would ever have an opportunity to prove them wrong [18].

When John left the *Unicorn* he transferred to the Australian Navy and it was a further six months before he was discharged. He had built up a network of navy friends around Sydney and was hoping to pick up a job through one of them. On the day of his discharge John went to the Sydney Showgrounds, completed the necessary forms, and was interviewed by an official about his future employment plans. The official explained that he was looking for carpenters, bricklayers and other tradesmen and there was not much he could offer a Cambridge graduate. After a couple of phone calls another official arranged an appointment for John with the Chief of the Radiophysics Laboratory, part of the Council for Scientific and Industrial Research (CSIR), Australia's leading research organisation [19].

Bolton met E. G. 'Taffy' Bowen the following morning in his office in the grounds of the University of Sydney. They had never met but John knew that Taffy had at one time been a senior figure at the Telecommunications Research Establishment and that he had gone to the United States to become the chief liaison officer between British and American radar research. They knew a lot of people in common. Taffy gave John a tour of the Lab and was clearly impressed by the young Yorkshireman. He told John that the Lab was about to advertise for a new research officer position and he encouraged him to apply. John's future career was basically sorted out less than 24 hours after his discharge. Bowen would have more influence over the course of Bolton's career than any other person.

The advertisement for the position specified the duties as 'Research and development in connection with the application of radar techniques' and that the applicant must have a 'University degree in electrical engineering or science with physics as a major, or equivalent qualifications'. In order to attract the best scientific talent it was CSIR policy to advertise research positions Australia-wide and also in London and Washington. It was a lengthy process and positions usually took about three months to fill. John put in his application before the deadline in early July 1946. For the first time since his school days, he had time on his hands. In September he received the letter that he had been anxiously waiting on: 'I have pleasure in informing you that your application has been successful and hereby offer you appointment as an Assistant Research Officer of the Council for Scientific and Industrial Research' [20].

2.2 Origins of the Radiophysics Laboratory

Australia had played a significant part in the development of radar. Early in 1939 Britain decided to share its knowledge of radar with several countries in the British Commonwealth. Each country was invited to send its best-qualified physicist to learn of the secret research. Australia chose David Martyn for the clandestine mission, who had already gained an international reputation for his theoretical studies on the upper atmosphere. During 1939 Martyn spent five months touring British radar establishments and returned to Sydney with a large trunk containing classified reports and numerous blueprints and technical specifications for constructing radar equipment. Martyn reported to two key figures in Australian science. One was David Rivett, chief executive officer of CSIR, and the other was John Madsen, professor of electrical engineering at the University of Sydney. The three men drew up a set of recommendations for the establishment of a national laboratory for radar research, and then travelled to Canberra to present their proposal to the federal government. Their recommendations were accepted without change and funds were immediately allocated for a new building, fitted out with the best laboratory and workshop equipment available. The name chosen – the Radiophysics Laboratory – was a fairly innocuous one, designed to disguise its real purpose to carry out secret radar research [21].

Figure 2.4. The Radiophysics Laboratory was built in 1940 in the grounds of the University of Sydney. In 1968 the Lab moved to new headquarters in the north–west suburb of Marsfield. [courtesy: RAIA]

The site chosen for the new laboratory was in the grounds of the University of Sydney. CSIR had already begun construction of a National Standards Laboratory on the site and the first stage had been completed late in 1939. The new radar laboratory would form an additional wing of the main laboratory which would have the advantage of making its secret work less conspicuous. Under the urgency of war the construction pushed ahead rapidly and by March 1940, only three months after the foundations had been laid, the building was near enough to completion for staff to move in. David Martyn was appointed chief of the new laboratory and by the end of 1940 about forty scientists, engineers and support staff had been recruited (see Figure 2.4).

Among the first to join the new Radiophysics Laboratory was Joseph Lade Pawsey, recruited to lead the theoretical research group. Born at Ararat in Victoria in 1908, Joe Pawsey studied physics at the University of Melbourne and then began a PhD thesis at the Cavendish Laboratory in Cambridge on the phenomenon of broadcast fading, caused by the irregular reflection of radio waves by the ionosphere. After completing his doctorate in 1934, Pawsey joined Electronic and Musical Industries (EMI), a firm that had recently won a BBC contract to develop a national television system. At the BBC station at Alexandra Palace, Pawsey was responsible for the design of transmission lines and aerials necessary for television’s broad bandwidth [22].

Initially, the Radiophysics Laboratory concentrated on constructing radar sets to suit the needs of the three Australian armed services. In 1940 it seemed that the most likely attack on Australia would come from the sea. In response, the first major project was the development on behalf of the Army of a shore defence radar system to be used by coastal artillery for locating enemy ships. A prototype model was erected in May 1940 at an army testing ground on the cliff-tops of Dover Heights, south of the entrance to Sydney Harbour (Figure 2.5). The trials were promising and led to a major innovation by Joe Pawsey and Harry Minnett, who developed an ingenious switching device so that only one tower and one aerial were needed for both transmission and reception of the radar signal. In England at this time, radar systems had their transmitting and receiving equipment isolated on separate towers which added substantially to the cost of the system.

Figure 2.5. The Dover Heights field station operated by the Radiophysics Lab, south of the entrance to Sydney Harbour, in 1943. The radar unit on top of the blockhouse was originally used for the detection of ships along the Australian coast, but then a new version was hurriedly developed for air warning following the Japanese attack on Pearl Harbor in December 1941. The radar unit was removed early in 1947. The cottage at left was occupied by the site caretaker. This site was later to become one of the main Radiophysics field stations for radio astronomy. The blockhouse was to be Bolton's workplace over the period 1946–53. [courtesy: RAIA]

After Pearl Harbor in December 1941 it became obvious that air attack would be the greatest danger to Australia. A Radiophysics group worked at top speed to improvise an air-warning system based on the shore defence developed for the detection of ships. In its first week of trials at Dover Heights the new system detected aircraft at distances more than 100 km out to sea. The prototype was rushed into production and the new radar hurriedly installed along the east coast of Australia. Arrangements were also made to set up the system in Darwin on the north coast of Australia, but an argument broke out over which of the three armed services should bear the cost and the installation was delayed. In February 1942, without warning, the Japanese staged a devastating bombing raid. A Radiophysics group immediately flew to Darwin and assisted in getting the system operational in time to detect the approach of a further Japanese bombing raid three days later. The Japanese eventually made over fifty air raids on Darwin, despite brave resistance from the hopelessly outnumbered Australian and American aircraft. The number of deaths caused by the Darwin raids was much larger than the number killed in the single attack on Pearl Harbor.

The Radiophysics Lab expanded rapidly as the war progressed with the number of staff and the size of the budget increasing each year in leaps and bounds. There was also a change of leadership which would later prove crucial to the Lab's postwar future. Although a brilliant scientist, Martyn's ability as a manager was poor and tensions soon arose between the Lab and the three armed services. By early 1942 the CSIR Executive was forced to act. Martyn was transferred sideways to an army operational research group and, to replace him, an approach was made to Frederick White, the professor of physics at Canterbury University College in Christchurch, New Zealand. With a background similar to that of several of the Radiophysics staff, White had completed a doctorate at Cambridge in 1932 and then been appointed lecturer in physics at King's College, London. White returned to New Zealand in 1937 and began a vigorous program of radio research in Christchurch. He was officially installed as the new chief of the Radiophysics Lab in September 1942 [23].

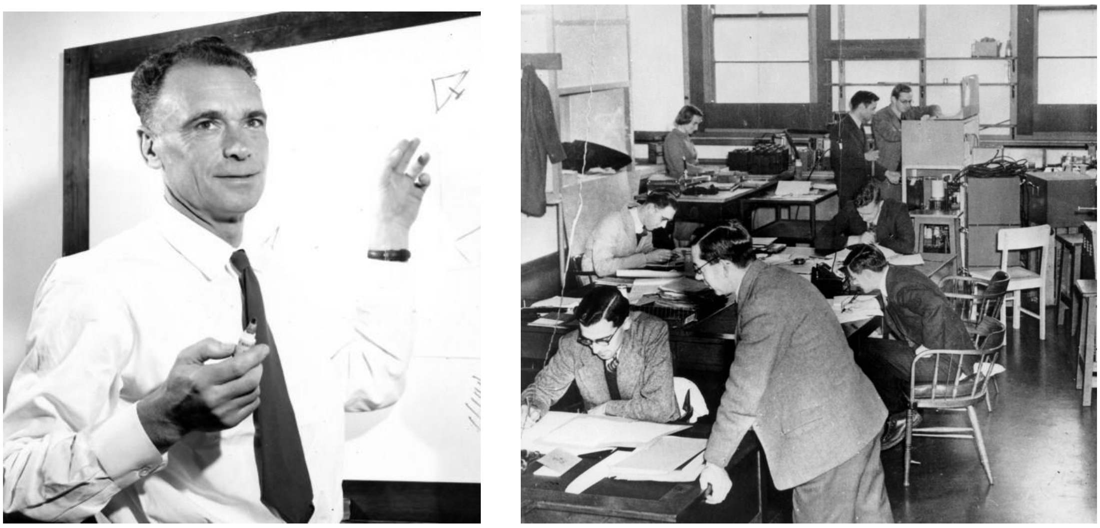


Figure 2.6. E. G. 'Taffy' Bowen (left) joined the Radiophysics Lab in 1944 and was promoted to chief early in 1946. (right) By the end of the war the staff of the Radiophysics Laboratory had grown to over 300. In the foreground are Frank Kerr (left) who became one of the senior radio astronomers, and Arthur Higgs who became the chief administrative officer under Taffy Bowen. [courtesy: RAIA]

Fred White soon proved himself a gifted manager with the qualities to steer a firm course through the complex and often contradictory priorities faced by the Lab. In mid 1943 he toured radar establishments in Britain and the United States. At the MIT Radiation Lab in Boston he met with E. G. 'Taffy' Bowen (Figure 2.6) and renewed a friendship that had begun at King's College when Bowen had been a research student and White a lecturer. In an inspired move, White invited Bowen to become assistant chief of the Radiophysics Lab and to take charge of the research activities. Bowen agreed and arrived in Sydney in January 1944, pleased with what he found [24]:

> 'It was already a flourishing concern with a staff of two hundred people; it had an excellent mix of highly qualified scientists and engineers and the permanent building included first-rate workshop facilities. For its size, it was one of the best equipped laboratories in which I had worked up to that time. The laboratory had good connections with industry and in spite of the enormous distances and the difficulties of wartime travel, it had kept closely in touch with radar research in Britain and America.'

By the time of Bowen's arrival, the war in the Pacific had swung decisively in favour of the Allied forces. As the immediate danger to Australia receded, there was a gradual shift in emphasis in the Lab away from a total commitment to applied military projects towards longer term studies in basic research. The time had come to make plans for the postwar era. The Lab itself had grown rapidly with staff numbers peaking at 300 by war's end, 60 of whom were classified as research scientists (see Figure 2.6). By 1945 the Lab had outgrown most of the other CSIR divisions, even though CSIR itself had grown rapidly during the war. The Lab's workshops and laboratory benches were fitted out with the most advanced equipment available. At least in the physical sciences, the staff formed the most talented and motivated group of scientists ever assembled in Australia, a group that had been right at the forefront of research and development of wartime radar [25].

A critical decision made at the end of the war, largely at the insistence of the chief executive officer David Rivett, was that CSIR would turn over all secret military work to other government agencies. CSIR was to concentrate solely on research that would bring direct economic benefit to Australia or add to the general store of scientific knowledge. Two options were open. First, the Radiophysics Lab could fulfil its military commitments and then steadily wind down its staff to more modest peacetime proportions. This was the course followed at the two largest radar centres overseas, the Telecommunications Research Establishment in England and the MIT Rad Lab in the United States. At the end of the war hundreds of scientists in both countries made a mass exodus back to the universities and corporate research laboratories from where they had been recruited. However, a high proportion of the Radiophysics scientists had been recruited as students straight from university and the possibility of pursuing a full-time research career in any of the Australian universities in the 1940s was very limited, even more so in industry. For most of the staff, the second option open to the Radiophysics Lab was the one they preferred: basically to keep the Lab intact even though this would mean a major reorientation of its research program.

Early in 1945 Taffy Bowen set about the challenging task of drawing up a list of possible peacetime research areas. In Bowen's view, the Lab would need to pass through a transition phase lasting about two years. This would consist of a type of postwar spring cleaning where the knowledge and techniques of radar would be handed over to the armed services and, where appropriate, to other areas of government and industry. At the same time the Lab would begin to strengthen its commitment to fundamental research and this would require recruiting new staff to replace the relatively small number of those who decided to go their own way after the war.

Bowen drafted a report which divided the proposed research program into nine main areas, ranging from studies of radio propagation, radio methods of air and marine navigation, airborne surveying techniques, vacuum tube research, through to radar studies of cloud and rain formation. The first of these nine areas, under the heading 'Propagation of radio waves', was further subdivided into five categories covering topics such as ionospheric propagation and the scattering of radio waves in various layers of the atmosphere. In the second of these five subcategories, with the innocuous title of 'Radio noise', Bowen noted that there is a certain type of radio noise which is thought to originate in the stars or in interstellar space: 'Little is known of this noise and a comparatively simple series of observations on short wavelengths might lead to the discovery of new phenomena or to the introduction of new techniques.' This seemed a humble sentence, but it contained the seed of a major new science in Australia [26].

In July 1945 Bowen's future program for the Radiophysics Lab was presented to a meeting of the CSIR Council, the organisation's full governing body. The document was assured of a favourable reception. Earlier in the year Fred White had been promoted to the CSIR Executive in recognition of the leadership skills he had displayed during the tough baptism of war. Having been groomed for the position by White, Bowen's appointment as chief of Radiophysics early in 1946 completed the formalities. The enthusiastic endorsement of Bowen's postwar research program signalled a major reorientation in CSIR. There had been increasing political pressure on CSIR to move away from its traditional emphasis on research in the agricultural and mining industries. The new emphasis was to be on areas of modern technology which underpinned Australia's emerging manufacturing industries, some of the newer fields of research pointed to in Bowen's report.

The Executive's support of Bowen's program also carried with it an implicit understanding. As chief, Bowen would be free to direct the research program of Radiophysics with a minimum amount of interference by the Executive. This idea of individual responsibility in CSIR had been championed by the chief executive Rivett who believed that the best science comes from choosing the best qualified people and then giving them a free hand. Rivett maintained that CSIR's approach to research should be in line with the academic freedom offered to university scientists, rather than the approach usually adopted in government laboratories where scientists were moulded to fit structured research programs [27]. This promise of research freedom had in fact been an important precondition in Bowen's decision to accept the position of chief. At the relatively young age of 35, brimming with self-confidence, Bowen shared Rivett's ideals and his faith in the value of small, independent research teams. A proposal at this time to amalgamate the Radiophysics Laboratory with the National Standards Laboratory to form a monolithic Commonwealth Physical Laboratory was successfully opposed by Bowen for just these reasons.

With a free hand to pursue any of the research fields listed in his report, Bowen's strategy was simple and flexible. Small groups would be turned loose on a wide variety of topics, but then a kind of Darwinian natural selection would prevail. Projects that showed early promise would be rewarded with the support of more staff and funds at the expense of those that failed to make headway. Promising starts were made in a number of fields, but by 1950 only two areas had flourished in the contest of ‘survival of the fittest’ – radio astronomy and cloud and rain physics. Radio astronomy proved to be the wild card in the pack, emerging in just a few years to become the largest and by far the most successful of the Lab’s activities.

2.3 A Mysterious Cosmic Hiss: Karl Jansky and Grote Reber

To understand how Bolton’s career developed during the late 1940s, we need to trace the origins of radio astronomy, some years earlier. The first attempt to detect radio waves from space now goes back over 120 years. In 1887 laboratory experiments by the German physicist Heinrich Hertz conclusively demonstrated the existence of radio waves, which had been predicted earlier by the Scot James Clerk Maxwell in his theory of electromagnetic radiation. The experiments by Hertz showed that radio waves are simply another type of electromagnetic radiation, differing from visible light only in that their characteristic wavelengths are very much longer. Besides opening up a range of potential applications in communications, the discovery of radio waves raised an obvious question – are there any natural sources of radio emission on the Earth, or from the stars above?

The first attempt to detect radio waves from the Sun was made shortly afterwards in 1890 by the brilliant American inventor Thomas Edison. Edison planned to suspend a long loop of telephone wire around the perimeter of a large deposit of iron-ore in a New Jersey field. He reasoned that if radio waves are produced from violent electromagnetic disturbances on the Sun, their arrival on Earth might magnetise the iron-ore and set up a small flow of electric current in the telephone wire. It appears that the wooden poles for the telephone wire were delivered to the field, but there is no evidence that this huge radio receiver was ever erected. Another unsuccessful attempt was made in 1901 by the Frenchman Charles Nordmann, who decided to get well away from industrial sources of radio interference by setting up an aerial on a glacier high in the French Alps. Nordmann guessed correctly that radio emission from the Sun, if it did exist, might originate from the violent disturbances associated with sunspots. Unfortunately, Nordmann gave up the search after only a few days.

With more perseverance he might have succeeded as 1901 turned out to be a year of minimum sunspot activity [28].

Many new fields of science have started as a result of good fortune rather than planning, serendipity rather than design. Radio astronomy is a shining example. After graduating in physics from the University of Wisconsin-Madison, Karl Jansky joined the Bell Telephone Laboratories in 1928 and was assigned the task of investigating any source of atmospheric static which might interfere with a new trans-Atlantic radio communication system then under development. In 1931, at Bell's field station near Holmdel, New Jersey, an aerial array 30 metres long and 4 metres high was constructed from timber and brass pipes. The array was mounted on four wheels taken from an old model T Ford, with a small motor and chain drive which could turn the array through one revolution every twenty minutes. The contraption earned the name the 'merry-go-round' (see Figure 2.7).

Jansky was able to distinguish three distinct types of radio static. The first arose from the intermittent crashes of local thunderstorms and the second was a weaker, steadier static due to the combined effect of many storms far off in the atmosphere. The third type was composed of a very weak and steady hiss of unknown origin. Initially Jansky thought that this weak hiss was caused by some source of industrial interference, but then he noticed that the maximum strength of the signal came from a direction which moved around the sky each day and seemed to correspond roughly with the position of the Sun. The observations continued throughout 1932 and Jansky found that with the passing of the months, contrary to what he first believed, the direction of the static began to drift further and further away from the position of the Sun. Obviously the Sun could not be the source of the radio noise. The daily period of variation of the noise in fact turned out to be 23 hours and 56 minutes, four minutes less than the daily period of the Sun. This is known as the sidereal day – the period of the Earth's rotation with respect to the stars – and so Jansky could conclude that the source of the noise must lie beyond the Sun, and beyond the Solar System as well.

In a paper published early in 1933, Jansky could cautiously state in the journal *Nature* that 'the source of the noise is located in a region that is stationary with respect to the

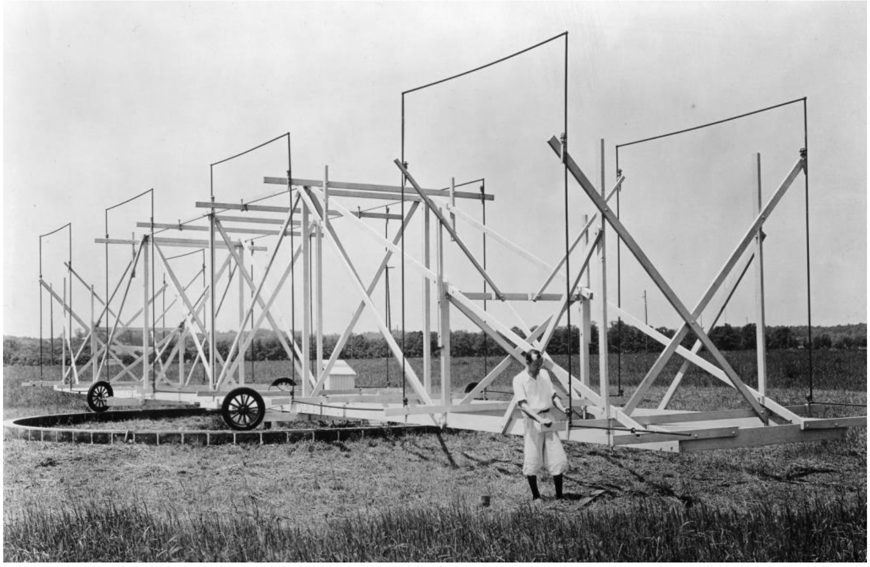


Figure 2.7. Karl Jansky and the 'merry-go-round' aerial at the field station operated by Bell Telephone Laboratories near Holmdel, New Jersey. In 1932 the aerial was used to discover radio waves from space. [courtesy: AIP Emilio Segré Visual Archives (above); NRAO (below)]

stars' [29]. The distribution of the cosmic noise across the sky was shown to approximately coincide with the distribution of stars, dust and gas visible to us along the plane of the Milky Way. Because he had been unable to detect radio waves from the Sun itself, Jansky ruled out the far more distant stars as the source of this cosmic static. Instead, he speculated that the source of this new radiation arose from charged particles in rapid motion through interstellar space.

The publicity department at Bell Labs made sure that Jansky's discovery received wide exposure. In May 1933 the *New York Times* carried a front-page report with the banner 'New radio waves traced to center of Milky Way' and a radio station featured a special evening program in which radio astronomy went on air for the first time. Cosmic static picked up by Jansky's aerial in New Jersey was relayed to the New York station, and the 'hiss of the Universe' then broadcast to a national audience. Despite this initial interest, Jansky did not pursue his discovery any further. From the point of view of Bell Labs, Jansky had completed his original project to identify the sources of static noise and their effects on radio communication. Jansky continued his work on terrestrial sources of radio interference, a research program he carried out until his premature death at age 44 [30].

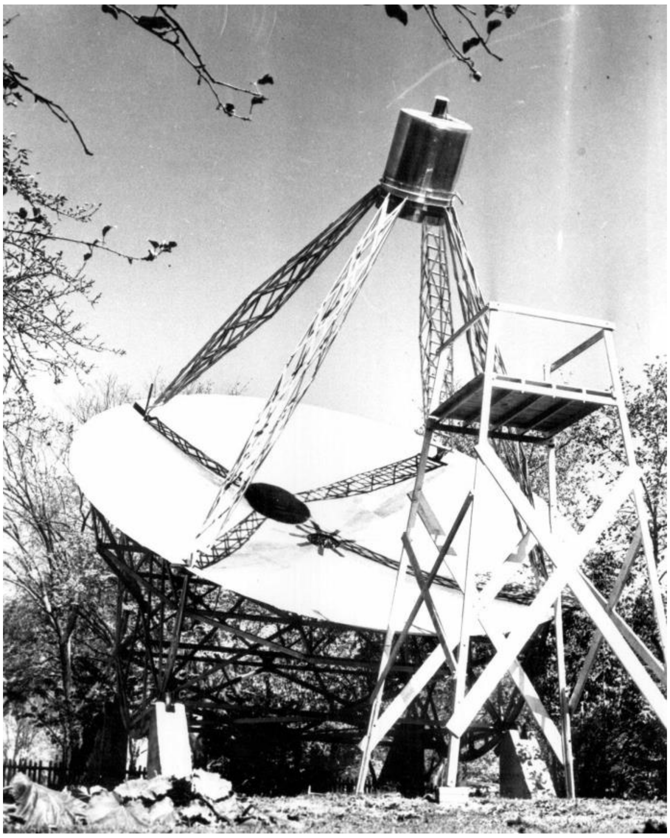
Jansky's discovery opened up an entirely new approach to astronomy. Until 1932 almost our entire knowledge of the Universe had been gained from a narrow section of the electromagnetic spectrum – the optical region extending from the red through to the violet. Radiation from astronomical objects in this part of the spectrum penetrates the Earth's atmosphere without appreciable absorption, and so this part of the spectrum provides a 'window' to look out to the Universe. The new window opened up by Jansky provided an opportunity to observe the Universe in a completely new 'light'. The radio window is about a thousand times wider than its visible or optical counterpart, covering a range of wavelengths from roughly a centimetre in length up to several tens of metres. The lower cut-off at wavelengths shorter than one centimetre is caused by oxygen and water vapour in the atmosphere, while the upper cut-off at long wavelengths is caused by reflection or absorption of incoming radio waves by the ionosphere, a layer of charged particles high in the atmosphere.

In 1936, a year after Jansky published his final paper on cosmic noise, his discovery was confirmed by Gennady Potapenko, a professor of physics at the California Institute of Technology (Caltech) in Pasadena. Potapenko and his graduate student Donald Folland built a receiver and antenna and they began observing on the roof of a Caltech building. However, Pasadena proved too radio noisy so they moved their equipment to the Mojave Desert where they succeeded in confirming Jansky's results. Although their work was never published, it was a promising start and showed the need for a much larger antenna. They made a rough design for a large rotating rhombic antenna, but they were unable to find funding and the project did not go ahead. It is interesting to note that in 1955, almost twenty years later, Caltech re-entered the field of radio astronomy when John Bolton and his close colleague Gordon Stanley arrived from Australia (see Chapter 7) [31].

Although Jansky's work created some interest among astronomers, none of the US observatories decided to follow up his discovery – for the simple reason that no astronomer knew enough about radio engineering. The new science of radio astronomy might have fallen into limbo had it not been for the extraordinary initiative of Grote Reber, a young engineer with a passion for all aspects of radio science. As a teenager Reber had built his own transmitter–receiver and, from his hometown in Wheaton, Illinois, communicated with fellow radio 'hams' all over the world. Reber read Jansky's research papers and immediately understood their significance [32].

Jansky had exploited his discovery to the technical limits of his merry-go-round aerial, so Reber realised further progress would require the construction of new equipment specifically designed to observe the cosmic static. The 'radio telescope' would need not only to determine in sharper detail how the intensity of cosmic radiation is distributed over the sky, but also how the intensity varies with wavelength. The best solution seemed to be a large parabolic reflector or 'dish' which could be accurately pointed at any selected position in the sky. Incoming radio waves would be reflected from the dish's surface and focused to a single point. Different radio wavelengths could be investigated by installing the appropriate receiver at the focus of the dish.

Reber decided to build the radio telescope himself, in the backyard of his parents' home in Wheaton. The dish was surfaced in sheet metal and mounted on a movable wooden support structure. Apart from a few parts ordered from a local blacksmith, Reber made each component and completed the entire construction by himself over a period of four months (see Figure 2.8). By the standards of 1937, the cost of $1300 was a large sum for a young engineer in pursuit of an untried idea. Reber's first



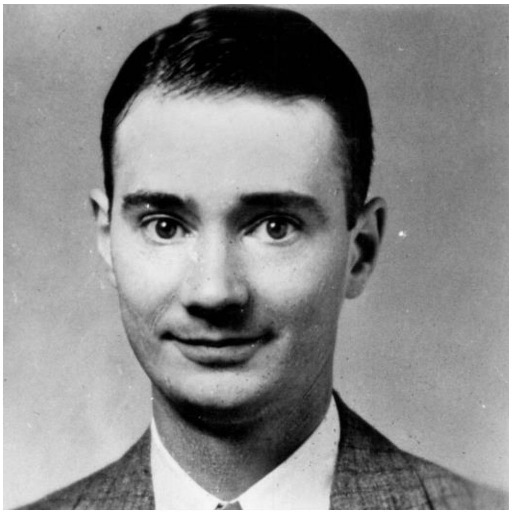


Figure 2.8. Grote Reber and the radio telescope he built in the backyard of his parents' home in Wheaton, Illinois. Reber used the telescope to map the strength of radio emission across the sky. As a tribute to Reber's pioneering efforts, a replica of the telescope was later erected at the US National Radio Astronomy Observatory at Green Bank, West Virginia. [courtesy: NRAO]

attempts to detect radio waves from prominent objects such as the Sun, Moon, planets and several bright stars produced no response. Over a year passed and Reber feared that his wild idea was doomed to failure. He persevered and built a new receiver working at a wavelength just short of 2 metres. Early in 1939 he was at last rewarded by receiving signals from the plane of the Milky Way. Full of enthusiasm, Reber then launched into an observing schedule that would have tested any astronomer. At night he carried out measurements from midnight to 6 am when local radio interference was at a minimum, and then caught a train to his job with a Chicago radio company. After the evening meal he would sleep to midnight, and then resume the observations.

In his first paper, published in the same radio engineering journal used by Jansky, Reber reported that the cosmic static is strongest along the plane of the Milky Way, thereby confirming Jansky's earlier discovery [33]. Unlike Jansky's aerial, Reber's telescope could be pointed fairly accurately (though with extremely low resolution), which meant that he was able to make detailed measurements of the variation in radio strength across the sky. Plotting the contours of strength gave a celestial radio map – similar in appearance to the maps which show the elevation of the Earth's terrain. In addition to the main radio strength which peaked near the centre of the Galaxy in the Sagittarius constellation, other subsidiary peaks were prominent in the constellations of Cygnus and Cassiopeia. At that time, however, Reber could not detect emission from the Sun, which seemed to support Jansky's hunch that the radio emission did not originate from the stars themselves, but probably from energetic charged particles moving freely in interstellar space.

While Jansky's discovery laid the first foundations for the new science of radio astronomy, Grote Reber became its first practitioner. For a lone-hand working in his spare time, his achievement was exceptional. The Wheaton radio maps of the sky were not improved upon until the work of the Radiophysics group at Dover Heights in the late 1940s. Reber can also claim credit for having built the first successful radio telescope, his parabolic dish beginning a line of development of similar instruments which, as we see in Chapter 7, included the large Parkes telescope over twenty years later [34].

Notes to Chapter 2

Here and elsewhere the NAA files refer to the Radiophysics correspondence files held in the National Archives of Australia. All files belong to the series C3830, unless indicated otherwise. Similarly, the NLA files refer to the 'Papers of John Gatenby Bolton: MS 9063. Series 1: Correspondence 1940–93' held in the National Library of Australia, Canberra.

[1] Hanbury Brown in Kellermann and Sheets (1983), p. 213.

[2] Bolton interview with author, Buderim, Queensland, 2 April 1984.

[3] Information on the Bolton family is based on interviews of Sue Flavin and Joanne Goldsworthy (two of Bolton's three nieces) at Knaphill, Surrey, 20 October 2009, and of Janet Davies (Bolton's cousin) at Aberystwyth, Wales, 23 October 2009.

[4] Tony Kettlewell interview with author, North Cave, Yorkshire, 29 October 2009.

[5] Butler (1997).

[6] Bolton interview by Lennard Bickel, 13 January 1975, TRC 324, cassette 1, Oral History Section, National Library of Australia, Canberra.

[7] Cornwell (2005), p. 147.

[8] See note [6].

[9] Gow (1945), p. 59.

[10] See e.g. Trevelyan (1990), pp. 102, 113. The discoverer of the electron and former head of the Cavendish, J. J. Thomson, was a Master of Trinity who died in office in April 1940. The next Master appointed was G. M. Trevelyan, a case of one of Britain's greatest physicists passing on the baton to one of its greatest historians.

[11] Hoyle (1994), p. 123.

[12] See note [6].

[13] See note [4]. The novelist Snow is best known for coining the term 'Two Cultures', when delivering the Rede Lectures in 1959. He warned that modern society was becoming polarised into two groups – those with a scientific and technological background and those with an arts and humanities background – and that the two groups were finding it increasingly difficult to communicate with each other.

[14] Bowen (1987), chapt. 1.

[15] See note [6].

[16] See 'HMS *Unicorn*', unpublished history, Sydney, November 1945, 24 pp. I am grateful to David Orchard, Surrey, for providing a copy.

[17] Bolton to author, 26 March 1990.

[18] Cavendish Laboratory to Bolton, 26 May 1945. The letter is in possession of the Bolton family and is only one of a handful of documents surviving from John's life before arriving in

Australia. In fairness to the Cavendish, it was flooded with requests from servicemen returning to civilian life and the contest for student places was exceptionally fierce. Lawrence Bragg was born in Adelaide where his English father William was the Professor of Mathematics at the university. In 1909 William and family returned to England where he and Lawrence carried out research that led to the new field of X-ray crystallography. In 1915 they created history by being the first, and only, father–son team to be awarded the Nobel Prize for Physics. At the age of 25, Lawrence became – and remains – the youngest of all Nobel Laureates – see the masterly study by the Melbourne science historian John Jenkin (2008).

[19] See note [2]. Bolton effectively left the Navy in April 1946 and was then entitled to three months leave. His discharge letter came through in July 1946: 'The good wishes of My Lords Commissioners of the Admiralty go with you on your return to civil life.' Admiralty to Bolton, 30 July 1946, Bolton papers, NLA file 1-1.

[20] G. A. Cook to Bolton, 6 September 1946, NAA file PH/BOL/005, part 1.

[21] Schedvin (1987), chapt. 6.

[22] See Lovell (1964) and Robertson (2000).

[23] Minnett and Robertson (1996).

[24] See note [14], p. 198.

[25] The collective wisdom of the Radiophysics Lab on radar and its applications was published in Bowen (1947).

[26] NAA file D1/1, series C3830, E. G. Bowen, 'Future Programme for Division of Radiophysics', 2 July 1945, 26 pp. The report was circulated for comment in CSIR. The chief of the division of Animal Health and Production, Lionel Bull, noted: 'It is interesting to have some evidence of your activities as for so long no one has even dared to suggest that you even existed.' Bull to Bowen, 25 September 1945, file D1/1.

[27] See e.g. Rivett (1972), p. 188.

[28] For a comprehensive and definitive account of the origins of radio astronomy see Sullivan (2009). For more on Nordmann's attempt to observe solar radio emission in 1901, see Débarbat *et al.* (2007).

[29] Jansky (1933), *Nature* **132**, 66. For his first paper on cosmic noise see Jansky (1932), *Proc. Inst. Radio Eng.* **20**, 1920–32.

[30] In 1973 the International Astronomical Union adopted the name 'jansky' (symbol: Jy) for the fundamental unit used to measure the emission strength of signals across the electromagnetic spectrum. A scientist can receive no higher honour.

[31] Cohen (1994), p. 9.

[32] See Robertson (1986). Reber emigrated to Australia in 1954. The description of his work is based on an interview by the author on 6 February 1986 at Bothwell, Tasmania. See Kellermann (2004, 2005) for biographies.

[33] Reber (1940), *Proc. Inst. Radio Eng.* **28**, 68–71; see also *Astrophys. J.* **91**, 621–32. The Jansky and Reber papers were reproduced in Sullivan (1982).

[34] After meeting Reber during a visit to Washington in 1948, Joe Pawsey noted: ‘Among the radio workers Reber impressed me very favourably. I forgive him the imperfections in his papers when I consider how he worked, alone with no encouragement, working in his spare time and buying equipment with his own money. He lacks the research background that many of us have, but I believe he “has what it takes” to make a success of things. He is a young bachelor and has a delightfully direct personality. My feeling is that if there is anything we can do to help him along, let us do it. He will give back as much as he gets.’ Undated report, ‘Solar and Cosmic Noise Research in the United States and Canada’, NAA file C4659, Pawsey correspondence, part 8.

Chapter 3

Discovery of the First 'Radio Stars'

Radio astronomy was not completely dormant during the war years. In fact, the next major development came, again through serendipity, as a direct result of wartime radar research. Late in February 1942 radar stations throughout England reported severe bursts of radio noise which had made normal operation impossible for several days. The War Office knew that the Germans had been developing methods of jamming radar and assigned J. Stanley Hey of the Army Operational Research Group the top priority task of investigating the problem. After an analysis of the records, Hey [1] realised that the mysterious interference was not the result of enemy jamming, but came from a direction in the sky which seemed to coincide with the Sun. Hey checked with the Royal Greenwich Observatory and learnt that during the days of maximum interference an exceptionally active sunspot had been in transit across the solar disc. In his secret report Hey concluded that despite previous German successes in jamming British radar, this time the reason had been the Sun. Across the Atlantic, at about the same time, George Southworth and a group at the Bell Telephone Labs – colleagues of Karl Jansky – made the same discovery.

3.1 The Beginning of Radio Astronomy in Australia

The existence of solar radio emission had been known in the Radiophysics Lab well before the end of WWII. Both Taffy Bowen and Joe Pawsey (Figure 3.1) had visited the Bell Telephone Labs and learnt of Southworth's work. Early in 1944 Frank Kerr made some preliminary observations but then had to abandon the project to concentrate on more urgent wartime work. Similarly, in April 1944 Pawsey made a somewhat half-hearted attempt to detect sources of extraterrestrial radio noise, one that can at least be admired for its simplicity. Pawsey stuck a small parabolic dish out a laboratory window and pointed it around the sky, hoping to register an increase in the noise level above that generated by the receiver. The experiment failed but the attempt can be said to mark the birth of radio astronomy in Australia [2].

Figure 3.1. Joe Pawsey was head of the Radio Astronomy Group and deputy chief of the Radiophysics Lab. [courtesy: RAIA]

Figure 3.2. Sydney localities referred to in the text: 1 = Collaroy, 2 = Dover Heights, 3 = Long Reef, 4 = Parramatta Observatory, 5 = Potts Hill, 6 = Radiophysics Laboratory, 7 = Georges Heights, 8 = West Head. [courtesy: Wayne Orchiston]

About a year later Pawsey's curiosity was again aroused by the receipt of two reports that supported Southworth's work. The first dealt with the so-called 'Norfolk Island effect', bursts of radio noise from the Sun detected by New Zealand radar operators stationed on this small island in the Tasman Sea. A report on these bursts had been prepared by Elizabeth Alexander at the Radio Development Laboratory in Wellington (the Kiwi equivalent of the Radiophysics Lab) [3]. Shortly afterwards, Pawsey was spurred into action by a letter from Stanley Hey enclosing a copy of his secret 1942 report. Assisted by Ruby Payne-Scott and Lindsay McCready, Pawsey began observations in October 1945 using an RAAF radar antenna overlooking the sea at Collaroy, a northern Sydney suburb (see Figures 3.2 and 3.5). Success came immediately. Their observations not only confirmed the overseas reports, but then an analysis of certain features in the signals, received at a wavelength of 1.5 metres, yielded a very surprising result. Even with sunspot activity at a minimum, the strength of the radio emission indicated that some regions of the Sun were at temperatures as high as one million degrees. Their results, anticipated on theoretical grounds by David Martyn then at the Commonwealth Observatory at Mt Stromlo, were summarised in two letters to *Nature*, published in early in 1946. As an indication of how radio astronomy was still in its infancy, the first letter contained only four references to earlier work – the papers by Jansky and Reber, and the wartime reports by Hey in England and Alexander in New Zealand [4, 5].

Radio astronomy in Australia was now underway. The historian Woody Sullivan has eloquently noted the significance of Pawsey's work [6]:

> 'Australia's history was linked with astronomy from the start – Captain Cook's first voyage was as much to observe the 1769 transit of Venus across the solar disc in Tahiti as it was to explore for *Terra Australis Incognita,* leading to the discovery of Australia's eastern coast the following year. But 175 years would pass before Australians became part of the first rank of world astronomical research. And when this happened, from cliff edges only a few miles removed from Cook's landing site at Botany Bay, it was in a most unlikely manner, for they did their astronomy not with glass lenses, but with rods of metal.'

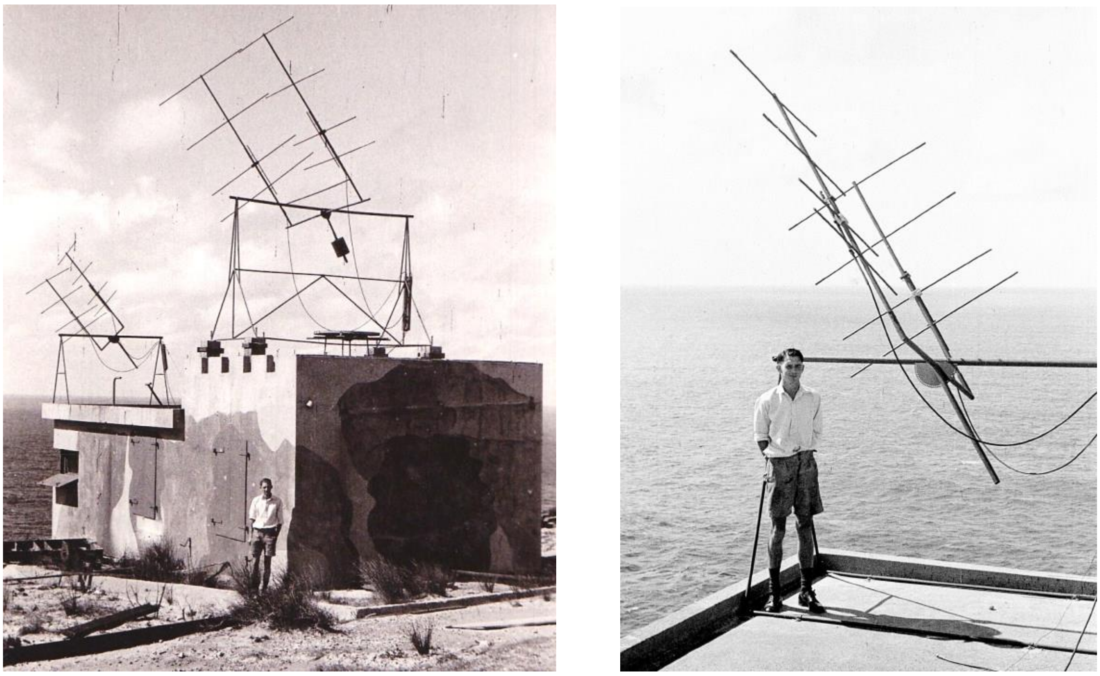


Figure 3.3. Bolton at the Dover Heights blockhouse in May 1947, a month before the detection of the Cygnus source. (left) Two of the Yagi antennas used for solar observations at 100 MHz (left) and 60 MHz. The 200 MHz antenna was on the far corner and is not visible. Note the WWII camouflage paint on the blockhouse. (right) The two elements of the 100 MHz Yagi were orthogonal to each other in the attempt to detect polarisation in the solar emission. The two elements could be positioned horizontally, pointing to the eastern horizon, to form a sea interferometer. This aerial was used for the discovery of the first eight discrete sources. [courtesy: Stanley family]

John Bolton commenced work at the Radiophysics Lab in September 1946 and was assigned to Pawsey's solar group [7]. He was given the task of investigating the polarisation properties of the sunspot radiation, an area of interest to David Martyn. Bolton spent the first month designing and building an antenna in the Radiophysics workshop. The antenna consisted of two Yagi aerials (named after the Japanese physicist Hidetsuga Yagi), basically the same as the first television aerials. The antenna was mounted on a movable platform, so that it could track the Sun, and connected to a modified radar receiver operating at 60 MHz. Bolton installed the antenna at the Dover Heights field station near the entrance to Sydney Harbour (see Figure 3.3). He was assisted by another new recruit to Radiophysics, Bruce Slee (see Figure 3.4), who would become Bolton's first scientific collaborator.

Owen Bruce Slee had an interesting background leading up to his appointment. During the war he had worked as a radar mechanic at an RAAF station at Lee Point near Darwin. On several occasions late in 1945 he noticed that when his radar set faced west out to sea at sunset there was a sudden increase in radio noise, which he soon showed came from the Sun. Slee became yet another wartime radar operator to have independently discovered solar radiation. He reported his discovery to the Radiophysics Lab in March 1946 [8]:

> 'In a recent newspaper article, I saw that the Council was investigating and measuring the signal strength of electromagnetic radiations in the radio-frequency spectrum from the Sun. For some months past I have been noticing that when the radar set was turned on around sunset, that a peculiar C.W. interference made itself evident on a certain bearing: this bearing is almost due west. I am now convinced that the interference is solar radiation as the bearing is looking out to sea and there can be no other radio apparatus out there to cause that effect. … If you want any further observations carried out, I shall of course be only too pleased to cooperate.'

Figure 3.4. Bruce Slee was John Bolton's first collaborator at Dover Heights and part of the team that discovered the first discrete radio sources. Slee was born in Adelaide in 1924 and trained as a radar technician. After serving at a number of radar stations in WWII, he joined the Radiophysics Laboratory in November 1946. [courtesy: Bruce Slee]

Slee enquired whether there might be an opportunity to join the Radiophysics staff. Pawsey was impressed and, following a meeting in Slee's home town of Adelaide, offered him a job on the spot. It was the beginning of a remarkable career. Slee started as a lowly technical assistant; studied evenings, eventually being awarded B.Sc. (Hons) and D.Sc. degrees; and worked his way up the ranks to become one of Australia’s most distinguished radio astronomers [9]. Slee recalled some of the privations during the early days at Dover Heights [10]:

> ‘In these late-1946 and early-1947 days, John lived at Bellevue Hill and I at Bondi Beach. We would catch the bus from Bondi to Dover Heights and return the same way. The weather was seldom good, the Sun was rather uncooperative and the exposed position made any outside work very uncomfortable. I remember we spent much of our time in the blockhouse reading astronomical texts, for we were both unfamiliar with astronomy. It was a time of severe postwar shortages. I recall having difficulty in getting cigarette papers for making our own cigarettes and, at one stage, we were reduced to rolling tobacco in used bus tickets. Power blackouts were frequent, especially during cold weather, and the power supply itself was very unstable in voltage and frequency.’

The attempt by Bolton and Slee to detect polarisation in the sunspot radiation was a failure. The Sun had entered a dormant period with no sunspots visible on its surface. However, Bolton had another idea. He had learnt of Jansky’s discovery of cosmic noise while a student at Cambridge. He was also aware from his time on *The Unicorn* that pointing a radar aerial along the plane of the Milky Way would lead to a significant increase in the amount of radio interference. For most radar operators, Jansky’s noise was considered an operational nuisance rather than an important astronomical discovery. However, Bolton speculated that if the Sun can emit strong radiation, could there be other astronomical objects that contribute to Jansky’s noise? He later noted [11]:

> ‘I went back to my wartime interest in this extraterrestrial radiation associated with the Milky Way. I had reasoned that if one had eyes with the directional ability of a radio aerial, one would not see the Milky Way as a set of stars; one would see it as a great blur. So I wanted to try and break this blur up into individual stars, and the way to do this was to point an aerial over the sea. The effective resolution is determined by the ratio of the wavelength to the height of the cliff and not the wavelength to the size of the antenna. So I started doing this with Bruce. A lot of the time when we were supposed to be looking at the Sun, we in fact pointed our aerials over the sea and just watched to see if anything came up with a telltale pattern.’

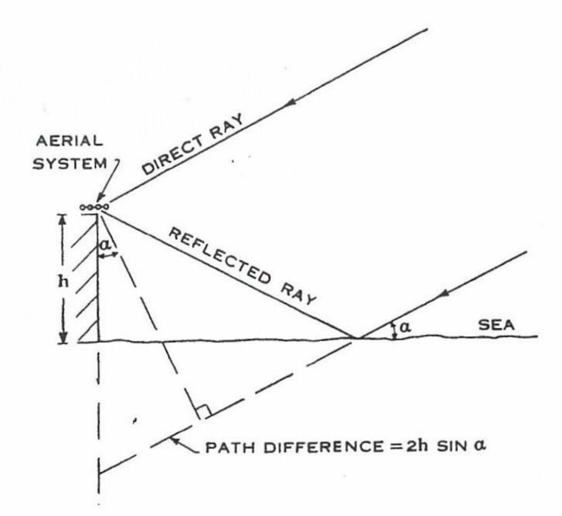


Figure 3.5. Radio astronomy began in Australia with the sea interferometer observations of the Sun by Joe Pawsey, Lindsay McCready and Ruby Payne-Scott. The cliff-top aerial combines the direct signal with the signal reflected from the sea to create an interference pattern. As the differential pathlength between the direct and reflected signals changes, the interference pattern goes through a series of maxima and minima. The reflected signal simulates an imaginary aerial, spaced from the real aerial at a distance equal to twice the height of the aerial above sea level. The difference in pathlength between the direct and reflected signals is given by $2h \sin\alpha$, where h is the height of the aerial above sea level and α is the angle of incidence of the reflected signal to the sea surface, corrected for the curvature of the Earth and atmospheric refraction of the signal (see equation 4.2 next chapter). Sea interferometry was also known as ‘cliff’ or ‘sea-cliff’ interferometry. The technique is the radio analogue of Lloyd’s mirror in classical optics, named after the Irish physicist Humphrey Lloyd (1800–81). In 1834 Lloyd demonstrated that a monochromatic beam of light reflected from a glass surface, at a low angle of incidence, combines with the direct beam to produce an interference pattern, strong evidence at the time for the wave-like nature of light. [after Stanley and Slee, 1950: Fig. 1]

Bolton and Slee reconfigured their 60 MHz solar antenna and pointed the two Yagi aerials towards the eastern horizon to work as a sea interferometer [see Bolton and Slee (1953) and Figure 3.5 for an explanation of the technique]. They consulted an astronomy textbook to make guesses as to which types of object might have strong radio emission, and then a star atlas to find the position of the brightest candidate in each class, both texts borrowed from the local municipal library [12]. After a couple of weeks attempting to detect a number of objects as they rose above the sea, the project was cut short by an unexpected visit from their boss Joe Pawsey, who saw immediately that their 60 MHz antenna was not pointing at the Sun. Pawsey was not impressed and ordered the pair back to the Radiophysics Lab [13].

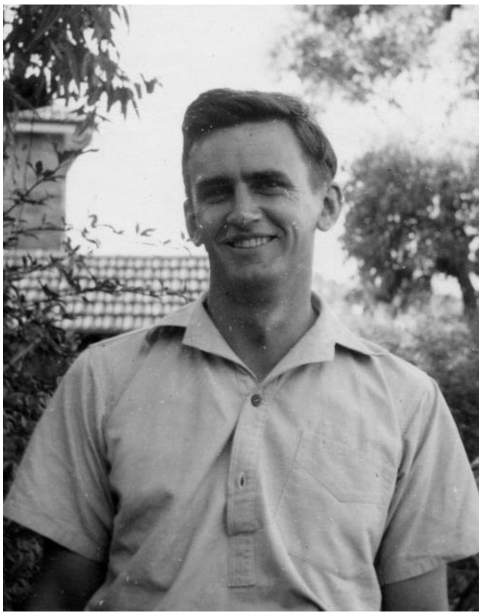


Figure 3.6. Gordon Stanley was the third member of the Dover Heights team. He was born near Auckland in New Zealand in 1921 and trained as an engineer. He joined the Radiophysics Lab in 1944 where he specialised in receivers and electronics. [courtesy: Stanley family]

At the time Pawsey was planning an expedition to Brazil to observe a total eclipse of the Sun. The passage of the Moon across the solar disc would allow the location of the sunspot radiation to be measured with far greater precision than Pawsey could achieve with a sea interferometer. Pawsey reassigned Bolton to work with Gordon Stanley (see Figure 3.6) who was building equipment for the expedition. It was the start not only of a lifelong friendship, but also of a collaboration that would be the most important of both their careers. Gordon James Stanley was born in 1921 in the small town of Cambridge, south–east of Auckland, New Zealand. His father suffered from tuberculosis and so the family decided to move to the warmer and dryer climate of Sydney when Gordon was six. He left school early and joined a company that manufactured a wide range of electrical products, where he began to show an exceptional talent for understanding the operation of anything electrical. Dividing his time between work and study he earned his high school diploma and then a Diploma of Engineering from the Sydney Technical College (now the University of New South Wales). When war broke out Stanley enlisted in the army for a period and then in 1943 he was transferred to the Radiophysics Lab where the authorities thought he would be of more value to the country’s war effort [14].

As it turned out, the expense and the logistical difficulties of getting personnel and equipment halfway round the world to Brazil proved too great and the eclipse expedition was cancelled [15]. Bolton recalled [16]:

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

It was an opportunity too good to miss. Bolton and Stanley spent an afternoon loading up a truck with the eclipse equipment, together with tools, spares and test equipment, and next morning headed out to the blockhouse at Dover Heights. Their first priority was to rig up a radio so that they could listen to a broadcast of the fifth Test Match between England and Australia, starting later that day at the Sydney Cricket Ground. They managed to install two of the solar receivers, operating at 100 and 60 MHz (see Figure 3.3), when one of the largest sunspots seen for several years appeared on the limb (edge) of the Sun and began its transit across the solar surface. The sunspot was inactive for almost a week until one afternoon when Bolton was about to start an observing shift. He heard the chart recorder for the 100 MHz antenna jump off scale and he moved quickly to turn the gain setting down as low as possible. After several minutes the strength of the signal began to decrease when suddenly the 60 MHz recorder also went off scale. After about 15 minutes the signal from both antennas had dropped back to normal.

The 200 MHz antenna was not in operation at the time, so Bolton checked with the Mt Stromlo observatory which had been monitoring the Sun with its own 200 MHz antenna (see note [5]). It had also gone off scale, but two minutes before the 100 MHz recording at Dover. Further work confirmed that the outburst was caused by a large solar flare which generated intense radio emission first at the higher frequency of 200 MHz, followed by intervals of several minutes to the lower 100 and 60 MHz frequencies. The explosive force of the flare ejected a column of ionised material out through the solar atmosphere at speeds of up to 1500 km per second. The arrival of the ionised material in the Earth's atmosphere a day or so later caused auroral displays and strong magnetic storms. The following day a bright aurora could be seen in the Sydney sky, a rare event at this latitude (nearly 34° S) and demonstrating just how powerful the solar flare had been.

The flare observations led to the first research paper of Bolton's career [17], a two-page article in *Nature*, which was co-authored by Ruby Payne-Scott and Don Yabsley (Gordon Stanley was overlooked).   Payne-Scott and Yabsley had also been observing the Sun at Dover Heights and noticed a time delay, from high to low frequencies, for another type of outburst which lasts only a few seconds. Bolton and Stanley continued to monitor the emission from the sunspot region. A month after the occurrence of the solar flare, during the second transit of the sunspot across the solar disc, they were able to observe circular polarisation in the sunspot radiation, succeeding where previously Bolton and Slee had failed. They could also confirm a prediction by David Martyn that the circular polarisation would reverse its direction of rotation when the sunspot is halfway across the disc. As it turned out, this would be Bolton's final contribution to solar radio astronomy.

Figure 3.7. J. Stanley Hey pioneered radio astronomy in Britain. As well as his wartime studies of the Sun, Hey made two other important discoveries. One was that radar could be used to detect and track meteors more accurately than visual observations. Hey and his group were also the first to report variations in the strength of radio emission from a region in Cygnus constellation. The detection led directly to the discovery of the first discrete radio sources by the Radiophysics group in Sydney. After the war, Hey established a radio astronomy group at the Royal Radar Establishment in Worcestershire. [courtesy: RR Establishment]

3.2 Cygnus A: The First Discrete Radio Source

By May 1947 the Sun had again entered a phase of low activity so Bolton and Stanley decided to return to the topic which Pawsey had brought to an abrupt halt six months earlier. Pawsey had said they could use the Brazil equipment for any purpose they liked, so they would take him at his word. By day they would continue routine monitoring of the Sun, but at night they would renew the search for other radio objects in the sky previously carried out late in 1946 by Bolton and Slee. To begin they decided to see whether they could confirm a recent report by Stanley Hey, the discoverer of radio emission from the Sun in 1942 (see Figure 3.7).

After the war Hey, James Phillips and John Parsons at the Army Operational Research Group near London carried out a sky survey of radio emission at 60 MHz, producing isophote maps similar to those published earlier by Grote Reber [18]. Hey and his group noticed that whereas radio signals from any given direction were relatively constant in strength, emission from the constellation of Cygnus exhibited peculiar fluctuations, changing in intensity during times as short as a minute. In a *Nature* letter reporting this discovery, Hey, Parsons and Phillips argued on physical grounds that this variable emission must come from a relatively small region of space, possibly from some unknown astronomical object [19]. As we shall see in the next chapter, this assumption turned out to be correct, but for the wrong reason.

In August 1946 the chief of the Radiophysics Lab, Taffy Bowen, was visiting England and sent Pawsey a reprint of the letter on the Cygnus fluctuations by Hey's group and encouraged him to try and confirm the discovery. Within a few days of receiving Bowen's letter Pawsey was able to announce the detection of the variable source in Cygnus. Pawsey reported to Richard Woolley, the director of the Commonwealth Observatory [20]:

> '… we immediately made some confirmatory measurements on 60 and 75 Mc/s, obtaining similar fluctuations of the same form as the "bursts" observed in solar noise. We have no hint of the source of this surprising phenomenon.'

Pawsey continued the observations hoping to find the cause of the phenomenon. The initial success, however, seems to have been followed by a period of conflicting observations, during which the reality of the Cygnus fluctuations came into question. In the end Pawsey stopped investigating Cygnus, unsure of whether or not he had confirmed the existence of Hey's source [21].

As mentioned above, late in 1946 Bolton and Slee had searched for radio sources by targeting specific objects they thought might be radio emitters. They were aware of the Hey *et al.* paper and of Pawsey's inconclusive attempt to confirm the source, and had in fact made their own brief but unsuccessful attempt to detect Cygnus [22]. In contrast, rather than target specific objects, Bolton and Stanley decided to carry out an empirical search of the southern sky with their 200 MHz antenna and the northern sky with the 100 MHz one. Bolton recalled [23]:

> 'We had found what we thought was one source in the south with our 200 MHz equipment when something suddenly went wrong with it. I had to go up on the roof and resolder the connection to the aerial. All of a sudden something electrical went wrong with the soldering iron and it exploded in a great shower of sparks. So we were limited to our other 100 MHz antenna at that time. So we thought, why don't we have a look at the region where Hey reported this variation? Sure enough, we did get a sea interference pattern of this object which showed its basic pattern modulated by a short period pattern. The basic sea interference pattern was about 10 minutes between one maximum and the next maximum, but modulating this were variations of 20 or 30 seconds on top of it.'

The signal was not as strong as the solar bursts they had been observing, but the source did produce the distinctive fringe pattern on their chart recorder (see Figures 3.8 and 3.9). They continued the observations as the source rose each night and, by the end of June, they had enough data for Bolton to give a brief talk at the Radiophysics Lab, with the title 'Variations in cosmic noise from the constellation Cygnus' [24].

Bolton could report that the source had been detected at 100 and 60 MHz, but not yet at 200 MHz, and he gave an approximate position for the source which differed by about 3° from the one listed by Hey. Bolton also reported that no polarisation had

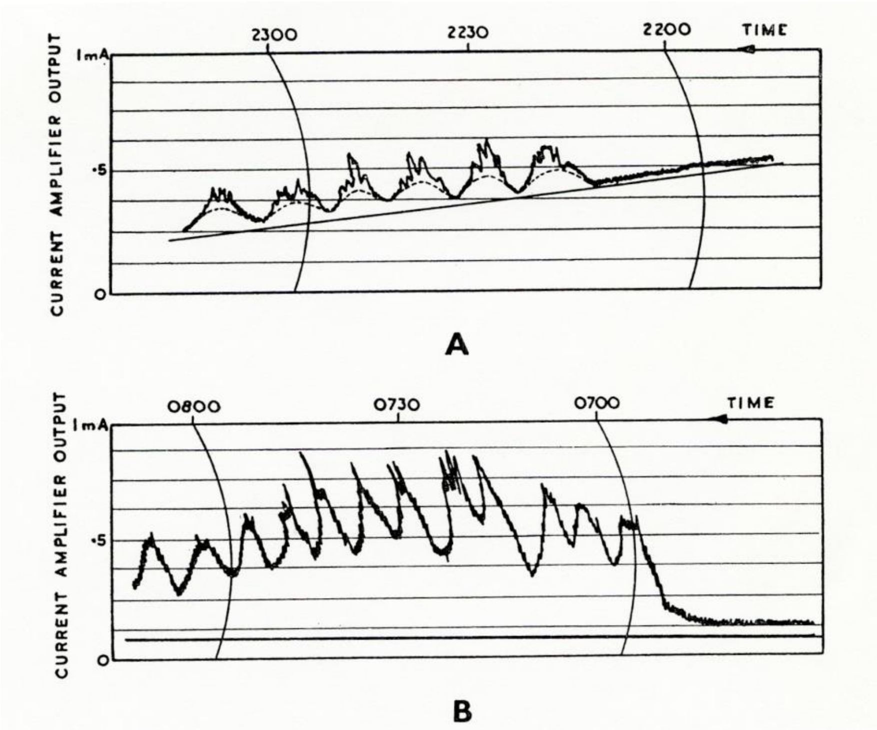


Figure 3.8. (A) Interference pattern for the Cygnus source recorded at 100 MHz after 10 pm on the evening of 19 June 1947 at Dover Heights (from right to left). Note the spiky fluctuations superimposed on the Cygnus fringes and the sloping baseline from decreasing Galactic noise (referred to as 'cosmic noise decline' in Figure 3.9). The dashed curve shows the base level of the variable component. (B) For comparison, the interference pattern recorded for the Sun at dawn on 24 June 1947. [after Bolton and Stanley 1948b, p. 60]

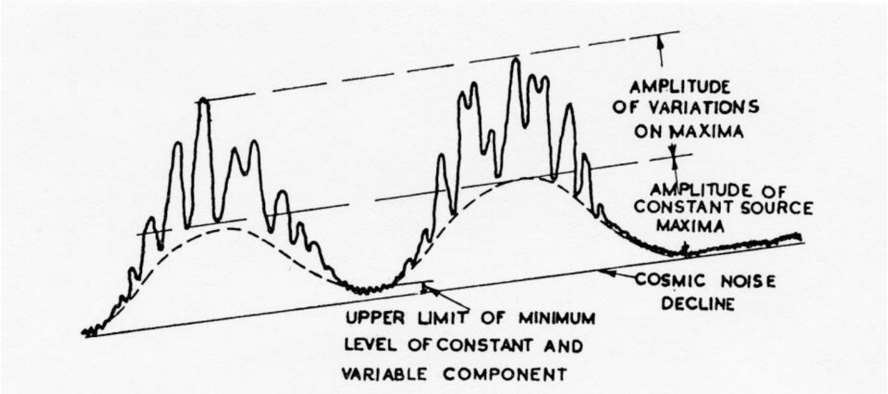


Figure 3.9. An enlarged section of the Cygnus record in Figure 3.8 showing how the maxima and minima of the constant and variable components are identified. The dashed curve results from the sinusoidal variation in path difference given by $2h \sin\alpha$ (see Figure 3.5). Note that the amplitude variations never fall below the dashed curve. The relative heights of the maxima and minima in the dashed curve provide an upper limit on the angular size of the source. [after Bolton and Stanley 1948b, p. 63]

been detected at 100 MHz. There was some evidence for another weaker source near Cygnus and also the possibility a source much further south in the Centaurus constellation: 'A large part of the southern sky has been surveyed now with negative results except for the Centaurus region which shows very small fluctuations. The source if any is probably circumpolar [i.e. permanently above the horizon at Sydney's latitude] which adds considerably to the difficulties of detection.' The difficulty was of course that the sea interferometer is far less effective if the source does not rise above the horizon. Despite several attempts Bolton and Stanley were unable to verify the Centaurus source as their signal-to-noise ratio was too poor.

A week after his Radiophysics talk, Bolton reported to David Martyn [25]:

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

The most important quantity in Bolton's letter was an upper limit to the angular size of the source, which he derived from the interference fringes, using the following formula:

$$W = (\lambda/\pi h)\,(3R)^{1/2}\,, \qquad (3.1)$$

where W is the equivalent radiating strip, λ is the wavelength, h is the height of the aerial above sea level, and R is the ratio of the heights of the interference fringe maxima and minima above an extrapolated cosmic drift background level. Bolton's figure of $<8'$ was an improvement by a factor of 15 on the value arrived at by Hey's group. The beamwidth of Hey's aerial was 2°, so that the aerial could not resolve any detail smaller than a patch of sky equal to about four times the angular width of the

Moon. Hey had argued that the Cygnus source was most likely compact because of the rapid variations in its signal strength. Whereas Hey had *inferred* a small size, the Dover Heights data provided the first *proof* that Cygnus was indeed a compact star-like object. The existence of the first 'radio star', the first discrete radio source, had now been established. Years later, Bolton explained how the ratio of fringe maxima to minima provided an upper limit on the angular size of the source [26]:

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

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

Early in July 1947 Bolton and Stanley towed a trailer fitted out with their 100 MHz antenna to two headlands north of Sydney. The first of the sites, known as Long Reef near the suburb of Collaroy, had an elevation of only 30 metres above sea level, but it had the advantage of covering the whole hour angle range from rising to setting (see Figures 3.2 and 3.10). Observations made over a week enabled them to measure a right ascension accurate to ±1´. It was difficult work and there was no option but to camp out mid-winter to guard against their equipment being stolen or vandalized. Bowen wrote to CSIR head office to request out-of-pocket expenses for Bolton and Stanley [27]:

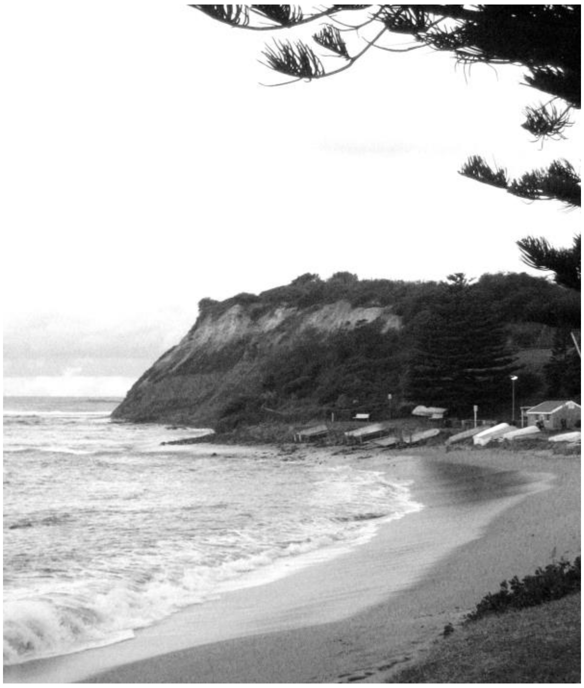


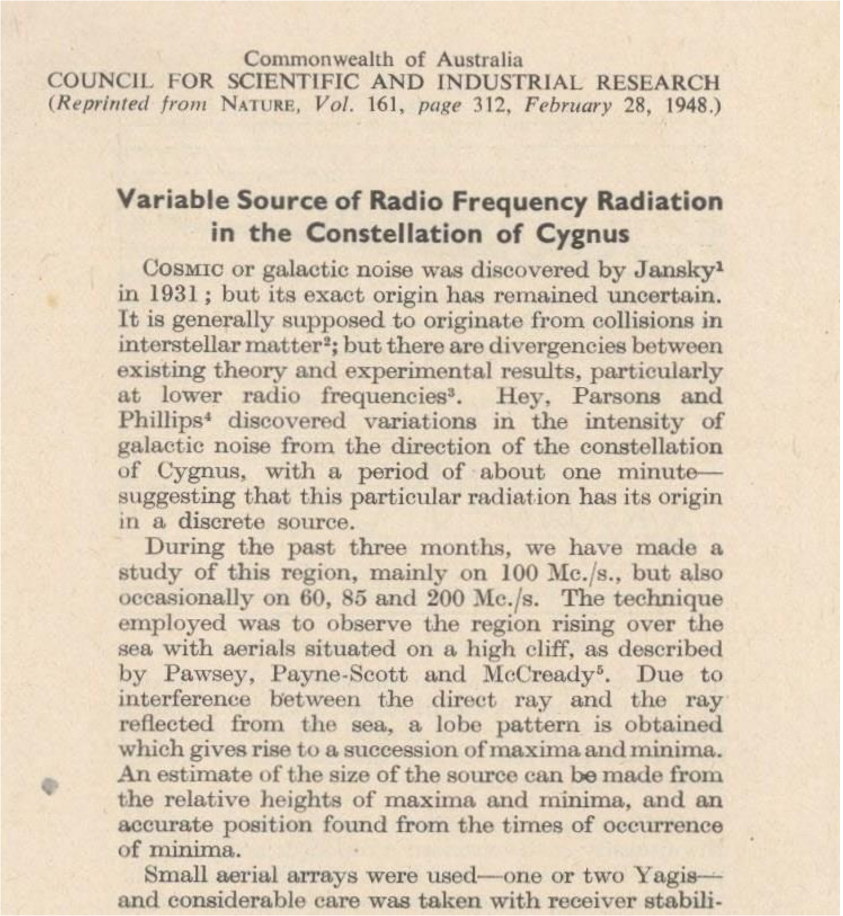
Figure 3.10. Two sites where Bolton and Stanley carried out observations on the Cygnus A source in July 1947: (above) Long Reef looking east to the Tasman Sea. The site is a short distance south of the northern Sydney suburb of Collaroy, close to where Joe Pawsey and his group made the first radio observations of the Sun in October 1945. (below) West Head looking north with Lion Island at right. The site is in the Ku-Ring-Gai Chase National Park, approximately 30 km north of Sydney.
[courtesy: author]

> ‘In our investigations into “cosmic noise” it became necessary to observe the radio noise received from the time of rising to the time of setting of certain constellations which at present are above the horizon only during the night. Over-water rising and setting were

> essential and the most convenient point for these observations was found to be at Collaroy, an outer northern suburb of Sydney. The necessary equipment was mounted in a trailer and taken to this point, and the observations were made by Messrs Stanley and Bolton who "camped" on the site over the abovementioned period. They worked all night and slept in shifts by day, one or other of them being on duty for most of the day to take calibration measurements on the Sun, to charge batteries and to guard the equipment. On this account it was not considered practicable or advisable for either of them to return to their homes throughout this period. Only bed and bedding could be provided for them and they were obliged to obtain all their meals at cafes nearby.'

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

By September 1947, after three months of observations, Bolton and Stanley had enough data to publish. Taffy Bowen thought that the Cygnus discovery was important enough to be published in the *Proceedings of the Royal Society of London*, the most prestigious science journal in the British Commonwealth. However the 'Royal', as it was known, was experiencing publication delays of over a year and there was a danger that the Cygnus discovery might be scooped by another group. After some debate it was decided to make a brief announcement in *Nature* (see Figure 3.11), followed by a detailed paper in the new *Australian Journal of Scientific Research* [28]. The *AJSR* was about to be launched by CSIR head office in Melbourne and would be the first nationwide science journal published in Australia. The Cygnus paper appeared in the first issue of volume 1 early in 1948. A brief



Commonwealth of Australia
COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH
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Variable Source of Radio Frequency Radiation in the Constellation of Cygnus

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

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

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

Figure 3.11. Part of the first page of the letter by Bolton and Stanley announcing the discovery of the discrete source in Cygnus. The letter to *Nature* was submitted on 4 December 1947 and published on 28 February 1948. [courtesy: *Nature* and Bolton papers, National Library of Australia]

announcement letter in *Nature*, followed by a detailed *AJSR* paper, became the standard publishing practice for the Dover Heights group over the following years.

Before the Cygnus paper was submitted to *Nature* a draft copy was sent to the Commonwealth Observatory, where it was read by David Martyn and the director of the observatory, Richard Woolley. A copy was also given to the professor of electrical engineering at the University of Sydney, John Madsen, a senior figure who had played a significant role in the foundation of the Radiophysics Lab (see Section 2.2). Several senior Radiophysics staff also read the draft, including Arthur Higgs (see Figure 2.6) who found a glaring error in the calculation of the Cygnus position. Bolton and Stanley, still trying to learn the rudiments of astronomy, had overlooked the Earth's precession, the slow periodic change in the direction of the Earth's axis of rotation [29].

Although the problem was soon fixed, the position of Cygnus turned into somewhat of a saga. After the paper had been dispatched to *Nature*, Bolton discovered that he had used the wrong longitudes for the Dover Heights and West Head sites. He recalculated the right ascension and then Bowen sent the new position to the Australian Scientific Liaison Office (ASLO) in London, which coordinated the publication of CSIR articles in British journals. Three weeks later Bowen discovered there had been a typographical error in his letter which gave the declination as +41° 41′ ±7′, instead of Bolton's value of +41° 47′ ±7′. Bowen sent off a second letter to ASLO requesting a further change, but it seems this letter was overlooked as the *Nature* paper appeared with the incorrect value of declination [30]. This however was not the end of the story. As we see in Chapter 5, continuing uncertainty over the true position for Cygnus became a contentious issue between the Radiophysics Lab in Sydney and the Cavendish Lab in Cambridge.

In the detailed paper in the *AJSR* the 'correct' position was given for Cygnus:

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

a vast improvement on Hey's position which was known to no better than 5° accuracy. Bolton and Stanley announced that the angular width of Cygnus was less than 8′ of arc and that its radio emission has two components, one believed constant, and the other showing considerable variations with time. In the discussion of their results they noted [31]:

> 'Reference to star catalogues, in particular the Henry Draper Catalogue, shows that the source is in a region of the Galaxy distinguished by the absence of bright stars and objects such as nebulae, double and variable stars, i.e. *the radio noise received from this region is out of all proportion to the optical radiation*. Although the experimental technique allows only an upper limit to be placed on the size of the source, this is believed to be effectively a point and therefore a single object. The determined position lies in a less crowded area of the Milky Way and the only obvious stellar objects close to the stated limits of accuracy are two seventh magnitude stars. There is certainly no comparable optical radiation from this region.' [my italics]

Astronomers at the Commonwealth Observatory at Mt Stromlo carried out a close examination of this region and produced a photographic plate that confirmed the Henry Draper Catalogue. The plate together with a semi-transparent overlay were reproduced in the *AJSR* paper There were two unremarkable stars of seventh magnitude close to the position – HD189957 and HD190112 – but no object that appeared in anyway unusual. The identity of Cygnus would remain a mystery for some time to come.

The *AJSR* paper also reported the detection of the source at 60, 85, 100 and 200 MHz, providing the first spectrum of the source. The intensity of the radio emission rose from 60 to 85 MHz, peaked at 100 MHz, and then fell away to about half the maximum intensity at 200 MHz. Thus, although the position, angular size and the spectral features were known in some detail, the distance to the object was unknown. Bolton and Stanley attempted to estimate a lower limit and an upper limit of distance. For the *lower limit* they noted that if the variations extended over the whole source, it is unlikely that the width of the source would exceed the product of the velocity of light and the period of the shortest variation. Assuming an angular width of 8´ and a period of variation of 0.25 minute, the distance of the source cannot exceed 100 light-minutes, which of course would place it well within the Solar System. As there had been no discernable parallax in the position of the source over several months, Bolton and Stanley argued that this was further evidence that the angular width of the source must be much less than 8´, and therefore that the source is much further away.

For the *upper limit* of distance, they assumed the source to be an average star but with its *total* energy output in the radio frequency spectrum. Taking a mean intensity of 2×10^{-23} W m^{-2} Hz^{-1} for the source spread over a bandwidth of 1000 MHz, the total radiation would be 2×10^{-14} W m^{-2} [32]. The Sun considered as an average star has a total radiation of about 1 kW m^{-2}. Applying an inverse square law, this gives a source distance of approximately 3000 light-years. Thus, according to Bolton and Stanley, it seemed likely that the Cygnus source was somewhere between 2×10^{-4} and 3000 light-years from Earth! As we see later, the *upper limit* proved hopelessly inadequate.

To conclude their paper, Bolton and Stanley speculated on a possible emission mechanism for Cygnus. They noted that if the size of the source was less than 8´, the effective temperature at 100 MHz would be greater than 4×10^6 K, making a thermal origin of the radiation improbable. Instead, they noted that a mechanism similar to the one proposed '… to account for the steady enhanced noise from a large active sunspot – perhaps the association of moving ionised matter and strong magnetic fields – is quite possible.' [33] In broad terms, Bolton and Stanley had correctly anticipated the mechanism later known as synchrotron emission (fast electrons spiralling around magnetic field lines), which was verified by theoretical work in the early 1950s (see Chapter 6).

The Dover Heights work was becoming known outside the Radiophysics Lab. In September 1947 Bowen enthusiastically wrote to CSIR chief executive David Rivett in Melbourne [34]:

> 'One of Pawsey's brightest men is Bolton … He has proved himself one of the best youngsters we have appointed for some time. He has exactly the right outlook for research and is full of original ideas. Just at present his chief interest is in the noise from the constellation Cygnus and he has obtained results which prove fairly conclusively that it comes from a confined source whose characteristics are similar to those of the Sun. This is quite contrary to existing theories of cosmic noise, which postulate that it originates in interstellar space.'

The Cygnus results also caught the attention of a number of prominent astronomers overseas. In September 1947 Joe Pawsey (see Figure 3.12) embarked on a year-long trip to the United States and Europe. As a brief aside, it is interesting to note here that it was during this trip that Pawsey coined the term 'radio astronomy'. Since Karl Jansky's discovery in 1932, the study of extraterrestrial radio waves had been variously known as 'cosmic static', 'cosmic noise' or 'galactic noise'. In December 1947 Pawsey received an invitation from Charles Burrows at Cornell University to attend a conference on 'Microwave Astronomy'. Neither Pawsey nor Bowen warmed to the new term. Bowen noted: 'I don't think much of Burrows' invention of the title "Microwave Astronomy". A lot of it is certainly not microwave and I am not at all sure whether it is astronomy.' As an example, the observations at Dover Heights spanned the frequency range 60–200 MHz, corresponding to a wavelength range 1.5–5.0 m, whereas microwave radiation was normally associated with the wavelength range 1 mm to 1 m. Pawsey first used the term ‘Radio Astronomy’ in a letter dated 14 January 1948, which immediately met with Bowen’s approval: ‘Incidentally, I like the term “Radio Astronomy” much better than Burrows’ effort and we might very well consider adopting it generally.’ [35]

Figure 3.12. From left: John Bolton, Gordon Stanley and Joe Pawsey in one of the workshop rooms at the Radiophysics Laboratory. [courtesy: Bolton papers, National Library of Australia]

Pawsey’s first stop in the United States was to the Mt Wilson Observatory near Pasadena, home to the 100-inch Hooker Telescope, the largest in the world (but soon to be overtaken by the 200-inch Hale Telescope further south in California on Palomar Mountain). Pawsey reported to Bolton and Bowen [36]:

> ‘I discussed the Cygnus work in some detail with the Mt Wilson people and found them intensely interested. They immediately searched out the region given in Bolton and Stanley’s paper but found nothing. Further, they promised to take further relevant

> photographs. I consider this collaboration is very worthwhile and told them we would be very happy to work in with them. At present, I think this collaboration will simply involve exchange of information.'

This source became of special interest to Rudolph Minkowski, one of the senior Mt Wilson astronomers, who would later play a significant role in Bolton's career (see Section 6.3 and Figure 4.12). In November, Pawsey visited the Yerkes Observatory near Chicago and held discussions with its director Gerard Kuiper and two visiting astronomers, Jan Oort (director of the Leiden Observatory) and Bengt Strömgren (director of the Copenhagen Observatory). As Pawsey reported to Bolton [37]:

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

Later correspondence revealed that it was Kuiper who had argued that the ionosphere might be the cause of the fluctuations [38].

Early in 1948 Bolton and Stanley took up Pawsey's suggestion and carried out further observations at 100 MHz at the Long Reef site, about 15 km north of Dover Heights. A comparison between the signals recorded at both sites showed a good correlation between the rapid fluctuations, confirming Bolton's own view that the fluctuations were intrinsic to the source and not caused by the ionosphere. As he wrote to Pawsey [39]:

> 'I am afraid I can't agree with the ionospheric cause of Cygnus' variations. To start with the variations are definitely on top of an apparently constant effect and at times they may be very large … As circumstantial evidence we have two other variable sources and five

> constant ones at 100 Mc/s. Of course the constant ones need not necessarily be point sources. I suspect though that some of the constant ones may show variations with a reduced bandwidth and give a clue as to their distance – stretching my imagination to its limit.’

In his reply Pawsey insisted that Bolton needed to resolve the issue [40]: ‘The question of ionospheric effects possibly causing variations *must be met in your next paper*. You have a number of lines of evidence but these must be followed in sufficient detail to leave no reasonable loophole.’ [his italics]

As it turned out Bolton was wrong. With the Long Reef site almost due north of Dover and, with Cygnus relatively low (~15° maximum) on the northern horizon, the signals at each site essentially passed through the same column of the ionosphere. If the observations had been done instead with 15 km separation in an east–west direction, there would have been a much poorer correlation between the Cygnus fluctuations at each site. We return to the nature of the Cygnus fluctuations in the next chapter.

3.3 A New Class of Astronomical Objects

Bruce Slee rejoined the Dover Heights team in September 1947 to assist Bolton and Stanley with improvements to the receivers and antennas. The operation of equipment needed to be monitored at all times and there were routine tasks to perform such as maintaining the flow of paper to the chart recorder. Slee recalled [41]:

> ‘It was left to us entirely how we allocated our time at Dover Heights. It was like John would do a shift and go home to sleep and then one of us would come on and, say, do work on the receivers. In some ways it was similar to the way we worked during the war, doing odd shifts around the clock, so it wasn’t really a shock to the system. Plus we were young in those days!’

Security was another issue. Earlier when the solar observations were in progress the blockhouse had been left unattended at night. Even though the site was fenced and a caretaker lived on site, on several occasions vandals had climbed onto the blockhouse roof and damaged the antennas. To guard against further damage a fringe of barbed wire was installed around the roof and the external ladder was removed and replaced by an internal one with a steel hatch. A new steel door and steel shutters on the windows completed the vandal-proofing.

To while away the night-time hours Bolton taught himself astronomy. Although he had read popular books on astronomy, such as those by his former Cambridge lecturer Arthur Eddington, he was in the same position as the other Radiophysics staff who were starting up projects in radio astronomy. Almost all had been trained as physicists or engineers and had to pick up the basics of astronomy on the run. Bolton began by reading back issues of astronomy journals borrowed from the physics department library at the University of Sydney. The two most useful were the leading American *Astrophysical Journal* and the leading British journal *Monthly Notices of the Royal Astronomical Society*. Bolton also began to have occasional contact with the astronomers at the Commonwealth Observatory at Mt Stromlo, although as he wrote to one astronomer [42]:

> ‘In Australia all our knowledge and information on astronomy is gained from books and papers and very little from personal contact. Although we have a rapidly developing observatory at Mt Stromlo, the interest there is mainly solar and of little value to those of us whose work has taken them into the realm of general astronomy.’

During daylight hours Bolton’s group shared the Dover Heights field station with other Radiophysics staff, notably Ruby Payne-Scott who continued her studies on the various types of solar radiation. Payne-Scott shared the distinction with Elizabeth Alexander in New Zealand of being the first two female radio astronomers. As noted in Section 3.1, during the war Alexander had discovered that solar radio emission was the cause of the interference experienced at New Zealand radar bases, independent of the same discovery by Stanley Hey and others. Although Payne-Scott had been the senior author on Bolton’s first research paper, there was no direct collaboration between the two. Soon tensions began to develop between the two groups. Part of the problem was that both groups often wanted to use the same piece of equipment at the same time, or one group wanted to carry out routine maintenance which might create radio interference for the other group. With space in the blockhouse limited, the two groups were getting in each other’s way.

The main problem however was a personality clash between Bolton and Payne-Scott. At a time when women physicists were a rarity, Ruby was regarded as one of the most talented physicists in the Lab and Bolton did in fact have a high opinion of her ability. However, it is doubtful whether he had ever come across anyone like her. Most of his life had been spent in a largely all-male environment, from grammar school, to Trinity College, and then to the navy. Ruby had forthright views on all sorts of issues such as politics and women's rights. Many of the young Radiophysics staff held left-wing views, but Payne-Scott went one step further. She and her husband were card-carrying members of the Communist Party, earning her the nickname 'Red Ruby'. Their feud at Dover Heights became well known back at the Lab. Pawsey was informed of these developments during his overseas trip by his right-hand man Lindsay McCready [43]:

> 'To cut a long story short, Bolton and Ruby have had a "bust up" at Dover – partly due to technicalities … and partly due to, I fear, her personality, and last but not least both parties wanting to use the same gear for different experiments at the same time! Anyhow after careful examination of the rights of all and facts we decided it would be better if Ruby moved to Hornsby. No-one objects and she … is quite happy about it.'

Although Pawsey was sympathetic to Payne-Scott: 'I think that Bolton has, through his hard work and effective results, earned the right to take control of Dover, so that anyone working there shall be doing so at his invitation.' [44]

In parallel with the Cygnus observations the search continued for other possible radio sources by scanning the sky at different declinations and looking for the telltale interference pattern. As mentioned above, just before the initial detection of Cygnus in June 1947, Bolton and Stanley thought they had found a source in the Centaurus constellation. However, repeated attempts to confirm the detection proved a frustrating failure. It soon became apparent that – if indeed other sources did exist – the sensitivity of the antenna systems was not good enough to pick out sources from the background noise: short time variations in the receiver noise were drowning out any signals fainter than the strong Cygnus source. Stanley made the crucial breakthrough in October 1947 when he developed a high-tension power supply that eliminated most of the noise variations in the receivers. The receiver output was stable to about one part in several thousand, so much fainter signals could now be detected. Early in November the Dover Heights team was rewarded by the detection of a second source in the Taurus constellation, followed early in December by a third in Coma Berenices and then (the one that had eluded them) a fourth in Centaurus. Taffy Bowen wrote excitedly to Pawsey in Washington, DC [45]:

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

Pawsey reassured Bolton that he was being non-committal when questioned about the existence of further sources [46]:

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

By Christmas 1947 a fifth and a sixth source had been added to the list [47].

It had been a vintage year for the Dover Heights group. It began in March with the lucky observation of a giant solar flare and was followed by the discovery in June that Cygnus is a point-like source. Evidence was now emerging for the existence of a whole new class of objects previously unknown to astronomers. As we see in the next chapter, most of 1948 was spent measuring more accurate positions for the radio sources in an attempt to identify some of them with known optical objects.

Notes to Chapter 3

[1] Hey (1946), *Nature* **157**, 47–48.

[2] Robertson (1992), p. 39.

[3] Orchiston (2005c).

[4] See Pawsey *et al.* (1946), *Nature* **157**, 158, and Pawsey (1946), *Nature* **158**, 633. Pawsey sent a copy of the first paper to Karl Jansky at the Bell Telephone Labs who replied: ‘The subject is one that has been of particular interest to me for some time and I want to thank you for the reprint.’ Jansky to Pawsey, 29 July 1946, NAA file A1/1/1, part 1. See also Section 6.2 for the Pawsey *et al.* (1946) letter. It is worth noting that Reber (1946), *Nature* **158**, 945, reported the detection of solar radiation at the same time as the two Radiophysics papers.

[5] As noted in the previous chapter, Martyn was removed as the chief of the Radiophysics Laboratory after just two years in the position. He left CSIR and moved to the Commonwealth Observatory at Mt Stromlo near Canberra. Together with his colleague Clabon ‘Cla’ Allen, Martyn wanted to start his own observational program of solar radio emission. Consequently, in early 1946 Radiophysics staff installed a steerable 200 MHz array of four Yagi aerials at the Commonwealth Observatory. This was virtually identical to the four-element Yagi set-up that Bolton, Stanley and Slee later would use at Dover Heights (see below). As I have noted previously (Robertson 1992, p. 109), this appears to have been the first significant collaboration between optical and radio astronomers anywhere in the world.

[6] Sullivan (1988), p. 340.

[7] Bolton (1982), p. 349. This article is a detailed recollection by Bolton of the Dover Heights years 1946–53, written a year after his retirement, and will be cited a number of times in this thesis.

[8] Slee to CSIR Radiophysics Lab, 4 March 1946, NAA file A1/1/1, part 1. For the origins of solar radio astronomy in Australia see Orchiston *et al.* (2006).

[9] See Orchiston (2004, 2005a) for a scientific biography of Bruce Slee. In 2015, at the age of 91, Slee is still actively publishing research papers on radio astronomy and on the history of radio astronomy (see e.g. Robertson *et al.* 2014). He began observations of solar emission in 1945 and published his first research paper in 1949, with coauthors Bolton and Gordon Stanley (see next chapter). His research career has spanned an extraordinary 70 years, unsurpassed by any other radio astronomer and no doubt one of the longest of any Australian scientist.

[10] Slee (1994), p. 518.

[11] Bolton interview with Lennard Bickel, Canberra, 13 January 1975.

[12] For the astronomy textbook consulted see Russell *et al.* (1926). For a recent edition of *Norton’s Star Atlas* see Ridpath (2004).

[13] Slee interview by author, Marsfield, NSW, 28 November 2006. Slee was not present at the time of Pawsey’s visit, but was later told of the encounter by Bolton. Slee recalls that Pawsey was a ‘stickler’ in insisting that his staff must not stray from the task that they were assigned. See also Slee (1994), p. 519.

[14] See Kellermann *et al.* (2005) for Stanley's biography.

[15] Similarly, the radio astronomy group at the Cavendish Laboratory, Cambridge University, had planned a solar eclipse expedition to Brazil, but it was also cancelled – J. A. Ratcliffe to Pawsey, 17 September 1946, NAA file A1/1/1, part 1. See also Wendt *et al.* (2008a).

[16] Bolton (1982), p. 350. For a detailed reconstruction of the following solar observations see Goss and McGee (2010), pp. 117–23.

[17] Payne-Scott, Yabsley and Bolton (1947). Later, Paul Wild at Radiophysics classified the solar flare emission observed by Bolton and Stanley as a Type II burst, lasting up to 15 minutes. The short duration emission observed by Payne-Scott and Yabsley, lasting several seconds, was labelled a Type III burst.

[18] Hey *et al.* (1946), *Nature* **157**, 234.

[19] Hey *et al.* (1946), *Nature* **158**, 296–97.

[20] Pawsey to R. Woolley, 11 September 1946, NAA file B51/14, as cited in Sullivan (2009), p. 139.

[21] Years later, when the true cause of the Cygnus fluctuations was known, Bolton speculated on the reason why Pawsey's attempt had been unsuccessful: 'Now, of course Pawsey was looking for variations, the short-term variations that Hey had reported. In fact these variations are a product of the condition of the atmosphere at the time. They depend on the time of day, the time of year, where you're looking from, and whether you're looking through a medium which will produce this kind of effect. I mean, you get nights in which the stars don't twinkle, and Pawsey had hit one of these occasions when this source in Cygnus hadn't got a variation imposed by the Earth's atmosphere.' See note [11].

[22] See note [13]. Slee remarked: 'We knew of Hey's work at that stage on the scintillations in Cygnus A, though we couldn't locate the source.'

[23] Note [11], cassette 1.

[24] See Bolton, 'Summary of Cygnus Results 4th – 25th June, 1947', 30 June 1947, NAA file B2/2, part 1. Bolton presented his report to a committee meeting of senior staff, chaired by Pawsey, known by the somewhat arcane name of the Propagation Steering Committee. The role of the committee was to coordinate and oversee the various groups and projects that were starting up in radio astronomy. The name was changed to the Radio Astronomy Committee in April 1949. Bolton did not become a regular member of the committee until July 1949.

[25] Bolton to D. F. Martyn, 9 July 1947, Papers of Woodruff T. Sullivan, NRAO Archives, Charlottesville, Virginia. The 'further attempt at localisation' referred to by Bolton were the observations made at Long Reef and West Head – see below.

[26] See note [11], cassette 1.

[27] Bowen to Secretary, CSIR, 11 August 1947, NAA personal history file PH/BOL/005, part 1. Bolton and Stanley were reimbursed a travel allowance of 18 shillings and sixpence.

[28] Bolton and Stanley (1948a, 1948b). *Aust. J. Scient. Res.* was published in two parts: Series A for the physical sciences and Series B for the biological sciences. In 1953 Series A

was split into a physics and a chemistry journal. The *Australian Journal of Physics*, together with its predecessor *AJSR*, published a total of 44 of Bolton's papers over his career, more than double any other journal.

[29] Gordon Stanley interview by Woody Sullivan, 13 June 1974, Owens Valley, California. I am grateful to Sullivan for providing a transcript of the interview.

[30] For the relevant correspondence see Bolton to Pawsey, 17 December 1947, NAA file C4659, Pawsey correspondence, part 8. I am grateful to Harry Wendt for drawing my attention to this letter. See also Bowen to L. G. Dobbie (ASLO), 16 December 1947 and 7 January and 4 March 1948, Sullivan papers, NRAO Archives.

[31] Bolton and Stanley (1948b), p. 68.

[32] Their paper used units of watts m^{-2} $(c/s)^{-1}$ for the radio intensity, whereas I use the modern SI equivalent for all quantities. See also the footnote to Table 4.1.

[33] Bolton and Stanley (1948b), p. 69.

[34] Bowen to A. C. D. Rivett, 2 September 1947, NAA file E2/B [Outside bodies].

[35] For the relevant correspondence see Pawsey to Bowen, 31 December 1947; Bowen to Pawsey, 8 January 1948; Pawsey to O. F. Brown, 14 January 1948, NAA file F1/4/PAW, part 1, and Bowen to Pawsey, 20 February 1948, NAA file C4659, Pawsey correspondence, part 8. In August 1948 Martin Ryle in Cambridge published a popular article entitled 'Radio Astronomy' in *British Science News*, an indication of how quickly the new term was adopted – see Sullivan (2009), p. 511.

[36] Pawsey to Bolton and Bowen, 11 November 1947, NAA file F1/4/PAW, part 1. To conclude his letter Pawsey listed a number of objects Minkowski had suggested as possible sources of radio emission, including the Crab Nebula: 'If we are interested in interstellar dust, etc. the "Crab Nebula", NGC 1952, is a good sample.' A reply to Pawsey's letter by Lindsay McCready on 18 November (same file) indicates that the source Taurus A had already been discovered at Dover Heights, independent of Minkowski's suggestion. The Bolton–Stanley paper on the probable identification of Taurus A with the Crab Nebula was submitted to the Australian journal over a year later in January 1949 [see Sullivan (2009), p. 142, and Section 4.3 below].

[37] Pawsey to Bolton, 9 December 1947, NAA file C4659, Pawsey correspondence, part 8.

[38] Pawsey to G. P. Kuiper, 15 March 1948, NAA file C4659, Pawsey correspondence, part 8. A year after Pawsey's visit, Kuiper proposed a radical new theory on the origin of the Solar System, including the prediction of a vast disc-shaped belt of small rocky objects and comets at radial distances of ~30–50 AU. Kuiper's prediction was verified in the 1990s and named the Kuiper Belt.

[39] Bolton to Pawsey, 1 February 1948, NAA file C4659, Pawsey correspondence, part 8. Bolton noted that Bowen had given him permission to give up monitoring the Sun and concentrate on the galactic noise problem. In his reply [40] Pawsey noted: '… I am entirely in favour of you concentrating on the galactic work. The astronomers of the US are waiting in a body on your results – so go to it.'

[40] Pawsey to Bolton, 16 February 1948, NAA file C4659, Pawsey correspondence, part 8.

[41] See note [13].

[42] Bolton to Jan Oort, 3 April 1950, Papers of Jan Hendrik Oort, University Library, Leiden. See Katgert-Merkelijn (1997).

[43] McCready to Pawsey, 18 November 1947, NAA file C4659, Pawsey correspondence, part 8.

[44] Pawsey to Bowen, 8 December 1947, NAA file C4659, Pawsey correspondence, part 8. See Goss and McGee (2010), Chapter 8, for a detailed account of the feud. Payne-Scott was forced to resign from Radiophysics in 1951. Australian public service rules at this time did not allow married women to hold permanent staff positions. Ruby had kept her marriage secret but with the arrival of her first child she had no option but to resign, ending the outstanding career of Australia's first female radio astronomer. In 2008 CSIRO established the Payne-Scott Award to support researchers who take extended career breaks to be the primary family carer.

[45] Bowen to Pawsey, 24 November 1947, NAA file F1/4/PAW, part 1. Bowen added: 'I would like to conclude by saying that, having been closely in touch with the solar and cosmic noise work since your departure, I am more than ever impressed by the excellent work which is being done and the spirit running through the group. It is obvious that you have brought them along wonderfully well and the influence is a lasting one. The way in which everyone is right on top of his job and continuing to do excellent work after your departure is a great tribute to your leadership.'

[46] Pawsey to Bolton 9 December 1947, NAA file C4659, Pawsey correspondence, part 8.

[47] As an indication of the difficulties in making the observations, it took a further three months to confirm the initial detection of the Taurus source. Gordon Stanley has made the point that, if the first radio sources had been discovered by a radio astronomy group elsewhere, then Bowen and Pawsey almost certainly would have assigned more senior staff to confirm the discovery. The junior Bolton and Stanley might never have continued in cosmic radio astronomy: Stanley to Kellermann, 31 March 1996. I am grateful to Ken Kellermann for providing copies of his correspondence with Stanley.

Chapter 4

Identification of the First Radio Sources

In March 1948 Bolton took a break from searching for new radio sources. He married Letty Leslie at Sydney's Registry Office and they spent their honeymoon on an island resort in the Whitsundays in Queensland. The couple had met in 1946 before Bolton's discharge from the navy and no doubt Letty was an important reason why John had decided not to return to England. Letty had first married Ernest Leslie in 1940 and they had two sons (who later John would formally adopt). Ernest went to England where he trained to be a navigator in the Royal Air Force. During a raid on a German submarine base his aircraft was shot down over France, killing all but one of the crew members [1].

In early April 1948 Bolton wrote up a further *Nature* paper on the new sources [2]. Aside from Cygnus, six new sources were now known at 100 MHz and approximate positions had been found for three of them (see Table 4.1). All six were weaker than Cygnus with radio intensities ranging from 0.25 down to 0.03 that of Cygnus. Initially Bolton named each source in the order it was found, followed by the year it was found; thus, source 1.46 corresponded to Cygnus, 2.47 to Taurus, etc. Later, this convention was dropped in favour of naming each source after the constellation where it was found, followed by a letter A, B, … to indicate that it was the strongest, second strongest source, etc. in that constellation. This naming convention was quickly adopted by radio astronomers around the world and it is still partly in use today. (For conciseness we omit the 'A' below unless it is explicitly required.)

When writing up the *Nature* paper Bolton was advised by the former Radiophysics chief David Martyn, then based at the Commonwealth Observatory near Canberra, to simply present the data on the new sources and not to engage in speculation on their possible nature [3]. However, Bolton felt that because the Dover Heights group had discovered the sources he had as much right as anyone else to put forward ideas. With Taffy Bowen's blessing, half the paper was a discussion of the possible origin and distribution of galactic radiation. Bowen sent a copy of the manuscript to Pawsey, then in London [4]:

Table 4.1: Radio sources detected at Dover Heights up to 1 February 1948 (adapted from Bolton 1948, p. 141)

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

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

[B] The source intensities were originally given in units of watts m^{-2} (c/s)$^{-1}$, equivalent to the contemporary unit of 1 Jansky ≡ 1 Jy ≡ 1×10^{-26} W m^{-2} Hz^{-1}.

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

Pawsey replied that he was pleased to hear that the letter was to be published [5]: ‘In particular it relieves me from the embarrassment of having to answer a question as to the existence of more discrete sources with a statement that I do not know.’ Bolton also justified his theorising to Pawsey [6]:

> ‘I hope you don’t think the letter to *Nature* was a bit too ‘sensational’ – as a matter of fact it is exactly as I first drafted it. I passed the draft to Bowen and the next thing I knew it had been typed and posted. Martyn reckoned I should have just cut it to the existence of the new sources. I said that as far as theorising went my guess was as good as anybody’s at the moment and that at least I had some observational evidence to present.’

In the *Nature* letter Bolton proposed that the radiation had three components, the first being the free–free transitions of charged particles in interstellar space, the mechanism favoured earlier by Reber and others (see Chapter 2). The second component was the aggregate of emissions from individual stars in regions of high star density. For the third component:

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

Both pre- and post-main sequence models may have seemed plausible at the time, but neither turned out to be correct. However, Bolton's possibility (*a*) involving 'gravitational energy of contraction' did anticipate modern theories of supermassive black hole formation, the difference being that the black hole may be a billion times more massive than a main sequence star. We return to theories of radio emission in Chapter 6.

4.1 The Expedition to New Zealand

After the despatch of the *Nature* letter, the overriding priority was to measure precise positions for the new sources in the hope of identifying some of them with known optical objects. A relatively accurate position for Cygnus had been found by observing the source rising at Dover Heights, combined with the observations at Long Reef and West Head. However, the six new sources were all at declinations well south of Cygnus. At Long Reef and West Head these sources would either rise or set over land and so a suitable fringe pattern could not be obtained. Bolton began scouting around for a new and better site. An island near Coffs Harbour, north of Sydney, was briefly in contention, but it soon became apparent that there was nothing suitable on the eastern seaboard of Australia. Lord Howe Island and Norfolk Island in the Tasman Sea were also investigated, but the best candidate appeared to be the region close to Auckland in New Zealand where there were exceptionally high cliffs on both the east and west coasts [7].

Taffy Bowen gave his immediate support to the planned expedition and began by contacting the Surveyor-General of New Zealand in Wellington [8]:

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

In March 1948 Bowen wrote to CSIR head office requesting its support [9]:

> ‘To determine as precisely as possible the positions and upper limits of angular width of the variable sources of cosmic noise already approximately determined by observations from Dover Heights. At present some seven such sources have been found. The accuracy with which these determinations may be made is considerably improved if both the rising and setting of the sources can be observed over a sea path. No site on the east coast of Australia satisfies these requirements. … All the radio gear has been assembled in a trailer and will be taken to New Zealand by boat, to arrive by 1 June next.’

Bowen also asked head office to contact its Kiwi counterpart – the Department of Scientific and Industrial Research (DSIR) – and request its support. The Radiophysics Lab would fully fund the project, but backup support on the ground would be needed. The DSIR agreed to arrange for the hire of a four-wheel drive truck for the duration of the expedition and for Alan Gardner from its Ionosphere Section to act as liaison officer. Bowen also contacted a number of local authorities in New Zealand. The Post Master General’s department reported on whether there were any significant sources of man-made radio interference in the region. Similarly, the Weather Bureau in Auckland made meteorological records available at potential sites, including various items such as relative humidity and temperature, rainfall and concentration, thunder and atmospherics, wind velocities, tides, and roughness of sea.

Bolton decided the expedition would start in June 1948 primarily because Cygnus, the main target of the trip, would rise in the evening about 10 pm and set about 4 am, the optimum times for making accurate observations. The other sources would have at least one rise or set time at night. Stanley spent April and May converting an ex-Army radar trailer into a mobile sea interferometer (see Figure 4.1). Five sites on the North Island were investigated with Cape Reinga on the northern-most tip considered to be the best, but then ruled out because of poor road access and, with the nearest town 100 km away, just too isolated. Instead, two sites were chosen, one on the east coast and the other on the west coast.

Figure 4.1. The ex-Army radar trailer in the grounds of the Radiophysics Lab. This mobile sea interferometer featured four Yagi aerials, a new 100 MHz receiver, recorders, chronometers, weather recording instruments and all the tools and backup equipment needed to operate reliably at a remote location. [courtesy: RAIA]

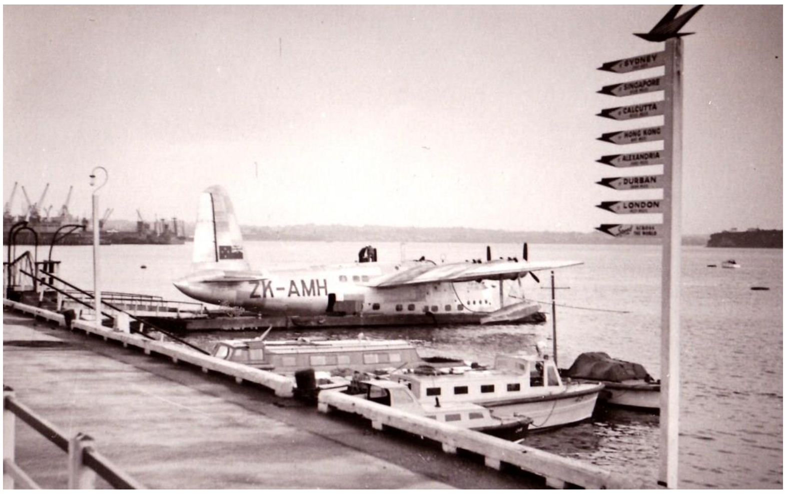


Figure 4.2. Both Bolton and Stanley travelled to Auckland by flying boat. Stanley arrived on 29 May 1948 and arranged for the mobile sea interferometer to be towed to the site at Pakiri Hill. Bolton arrived a week later. [courtesy: Stanley family]

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

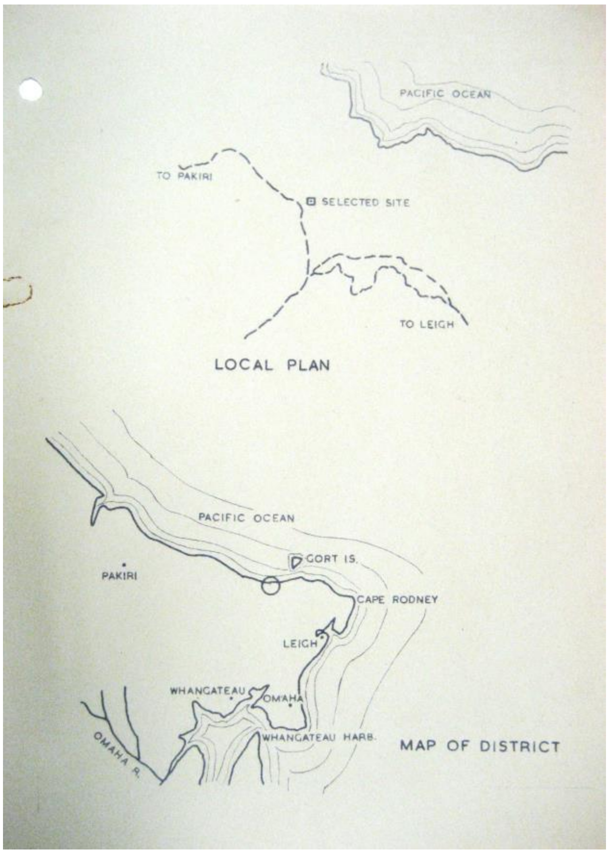


Figure 4.3. The observing site at Pakiri Hill north of the Leigh township showing (above) the local plan and (below) a map of the district (with the site marked by a circle). The coastline at the site runs approximately east–west and allowed Cygnus to be observed rising in the north–east and setting in the north–west. [courtesy: NAA file A1/3/14A]

The trailer was shipped to Auckland in mid-May, with Stanley flying over to arrange for its transport to the Pakiri Hill farm (Figure 4.2). Bolton arrived a week later and introduced himself to the Greenwood family who had owned the farm since the first European settlement of the district in the 1860s (Figure 4.3). Bolton was able to report to Bowen [10]:

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

Although initially there were problems getting the power connected, Bolton and Stanley settled into a routine of ten observing days, followed by four days of rest and recreation (see Figures 4.4 and 4.5). Typically each observing day consisted of about 16 hours broken into two shifts. Most of each shift was spent seated at a small desk inside the trailer cabin checking that the receivers and the various instruments were operating correctly. A control panel was used to rotate the cabin mounted on the trailer and point the antenna to different declinations along the eastern horizon. The main problem was the variable power output from the 3 kW transformer installed on site which made the chart recorders run at speeds varying by up to 10%. The time given by the chronometer, accurate to half a second, was written on the chart record at regular intervals. The accuracy of the chronometer was checked every hour, and recalibrated if necessary, by listening for the hourly time beeps broadcast by the local radio station. The heat generated by the bank of instruments had to be ventilated from the cabin by an electric fan, but at least the cabin could be kept warm during the freezing winter nights. The weather at times was appalling and operations were often shutdown with the cabin lashed by storms rolling in from the Pacific Ocean.

Figure 4.4. The mobile sea interferometer on the Greenwood farm at Pakiri Hill in June 1948. The cabin mounted on the trailer could swivel in azimuth to observe sources rising at different declinations along the horizon. [courtesy: Stanley family]

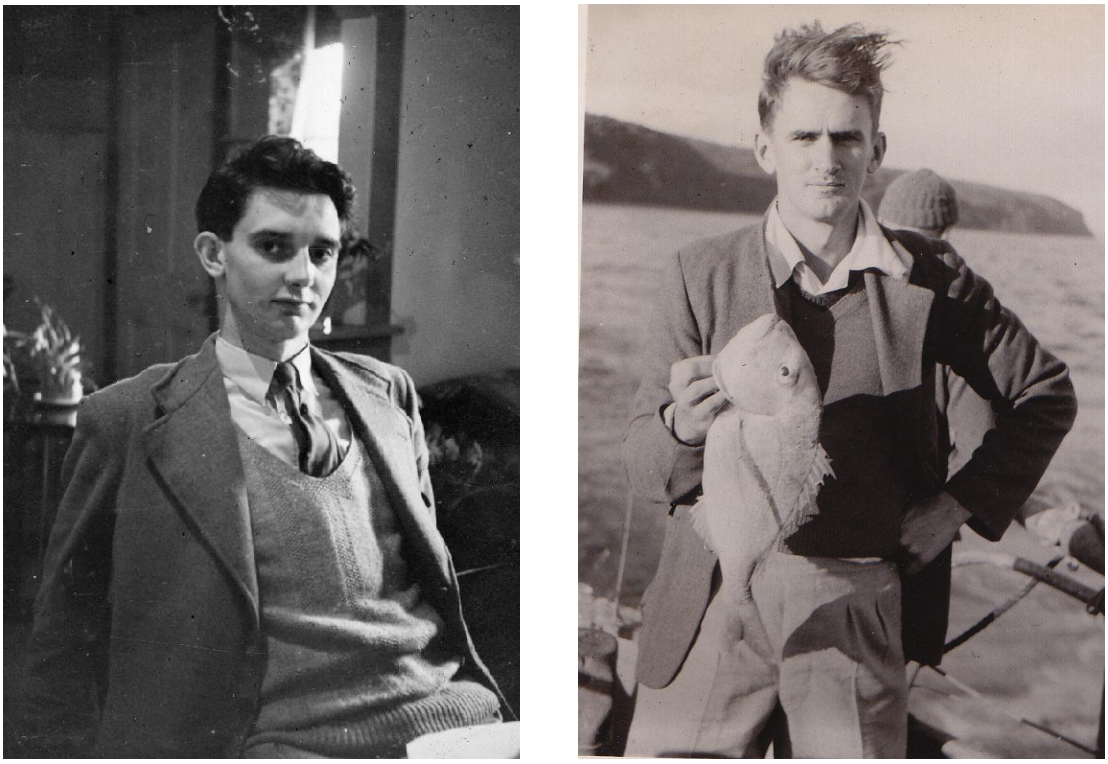
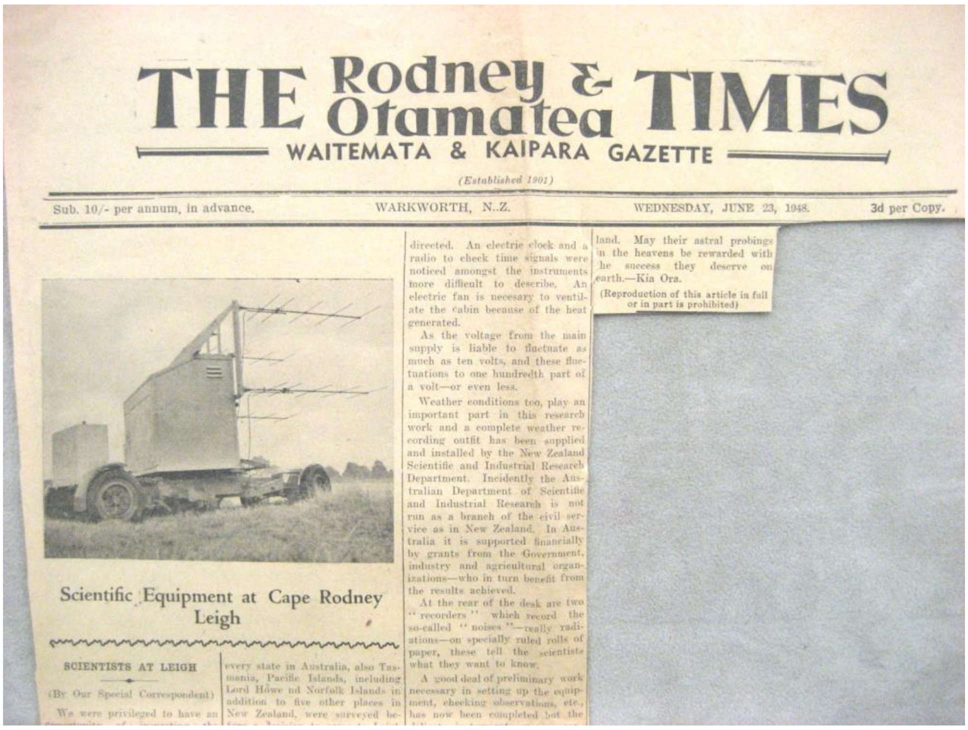


Figure 4.5. John Bolton (left) and Gordon Stanley stayed in the Cumberland Hotel in Leigh during their two-month observing run at Pakiri Hill. Gordon not only went fishing, but also visited relatives he had not seen since leaving New Zealand at the age of six. [courtesy: Stanley family]



THE Rodney & Otamatea TIMES

WAITEMATA & KAIPARA GAZETTE

(Established 1901)

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

Scientific Equipment at Cape Rodney Leigh

SCIENTISTS AT LEIGH

(By Our Special Correspondent)

We were privileged to have an

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

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

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

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

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

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

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

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

Figure 4.6. The expedition featured on the front page of the local newspaper. The article appeared under the pen name 'Kia Ora', the Maori term for 'good luck'. [courtesy: Bolton papers, National Library of Australia]

Despite the isolation of the Pakiri site, the expedition began to generate a fair amount of interest (see e.g. Figure 4.6). In May, even before the trailer had arrived, the *New Zealand Herald* ran a story on the forthcoming field trip and how the site near Leigh was much superior to the Sydney headlands. A couple of weeks after observations began, reporters from both the *Auckland Star* and the *NZ Herald* visited the site. The *Herald* opened its story 'Cosmic Noise from Region of the Milky Way' with the flowery paragraphs [11]:

> 'More of the deep mysteries of the Universe, which has yielded so many secrets to man in recent years, are being probed in a little trailer laboratory on a hill-top north of Leigh, overlooking the Hen and Chickens. Here the slow, silent tracing of inked pointers across graphs unwinding through the dark nights record the arrival at the Earth of mysterious radiations from outer space known as cosmic noise.'
>
> 'Two young scientists from Australia share the night watches, and collate the data for further study. Their enthusiasm for their abstruse studies in the realm of pure research

> derives largely from the knowledge that they are pioneers and perhaps leaders in one of the newest fields of science.'

The reporter concluded the story by asking Bolton whether the observations would be of any particular use. He replied by repeating the well-known story told about the British physicist Michael Faraday. When asked whether his discoveries on electric currents would be of any use, he replied: 'Madam, what is the use of a newborn baby?'

Most scientists will go out of their way to get publicity for their research. It reflects well on their university or research organisation, it helps to generate funding for their research, and it attracts young scientists to work in their group. Curiously, Bolton did not welcome the attention of the Auckland reporters and considered it both an intrusion and a distraction. He was particularly angry at the *Auckland Star* reporter, who turned up unannounced, and he refused to be interviewed. He tried unsuccessfully to persuade the reporter not to run a story, arguing that he and Stanley were not seeking publicity. The two *NZ Herald* reporters fared a little better and were permitted to stay overnight. In the morning John vetted their copy before giving them permission to publish.

Although Bolton's hostility now seems puzzling, it was in fact not unusual and should be seen within the context of the times. The prevailing view in CSIR, from chief executive David Rivett down to scientists at the laboratory bench, was that publicity should be avoided whenever possible. For the Radiophysics Lab this was partly a hangover from the wartime years when its work was shrouded in secrecy and publicity of any sort was unwelcome. There was also the view that reporters, in their attempts to simplify material for a general audience, were more likely to misquote or misinterpret a scientist and end up creating more bad publicity than good. (Skilled journalists who specialised in science reporting were a long way in the future.) When Bolton complained about the journalists, which he referred to as a 'menace', Bowen commiserated: 'Don't worry about the attentions of the press. It is just one of the misfortunes of this life and should be treated as such.' [12] We return to this theme in the next chapter.

Not all visitors to the site were unwelcome. Several DSIR scientists came to discuss the observations and also a group of physicists, which included Percy Burbidge, the professor of physics at Auckland University College (now the University of Auckland). Burbidge was an ionospheric physicist who, like Pawsey, did his PhD at the Cavendish Laboratory in Cambridge. Another visitor was Alan Maxwell, a young graduate student who was writing a masters thesis based on his observations of the Sun using a two Yagi antenna [13]. Burbidge invited Bolton to visit Auckland in August and give a public lecture, but Bolton refused for the same reasons he was reluctant to talk to the press. He did however agree to give a talk to the physics department, which he did later in August after the completion of the observations on the west coast. His talk presented a potted history of radio astronomy starting with Karl Jansky through to the Cygnus observations. Bolton pointed out that New Zealand had missed an opportunity of getting in on the ground floor of the new astronomy. New Zealand radar operators had discovered bursts of solar radio noise during the war and Elizabeth Alexander from the Radar Development Laboratory had followed up with a detailed report on the 'Norfolk Island effect', but since then there had been no significant developments in the country. Ironically, a detailed account of Bolton's talk appeared in the *NZ Herald* [14].

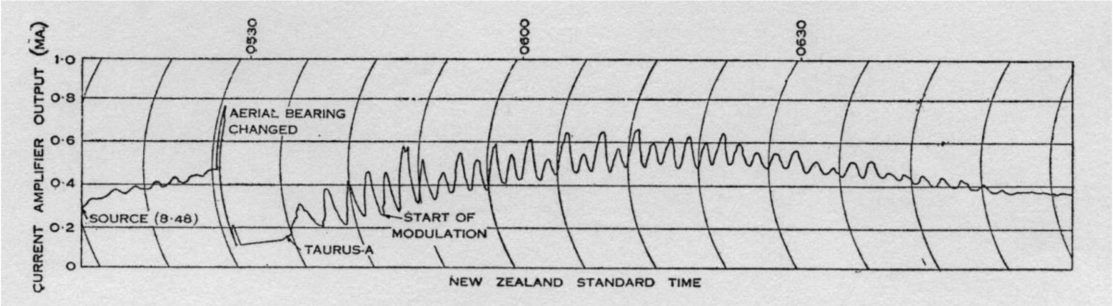


Figure 4.7. Record of sources (8.48) and Taurus obtained at Pakiri Hill on 13 July 1948 at a frequency of 100 MHz. Note the modulation of the Taurus interference pattern caused by a third source in this region. Note also the absence of the spiky structure observed for Cygnus (see Figures 3.8 and 3.9), a result of Taurus being an extended source with angular dimensions of 4′ × 6′ (see Section 4.3). [after Bolton and Stanley 1949, p. 141]

By the end of July, Bolton and Stanley had obtained good records for Cygnus on thirty nights and for Taurus on five nights (see e.g. Figure 4.7), and a handful of records for some of the other weaker northern sources. With the work at Pakiri Hill

Figure 4.8. (above) Bolton overlooks the resort town of Piha and Lion Rock, west of Auckland. (below) Early in August 1948 Bolton and Stanley stationed their trailer at a former WWII radar station, a short distance south of Piha. [courtesy: Stanley family]

completed, the trailer was then towed over to the west coast to start observations on the sources setting. The site chosen was a former WWII radar station a few kilometres south of Piha, a popular resort town about 30 km due west of Auckland (see Figure 4.8). The site had a number of advantages, including a very stable power supply which avoided the problem faced with the chart recorders at Pakiri Hill. The level of man-made interference compared with Sydney was so low that good quality records could be obtained for some sources that set during the daytime. The on-site accommodation meant that the truck could be rested from driving to and from the site. The weather was excellent and records were obtained over a two-week period for the four sources Cygnus, Taurus, Centaurus and Virgo. The Virgo source had previously been labelled Coma Berenices (see Table 4.1), but the Dover Heights declination turned out to be inaccurate by a massive 8°. The Piha observations meant that the source had to be moved from one constellation to another!

4.2 Analysis of the New Zealand Data

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

The Cygnus fluctuations also provided a further major discovery. During the expedition Bruce Slee had continued observations of Cygnus at Dover Heights. A comparison of the fluctuations in the Dover and New Zealand records, taken at a distance apart of 2100 km, showed no correlation between the two. As a control experiment, observations at both Dover and Piha had been made of a group of sunspots that had appeared on the Sun over a three-day period early in August. As expected, there was a strong correlation between the two sets of records. Thus, here was compelling evidence (but not yet conclusive) that the Cygnus fluctuations were not intrinsic to the source itself, but were caused by the radio signal passing through the Earth's ionosphere. Bolton's earlier belief that the fluctuations originated in the source was incorrect. The suggestion by Gerard Kuiper at the Yerkes Observatory, made to Pawsey in November 1947, that the Cygnus fluctuations might be analogous to the twinkling of starlight turned out to be correct [15].

Late in August 1948 Bolton began the long and laborious task of analysing the previous three months of observations. Bruce Slee recalled [16]:

> 'John set up a trestle table in the Dover Heights blockhouse where he did his computations and corrections. There were staff at the Radiophysics Lab who could do some of the calculations, but he made no use of them. He had an adding machine, one of those you crank by hand, but that was all. It was a complex task and took several months. He had to knit together records taken on the east and west coast of New Zealand to determine the right ascensions and declinations of the sources.'

Bolton decided to concentrate on calculating the celestial coordinates of the four strongest sources. Records for Cygnus and Taurus had been obtained at both Pakiri and Piha, but there were no records for Centaurus and Virgo from Pakiri as both sources rose over land rather than the sea. For these two sources it would be necessary to rely on the Piha observations of setting in the west and on further observations at Dover Heights of rising in the east. With the two sites 2100 km apart, the records would need to be 'normalised' before the data from each site could be combined. The calculation of declination had to take into account the different latitude at each site. Similarly, the calculation of Right Ascension had to take into account the longitude of each site and also the two-hour time difference between New Zealand and Australian Eastern Standard times. Bolton also had to take into account that the observations took place at different times of the year and convert solar times to sidereal times. Many of the calculations needed a good knowledge of trigonometry.

In mid-October 1948 Bolton took a break from the analysis to join in another expedition. On 1 November the Sun was to undergo a partial eclipse and the Radiophysics Lab planned to carry out observations from several sites in Australia, including Strahan on the west coast of Tasmania. Similar to the failed Brazil expedition two years earlier, the aim was to use the passage of the Moon to study the correlation between radio emission and visible features on the solar surface. Gordon Stanley spent a month converting the New Zealand trailer for solar work and he and Bolton teamed up with Don Yabsley and John Murray who were planning a separate observation at Strahan using different equipment (see Figure 4.9). In addition to the eclipse, Bolton and Stanley wanted to make further mountain-top observations of Taurus setting at night over the Southern Ocean. At Piha the setting had taken place in the afternoon and their records had been degraded by solar noise. Several 1000 metre peaks near Strahan were investigated as a possible site for the observations.

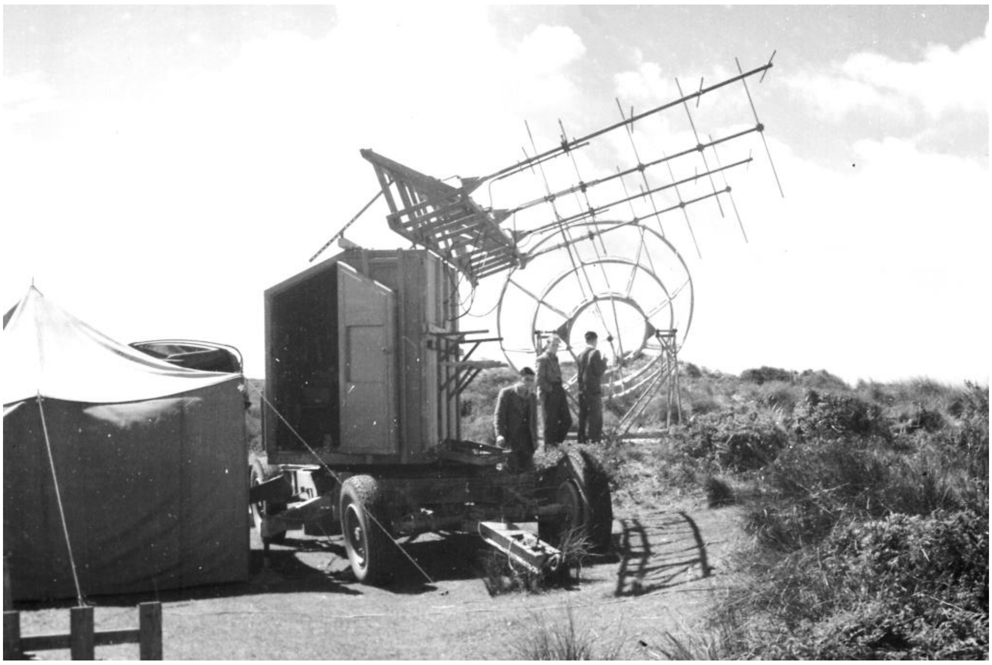
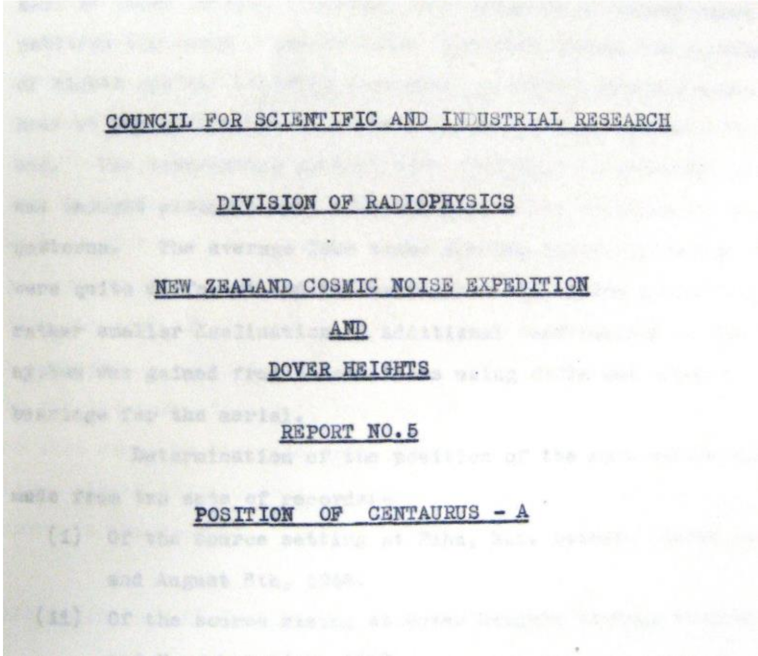


Figure 4.9. The Radiophysics Lab mounted an expedition to Strahan on the west coast of Tasmania to observe an eclipse of the Sun on 1 November 1948. The mobile sea interferometer used in New Zealand was modified by Gordon Stanley to observe the eclipse. The 3 m diameter dish was assembled on site and successfully observed the eclipse. From left are John Bolton, John Murray and Don Yabsley. [courtesy: Stanley family].

In contrast to the New Zealand expedition, which was shaping up as a great success, the eclipse expedition turned out to be a dismal failure. The trailer was towed from Sydney to Melbourne, but a dock strike delayed its shipment to Devonport on Tasmania's north coast, leaving little time to spare [17]. An ex-Army truck was used to transport the trailer to Strahan, but then Bolton and Stanley were unable to get the power generator working properly. Unknown to them, the generator had been drained of all fluids as a travel precaution, including its air filter, and by the time the problem was diagnosed it was too late to produce any usable records of the eclipse. To make matters worse, their plans for the mountain-top Taurus observations had to be abandoned because of unseasonal snowfalls. As a final straw, on their way back to Devonport, sparks from a hole in the truck's muffler set fire to an electrical cable and the fire quickly spread to the wooden tray and tarpaulin. A fire extinguisher from



COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH

DIVISION OF RADIOPHYSICS

NEW ZEALAND COSMIC NOISE EXPEDITION

AND

DOVER HEIGHTS

REPORT NO.5

POSITION OF CENTAURUS - A

Figure 4.10. After his return from New Zealand, Bolton prepared short unpublished reports on the position of each of the four sources Cygnus A, Taurus A, Virgo A and Centaurus A. [courtesy: NAA file A1/3/14B]

a passing bus was used to put out the blaze, but not before extensive damage to the truck and the loss of John’s briefcase. Stanley recalled [18]: ‘The expedition had the worst of everything one could imagine. Fire, snow, equipment failure, injury, near train wreck and fatigue. If I have left anything out you can assume that happened too.’

Back in Sydney, Bolton prepared a series of brief internal Radiophysics reports setting out his calculations for each of the four sources [19] (see e.g. Figure 4.10). For Cygnus, the angular size of the object was shown to be less than one minute of arc, eight times smaller than the earlier measurement at Dover Heights and proving without doubt the point-like nature of the source. The new position for Cygnus differed considerably from the old one and showed that the previous estimate of atmospheric refraction had been significantly in error [20] (no errors were given for either new coordinate):

Old position:	RA 19 hr 58 min 47 sec ± 10 sec	Dec +41° 47´ ± 7´
New position:	RA 19 hr 58 min 16 sec	Dec +40° 36´

Bolton studied the star charts with this new position, but to his great disappointment he could not see any object within the error box that seemed a likely candidate. The New Zealand expedition had been organised primarily to try to reveal the identity of the object – the time of the year when it would rise and set at night and the site at Pakiri Hill with its view of the source low in the northern sky – but frustratingly Cygnus continued to elude them. It would be almost three years before Cygnus was finally identified. As we will see in Chapter 5, in 1951 Graham Smith at Cambridge measured a new and far more accurate position for the source [21]. This prompted Rudolph Minkowski and Walter Baade at the Mt Wilson–Palomar Observatories to make extended observations of the position, revealing a very faint object at the extraordinary distance of approximately 1000 million light-years.

4.3 Optical Identifications of the First Three Sources

The disappointment of Cygnus was soon swept away by the results for the other three sources. The position measured for Taurus almost coincided with an ordinary star but, as Bolton noted [22]:

> ‘The source is close to the star ζ Taurus as far as identification from a star map is concerned but the limits of position enclose the most remarkable object in this region – NGC 1952 or the Crab Nebula. This nebula is believed to be the remains of a supernova Type I of about AD 1054 judging both from its rate of expansion and the reported appearance of a supernova in this area in Chinese history. The dimensions of the nebula are 4´ × 6´ and the present expansion rate 0.13 arcsecond per year. Doppler shift measurements show an expansion velocity of 1300 km per sec which with the angular rate gives a distance of 4200 light-years.’

Bolton’s observation was a considerable understatement. The object is not only remarkable in this region of the sky, but it is one of the most remarkable in the *entire* sky. Aside from objects within the Solar System, it has been estimated that there have been more research papers written about the Crab Nebula than any other astronomical object [23]. The Crab Nebula is a supernova remnant, the remains of a star that violently exploded in the year AD 1054. No account of this supernova can be found in European chronicles surviving from this time, but there are various

Arabic, Chinese, Japanese and Korean records of it [24]. In particular, astrologers in the court of the Chinese emperor kept a detailed record of this spectacular event. The supernova appeared suddenly and was said to develop spikes leaving it in all directions. Its reddish-white colour remained clearly visible even in bright daylight for three weeks and for months afterwards it dominated the night sky [25].

Bolton felt confident enough of the Taurus identification for him and Stanley to publish a detailed account in the Australian journal, with the title 'The position and probable identification of the source of galactic radio-frequency radiation Taurus-A' [26]. They gave a slightly revised position of RA 05 h 31 m 20 s ± 30 s and Dec. +22° 02′ ± 8′ and concluded the paper (p. 145):

> 'The limits in the position of the source enclose NGC 1952, otherwise known as the Crab Nebula. According to [Walter] Baade this nebula is the remains of the supernova of AD 1054 observed by Chinese astronomers. The angular dimensions of the nebula are 4´ by 6´ and the angular rate of expansion is 0.13″ per year. ... The measurements on 100 Mc/s give an effective temperature of two million degrees, assuming a source size of 5′ for Taurus-A. From the present values of temperature and density in the Crab Nebula it would be difficult to explain this result in terms of strictly thermal processes. However, it is not unlikely that non-thermal components would arise from differential expansion within the nebula and general expansion into interstellar matter. In view of this and the close agreement between the positions of the Crab Nebula and the source Taurus-A, *it is suggested that the Crab Nebula is a strong source of radio-frequency radiation.*' (my italics).

The paper was praised by Grote Reber [27]: 'I have been greatly impressed by your series of publications upon discrete sources of galactic radio waves. The last one, in the June 1949 issue of the *Australian Journal of Scientific Research*, is a beautiful piece of work.' Not all shared Reber's enthusiasm for the Taurus identification. An authority on the Crab Nebula, Simon Mitton, has noted [28]:

> 'The first suggested identification of a discrete radio source with an optical object came in 1948 from Australia. John Bolton and G. J. Stanley of Sydney suggested that radio source Taurus A could be matched to the Crab Nebula. Initially this finding did not cause any stir among astronomers in the northern hemisphere. They either felt that the

> positional information from far-off Australia was not good enough, or rejected the notion because it did not fit their own ideas as to what radio sources might be. Even four years after the initial suggestion, one of Britain's leading radio astronomers said that the coincidence of Taurus A with the Crab Nebula should not be taken too seriously.'

The two other radio sources, Centaurus and Virgo, provided an even bigger surprise, though initially Bolton did not realise the full significance of his identifications. For Virgo, Bolton noted [29]: 'The limits enclose M87 (or NGC 4486) one of the large group of nebulae and clusters in the Coma Berenices – Virgo area. The spectrum of this object is not known but its radial velocity has been measured and found normal for the group of clusters.' The object is distinguished by a bright blue jet of material extending from its centre, an extremely unusual feature (see Figure 4.11).

Figure 4.11. The first three radio sources to be identified with visible objects by the Dover Heights team (from left): Taurus A with the Crab Nebula (NGC 1952); Centaurus A with NGC 5128; and Virgo A with M87 (NGC 4486). [courtesy: RAIA]

The other source Centaurus turned out to be a bright and peculiar object with a dark dust band straddling its disc (see Figure 4.11). In his internal report (see Figure 4.10), Bolton noted [30]:

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

Of the four sources studied by Bolton, Centaurus was the only one located in the southern half of the sky. In an interesting historical twist, its optical counterpart NGC 5128 was first observed not far from Dover Heights, over 120 years earlier, by James Dunlop at the Parramatta Observatory, west of Sydney (see Figure 3.2). A brief digression is worth while.

In 1821 Sir Thomas Brisbane arrived in Sydney to become the sixth governor of the colony of New South Wales. Brisbane was a keen amateur astronomer and decided to build the first observatory in the country. Although a rudimentary observatory had been established soon after British settlement in 1788, it was used primarily for time keeping and as a navigational aid and did not produce any astronomical observations of significance. Brisbane built his observatory at Parramatta, 20 km west of Sydney, fitted it out with his own instruments and personal library shipped from Scotland, and hired two assistants, all at his own expense. Unfortunately, Brisbane’s term as governor was not a success and he was recalled to England just four years later. One of his assistants, James Dunlop, stayed on and commenced a survey of southern nebulae and star clusters early in 1826. In April he observed and sketched NGC 5128; however, from his written description it was clear that he had been misled by the dark dust band that lies across the object. Dunlop thought that NGC 5128 consisted of two independent nebulae of similar shape that, by pure coincidence, are positioned side by side. Dunlop’s catalogue totalling 629 southern objects was published in England two years later, one of the first astronomy papers produced from Australia [31].

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

Although Bolton was confident of the Taurus identification, the other two sources presented a difficult dilemma. He spent a week in February 1949 at the Commonwealth Observatory at Mt Stromlo talking to astronomers and scouring the literature for information on NGC 5128 and M87. Although both objects were classified as extragalactic, the evidence was not strong. Individual stars had not been resolved in either object which would prove that both were indeed galaxies outside our Galaxy. Since Centaurus and Virgo were among the strongest of the known radio sources, it seemed logical that both objects must be relatively close within the Galaxy and not at vast extragalactic distances. Bolton was concerned that an extragalactic claim for Centaurus and Virgo would be seen as sure evidence that he had guessed incorrectly for both and that other Galactic objects within the error boxes must be the actual sources of the strong radio emission. He suspected that the journal referees would probably come to the same conclusion, and in all probability his paper would be rejected for publication.

In March 1949 Bolton drafted a brief paper summarising the optical identifications of the three radio sources. The title made clear his decision: ‘Positions of three sources of Galactic radio-frequency radiation’. Before submitting the paper he wrote to Rudolph Minkowski at the Mt Wilson–Palomar Observatories (see Figure 4.12). Minkowski was familiar with the work at Dover Heights following his discussions in November 1947 with Joe Pawsey during his overseas trip (see Section 3.2). Minkowski and his colleague Walter Baade had in fact carried out the detective work that proved the Crab Nebula is the remnant of the supernova observed by the Chinese in AD 1054 [32]. In his letter Bolton gave the positions of the three sources and then noted [33]:

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

Figure 4.12. Rudolph Minkowski (left) from the Mt Wilson–Palomar Observatories with Bernard Mills during a visit to the Radiophysics Lab in 1956. Minkowski was the first prominent astronomer to realise the importance of the discovery of the first discrete radio sources by the Dover Heights group. Minkowski was an expert on the Crab Nebula and so the identification of the Taurus A source with the Crab was of particular significance. [courtesy: *Sydney Morning Herald*]

> equivalent temperature could be due to strictly thermal processes in the nebula. … I would be interested to hear your opinion on this.'

Minkowski replied providing the latest information available on the three optical objects, including new evidence that strengthened the case that Centaurus and Virgo were indeed external galaxies. Bolton was not persuaded and continued to maintain that both were Galactic objects [34].

Early in May 1949 Bolton, with co-authors Stanley and Slee, dispatched the letter to *Nature* where it was published on 16 July [35]. The heart of the paper was a brief table (see Table 4.2) giving the positions of the three sources and their possible associated visible objects (see Figure 4.11): 'It is found that all three sources correspond within limits of experimental error to positions of certain nebulous objects.' A strong case was made for the identification of Taurus with the Crab Nebula and how the emission was unlikely to arise from thermal processes: 'The present estimates of density and temperature in the Crab Nebula would fall well short of explaining this result by strictly thermal processes. Non-thermal components resulting from the expansion of the nebula do not, however, seem unlikely.' Their suggestion of 'non-thermal components' in the radiation proved to be an important step in the acceptance of the synchrotron emission mechanism developed in the 1950s (see Section 6.1 and note [16] in Chapter 6).

Table 4.2: Three radio sources and their possible associated visible objects (adapted from Bolton, Stanley and Slee, 1949: 101)

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

[A] Weak emission lines of H, He, forbidden lines of N, O and Si

[B] Weak emission lines, Hβ, Hγ, Hδ, and λ4686

In contrast to the confident Crab Nebula identification, NGC 5128 and M87 were described as 'unresolved nebula' and the case made for them to be Galactic objects [36]:

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

As indicated in the last sentence, Bolton believed that if the sources were extragalactic they must consist of a large number of unusual objects to account for such intense emission. It appears he did not consider the idea that the emission could come from a *single* extragalactic object. Bolton expressed this view more colourfully in further correspondence with Minkowski [37]: 'In a letter to *Nature* (written before I consulted you) I have suggested that these objects may be within our own Galaxy –

on the basis that a close "freak" is more probable than a large collection of "freaks" at a great distance.'

Bolton turned out to be spectacularly wrong. Baade and Minkowski made further observations of NGC 5128 and M87 and were able to resolve individual stars in both objects, proving almost certainly that they were external galaxies. Later, NGC 5128 was shown to be a peculiar galaxy at a distance of 15 million light-years, while M87 turned out to be a giant elliptical galaxy at the even greater distance of 30 million light-years [38]. It was an extraordinary development. The discovery of the two extragalactic objects did not diminish the importance of the *Nature* letter – on the contrary it raised some profound questions. What was the mechanism responsible for this prodigious output of radio energy? If two of the strongest radio sources were distant galaxies could some of the fainter sources be even more distant? Might the fledgling field of radio astronomy be able to 'see' much further out into the Universe than traditional astronomy? The historian of radio astronomy Woody Sullivan has summed up the significance of the paper [39]:

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

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

Notes to Chapter 4

[1] Letty Bolton interview by author, Round Corner, NSW, 28 November 2006.

[2] Bolton (1948). Stanley and Slee were not included as co-authors primarily because of Bolton's speculations on the origin of the radio emission: 'I was sticking my neck out a bit for one thing.' Bolton interview with W. T. Sullivan, 15 March 1978, Parkes, NSW.

[3] Bolton to Pawsey, 18 May 1948, NAA file C4659, Pawsey correspondence, part 8.

[4] Bowen to Pawsey, 30 March 1948, NAA file C4659, Pawsey correspondence, part 8.

[5] Pawsey to Bowen, 26 April 1948, NAA file A1/1/1, part 3.

[6] See note [3].

[7] See Orchiston (1993, 1994) and Stanley (1994) for accounts of the New Zealand expedition.

[8] Bowen to New Zealand Surveyor-General, 10 October 1947, NAA file A1/3/14A.

[9] Bowen to CSIR Executive, 3 March 1948, NAA file A1/3/14A. Bowen estimated the overall cost of the expedition to be £400, consisting of shipment of the mobile sea interferometer, airfares and travel allowances for Bolton and Stanley, the hire of a four-wheel drive truck, the installation of a power transformer, and some 200 gallons of petrol. Initially Bowen thought the expedition would need the approval of the New Zealand Ministry of External Affairs, but this turned out to be unnecessary.

[10] Bolton to Bowen, 15 June 1948, NAA file A1/3/14A. Bolton occasionally corresponded with the Greenwood family over the next ten years.

[11] NAA file D9-4H, part 1, Newspaper publicity. See also Bolton papers, series 3, folder 1, Newspaper cuttings. Another story told about Faraday is that he went to Parliament to ask for funding and demonstrated some of the effects of static electricity. When asked what good this was, he replied: 'I don't know, but some day you'll be taxing it.' [Kellermann to author, 27 May 2014].

[12] Bolton to Bowen, 29 June 1948, and Bowen to Bolton, 7 July 1948, NAA file A1/3/14A. Bowen did however add that the *Sydney Morning Herald* had published a good paragraph on the Pakiri observations a few days earlier.

[13] After completing his MSc, Alan Maxwell studied for a PhD at the University of Manchester. He built an international reputation in solar radio astronomy at the Harvard College Observatory and at its Radio Astronomy Station at Fort Davis, Texas (Orchiston 1994, Thompson 2010). Later, during his time at Caltech, Bolton became good friends with Maxwell.

[14] Bolton papers, series 3, folder 1, 'New Zealand Lost Opportunity', 12 August 1948.

[15] See note [38] in Chapter 3. Not all were convinced that the Cygnus fluctuations were caused by the ionosphere; for example, Martin Ryle was sceptical until the joint Cambridge–Jodrell Bank observations in September 1949 confirmed the Australian result – see Chapter 5.

[16] Slee interview by author, Marsfield, NSW, 28 November 2006.

[17] In Melbourne Bolton met with Joe Pawsey, who was on his way home from his year-long visit to the US and Europe, and they discussed a draft of the Taurus A paper (Bolton and Stanley 1949). Bolton later recalled: 'In Melbourne I showed Pawsey the draft of this paper – I had to get his approval. I was going on to Tasmania for an eclipse expedition at the time. This is one of the times when I've seen Pawsey really enthusiastic about something. This changed his attitude very much on the kind of things we were doing.' Bolton interview by L. Bickel, cassette 2.

[18] Stanley to K. Kellermann, 10 April 1996, Kellermann papers, NRAO, Charlottesville, Virginia. See also Wendt *et al.* (2008a). For an account of the truck fire see Stanley and Bolton, 'Report on fire damage to Army G.M.C. truck', undated, NAA file A1/3/18. The expedition was not a complete disaster. Yabsley and Murray assembled a portable 3 m dish at Strahan and made a successful observation of the eclipse – their records survived the truck fire. Bolton and Stanley visited Hobart on their way home and met the mathematician John Jaeger, who strongly recommended his former graduate student Kevin Westfold. In December 1948 Westfold became the fourth member of the Dover Heights team (see next chapter).

[19] Bolton, Cosmic Noise Expedition to New Zealand: Four unpublished reports (numbers 3–6) on the positions of Taurus A, Cygnus A, Centaurus A and Virgo A. Report 1 summarised the simultaneous sunspot observations at Piha and Dover Heights on 6–8 August 1948. Report 2, on an unknown subject, was planned but apparently never written. NAA file A1/3/14B.

[20] The amount of atmospheric refraction was calculated using a formula developed by Trevor Pearcey at the Radiophysics Lab. The formula was used by Pawsey and his group to show that the intense radio emission from the Sun comes from sunspots. In 1947 Pearcey and Maston Beard at the Radiophysics Lab began building Australia's first computer – see Section 5.2.

[21] Smith (1951), *Nature* **168**, 555. Smith carried out the accurate measurement of the Cygnus position as part of his PhD thesis at Cambridge.

[22] See note [19], report number 3.

[23] Mitton (1978), p. 175. Sullivan (2009, p. 383) has observed: 'It has been said that modern astronomy can be divided into two parts: (1) the portion dealing with the Crab nebula, and (2) the rest. The Crab's identification with the Chinese guest star of AD 1054 was a major step in understanding supernovae and stellar evolution, and its identification with Tau A … was an important milestone for radio astronomy.'

[24] See e.g. Stephenson and Green (2002, 2003).

[25] Note [23], p. 16. In 1973 Bolton published a paper in *Nature* on the prospects of astronomy in Australia and paid tribute to the Sydney Observatory and its director Harley Wood – see Bolton (1973). He concluded: 'To end on personal and somewhat nostalgic note, it is 25 years ago, this month, that I telephoned Harley Wood and said, "I think that I have identified one of my radio sources. What can you tell me about the Crab Nebula?" What indeed!'

[26] Bolton and Stanley (1949).

[27] Reber to Bolton and Stanley, 17 January 1950, NAA file A1/1/1, part 5. Reber concluded the letter: ‘Please give my regards to Dr Pawsey and tell him that I often think of the many pleasant conversations we had when he was in this country.’

[28] Note [23], p. 175. Mitton also noted: ‘There is no doubt that the study of the Crab Nebula has made a bigger impact on the development of astronomy in recent times than the investigation of any other single object beyond the Solar System. This nebula is truly a physics laboratory on a grand scale. In it we can see the four fundamental forces of physics played off against each other in eternal conflict. Weak and strong nuclear forces are at work in the neutron star, gravitational forces dominate in its vicinity, and the electromagnetic forces reign supreme in the magnetosphere and the nebula itself.’ (p. 175)

[29] See note [19], report number 6. The ‘M’ in M87 stands for the French astronomer Charles Messier who compiled a catalogue of the brightest nebulae in the late 1700s. NGC stands for New General Catalogue consisting of a list of nearly 8000 objects first published in 1888.

[30] See note [19], report number 5.

[31] For more on James Dunlop see Cozens *et al.* (2010). See Robertson *et al.* (2010) for a detailed account of the discoveries of NGC 5128 and its radio counterpart Centaurus A. The observations at the Parramatta Observatory did by no means mark the beginning of Australian astronomy. There is a growing body of evidence that astronomical knowledge among Aboriginal cultures was far more advanced than previously thought – see the publications by Ray Norris and colleagues (e.g. Norris and Norris 2009).

[32] See e.g. Bolton (1976), p. 130.

[33] Bolton to Minkowski, 4 April 1949, and Minkowski to Bolton, 14 April 1949, Minkowski papers, Bancroft Library, University of California, Berkeley. I am grateful to Professor Woody Sullivan (University of Washington, Seattle) for providing copies of both letters, along with the letter in note [37].

[34] In his later years Bolton recalled that, in addition to Minkowski, prior to publication he also wrote to Jan Oort (Leiden) and Bengt Strömgren (Copenhagen) and received enthusiastic responses from both [see e.g. Bolton (1982), p. 352]. It seems his memory failed him on this occasion. Searches of both the Oort papers and the Strömgren papers have failed to find any evidence of these letters. The earliest letter by Bolton to Oort is almost certainly one dated 5 October 1949 in which he discusses his work with Kevin Westfold on the structure of the Galaxy (see Section 5.4). Oort sent a positive reply and the following month Bolton submitted a letter on this work to *Nature* [see Bolton and Westfold (1950c)]. Bolton appears to have confused this exchange with the *Nature* letter on the optical identifications published earlier in July 1949. I am especially grateful to Jet Katgert-Merkelijn (Leiden Observatory) and to Henrik Knudsen (Aarhus University, DK), respectively, for carrying out these searches of the Oort and Strömgren papers on my behalf.

[35] Bolton, Stanley and Slee (1949).

[36] The letter cited a 1935 paper by J. S. Paraskevoulus in the *Harvard Bulletin* that noted the dark dust band in NGC 5128 is normally seen in Galactic nebula viewed on edge.

[37] Bolton to Minkowski, 20 May 1949, see note [33].

[38] Robertson (1992), p. 49.

[39] Sullivan (2009), p. 324. The Bolton–Stanley–Slee (1949) paper is the most cited of all the publications produced by the Dover Heights group, with the number of citations more than double the next best – see the Appendix.

Chapter 5

The Emergence of Radio Astronomy in Australia and England

In Chapters 3 and 4 we looked in depth at the research at the Dover Heights field station that led to the discovery and identification of the first discrete radio sources. The Dover Heights research was only one of a number of programs pursued by the Radiophysics Lab in the post-war years and, in turn, the Lab was only one of many divisions making up the Council for Scientific and Industrial Research. In Section 5.1 we see that CSIR came under sustained political attack during 1948 which threatened the future of radio astronomy within the organisation. In 1949 CSIR made the transition to CSIRO with the new body granted a fair degree of autonomy to be able to decide its own research programs.

Radio astronomy flourished in the new CSIRO. In addition to Dover Heights a number of field stations were established in and around Sydney, staffed by small groups working largely independently of each other. By 1950 radio astronomy made up about one-half of the Radiophysics research program, split about equally between solar and cosmic studies. In Section 5.2 we give a brief overview of the other research programs at Radiophysics, together with the radio astronomy program as a whole.

Until 1950 the only significant rival to Radiophysics was the radio astronomy group at the Cavendish Laboratory in Cambridge, England. As we see in Section 5.3, initially there were goodwill attempts to share information and ideas between the two groups and to avoid unnecessary duplication of research work. These attempts were however largely resisted by the Cambridge group so that, rather than a spirit of cooperation, a significant rivalry developed between the two centres.

Finally, to conclude this rather lengthy chapter, Section 5.4 will look at Australian radio astronomy in the context of developments elsewhere in the world. In 1950 Bolton spent nine months touring astronomy centres, both radio and optical, in

England, the Continent and North America. On his return to Australia, John could lay claim to being one of the world's most knowledgeable radio astronomers with a wide personal network of people working in the field.

5.1 Transition of CSIR to CSIRO

The fledgling careers of the Dover Heights group almost came to an abrupt halt at the time of their 1949 *Nature* letter. The group was largely self-contained and relatively isolated from the activities of the other groups in the Radiophysics Lab. Even more so, the group was completely isolated from the other activities of their employer, the Council for Scientific and Industrial Research (CSIR). Bolton went to the Lab about once a fortnight, usually to attend a meeting, to hear a talk or to arrange some typing, but he did not have an office or even a desk of his own. Bruce Slee rarely went into the Lab at all and, apart from his evening classes at the Sydney Technical College, he simply commuted to and from the Dover blockhouse and his home in nearby Bondi. Gordon Stanley was the exception. He lived in Mosman on the North Shore and frequently dropped in to the Lab on his way out to Dover Heights, usually to attend to equipment being built or under repair in the workshops. Gordon got to know many of the other staff and had a good idea of the progress being made by the other Radiophysics groups [1].

Figure 5.1. David Rivett was chief executive and then chairman of Australia's Council for Scientific and Industrial Research from 1926 to 1948. His forthright views on science enabled new fields such as radio astronomy to flourish within CSIR. [courtesy: CSIRO Archives]

In Chapter 2 we saw how the Radiophysics Lab near the end of WWII made the transition from secret radar research to peacetime applications of radar and its associated technology. Although Radiophysics no longer carried out classified research, there were still pockets of CSIR that were involved in defence related research, most notably the Aeronautical Research Lab in Melbourne with close links to the Royal Australian Air Force. Despite the relatively minor amount of defence research, early in 1948 a series of articles in a Sydney magazine, under the byline of a British scientist, accused CSIR of being loose on security and of allowing scientists who were members of the Communist Party to work on defence-related projects. The federal Opposition, consisting of a coalition of conservative Liberal and Country Parties, took up the issue and launched an attack on the Labor government. At first the Labor prime minister Ben Chifley ignored the attacks after being reassured by CSIR chief executive David Rivett (see Figure 5.1) that any sensitive research being carried out by CSIR had adequate security. The official CSIRO historian Brad Collis has noted [2]:

> ‘But the attacks intensified through 1948 when the Opposition began a campaign of smear and innuendo against the CSIR and some universities for employing researchers who, it claimed, were professed communists. The Opposition claimed vital, secret information was being denied to Australia by the United States and Britain. Several metropolitan newspapers had adopted strident anti-communist positions and often implicated Rivett and the CSIR in their indiscriminate salvos.’

In an attempt to diffuse the issue the Minister for CSIR John Dedman decided to remove both the Aeronautical Research Lab and the Radiophysics Lab from CSIR and place them within the federal Department of Supply in Canberra. Dedman was also Minister for Defence and he took the view that, although Radiophysics was not currently engaged in defence-related research, it may be needed to do so in the future. The staff of both labs would become Commonwealth public servants and be subject to stricter controls on their recruitment and the terms and conditions of their employment. Rivett was horrified and travelled to Canberra to negotiate with Dedman. Rivett wrote to Taffy Bowen: ‘Naturally this stirred up all my instincts of CSIR self-preservation … I do not know just what the political game is; but the sad fact is that CSIR has somehow or other become a pawn in the game' [3]. Rivett managed to persuade Dedman to keep Radiophysics within CSIR, at least for the time being, but in the process conceded the loss of the Aeronautical Research Lab. He had narrowly avoided losing both.

We can speculate on what might have happened if control of the Radiophysics Lab had been transferred to Canberra. Within weeks there would have been a review of its research program and no doubt radio astronomy would have come under close scrutiny. The solar radio studies may have survived the review. The observations of sunspots and solar bursts gave advance warning of possible disruptions to communication and navigational systems and therefore were of some practical value. On the other hand, studies of cosmic radio noise appeared to have no obvious practical value. While cosmic noise might be of academic interest, it had no contribution to make to the economic prosperity of the nation. Most probably the Dover Heights team would have been reassigned to a more 'productive' line of research.

A week after Rivett's meeting with Dedman, the conservative Opposition intensified its attack on CSIR in parliament, targeting Rivett in particular, and hammering the view that communists and communist sympathizers in CSIR were a threat to national security. For Rivett, the attack on CSIR went against his belief in scientific freedom [4]:

> 'Unless we can keep CSIR free from all the straitjackets that are all too freely offered to it from all sides, we are not going to count very much in 20 years' time, even if we do succeed in the meantime in doing a job or two that wins favour from the press, populace and politicians. I fully believe ... that we shall fail in the end unless quite 50% of our effort is directed to finding out how the machine of Nature works, without a thought as to whether that knowledge may or may not be useful in this decade, or next century, in showing farmers how to save sixpence or politicians how to increase revenue from taxation.'

The unprecedented personal attacks on Rivett led scientists across Australia to speak out in his support. Hundreds of letters, petitions and telegrams were sent to Canberra, probably the first occasion Australian scientists had protested collectively and publicly en masse. Bowen spoke on behalf of Radiophysics [5]: ‘I am writing to say how sorry I am that your name and that of CSIR has been used so badly by a minority in the House. Everyone I have spoken to in and out of CSIR is aghast at the statements being made. Need I say that we are wholeheartedly behind you and the point of view you have taken.’

The new recruit to the Dover Heights team, Kevin Westfold also weighed in to the controversy, writing to his local member Eric Harrison, the deputy leader of the Liberal Party who lead the attack in parliament. The conservatives argued that the only way to rid CSIR of communists and make it secure was to bring the whole organisation under the control of the Public Service Board. Westfold strongly supported Rivett’s views on scientific autonomy and freedom [6]:

> ‘People generally are agreed that scientific research on defence problems should be carried out under conditions of adequate security and secrecy. In introducing measures to implement such security, however, every effort must be made to ensure that in the sphere of civil scientific research the freedom from direct governmental control, which up to the present time has contributed so greatly to the effective conduct of such research in Australia, should be retained. Eminent scientific thinkers throughout the world are of the unanimous opinion that scientific research can be satisfactorily pursued only if completely unhampered by political control …’.

Westfold pointed to the Department of Scientific and Industrial Research in New Zealand which operated under public service control and, in comparison with CSIR, was widely regarded as second rate in its scientific output.

In March 1949 the Labor government drafted a bill abolishing the CSIR and replacing it with the Commonwealth Scientific and Industrial Research Organisation (CSIRO). At Fred White’s insistence the new name was kept as close as possible to the original to maintain the reputation and goodwill CSIR had established within Australia and internationally [7]. The new CSIRO reached a reasonable solution to the controversy of the previous year, with all defence-related research transferred to other government departments and the organisation established as an autonomous statutory authority independent of the Commonwealth public service.

Following the resignation of Rivett in April 1949, the young veterinarian Ian Clunies Ross was elevated from the previous CSIR Executive to become the new chairman of CSIRO. A charismatic figure, Clunies Ross became the public face of the new organisation and soon turned it into one of the most admired and respected institutions in Australia [8]. Clunies Ross entrusted most of the management of CSIRO to his loyal chief executive Fred White. Under White's patronage, Taffy Bowen and Joe Pawsey would be given a free hand over the next decade to develop the new field of radio astronomy. The 1950s would become the golden age of Australian radio astronomy.

5.2 Postwar Growth of the Radiophysics Lab

As we saw in Chapter 2, at the end of WWII Taffy Bowen drew up a list of possible research fields for investigation as the Radiophysics Lab made the transition from secret wartime research to peacetime applications of radar and radio technology. Small groups were to be assigned to investigate a wide variety of topics, but then a kind of Darwinian natural selection would prevail. Projects that showed early promise would be rewarded with the support of more staff and funds at the expense of those that failed to make headway. Promising starts were made in a number of fields including the application of radar to air navigation. During the war radar had been developed to guide aircraft to and from their home bases, and the main task in peacetime was to adapt this military equipment to civil aircraft. Numerous proposals for navigation systems were made around the world and among the most successful was the distance-measuring equipment (DME) developed by a Radiophysics group led by Brian Cooper. First installed on commercial aircraft in 1950, the DME provided pilots with a direct and reliable reading of the distance to and from airports [9].

Another successful project at Radiophysics was the design and construction of one of the first all-electronic computers. Immediately after the war, construction of the first computers began at several centres in the United States, Britain and Germany. Not far behind, Trevor Pearcey and Maston Beard at Radiophysics began building

Australia's first computer in 1947. Christened the CSIRAC, the computer came into operation in June 1951 at about the same time as two machines known as ILLIAC (University of Illinois) and EDSAC (Cambridge University). With over 1500 radio valves and able to carry out 500 arithmetical calculations per second, the CSIRAC eased the workload of a roomful of 'calculators' (mainly women) who had done most of the laborious, repetitive 'number crunching' calculations using electric desktop calculators. For the next five years, the CSIRAC not only provided a service for the research programs at Radiophysics, but also for a number of outside organisations. One task was the design of power-generation systems for the Snowy Mountains Project, a vast hydro-electric scheme built in Australia in the 1950s [10].

Despite these promising starts in air navigation, computing and other areas such as accelerator physics, by about 1950 the Radiophysics Lab had evolved into two main and quite independent groups. In addition to radio astronomy, research into cloud and rain physics became the other program to flourish at Radiophysics over the long term. During the war radar operators had become familiar with the echoes produced by cloud and rain. Earlier, laboratory experiments had revealed, at least in broad outline, how clouds form and also the important role played by condensation nuclei, but by 1945 surprisingly little was known about the fundamental causes of rain formation. The main barrier had been the difficulty of making direct measurements within clouds of the complex and interrelated physical quantities involved. This had to await the technological developments that occurred during the war – suitable aircraft to provide an airborne laboratory and radar to provide a way of probing deep within cloud systems.

The cloud and rain physics group at Radiophysics grew steadily after the war and by 1950 rivalled the radio astronomy group in staff numbers. With fewer expensive items such as large radio telescopes, however, the cloud and rain physics group consumed a comparatively smaller proportion of the Radiophysics budget. The aircraft and aircrew used in the experiments and trials were, for example, supplied free of charge by the RAAF. The research program developed into three closely related fields: cloud physics, the physics of rain formation, and the artificial stimulation of rain. The third field, rain-making, became the one most intensively studied and the one, even more than radio astronomy, that gave Radiophysics a high public profile. Great expectations were held for the success of this work. To a country noted alike for its droughts and floods, and still largely dependent for its prosperity on agricultural and pastoral industries, no natural phenomenon is more important. Since the time of the first settlers, farmers had alternated between elation and despair over the unpredictable patterns of rainfall. If the processes of rain formation could be understood well enough for even a small degree of control to be exercised, the consequences for primary industry and the national economy would be far-reaching [11].

The radio astronomy group itself evolved into two main subgroups of approximately equal size. The solar radio astronomy group continued on from the pioneering observations carried out by Pawsey and colleagues late in 1945. There were two broad research programs: one was to record radio bursts from short-lived phenomena such as solar flares and, the other, to map the radio brightness of the 'quiet' Sun and slowly varying features such as sunspots. The first line of research was led by Paul Wild and the second by Chris Christiansen (see Figure 5.2). The other main subgroup, which included the Dover Heights team, was known as the cosmic radio astronomy group. To avoid duplication of effort, Joe Pawsey assigned each of the cosmic teams a particular frequency range. The Dover Heights group was assigned the range 60 – 200 MHz, though observations had occasionally been made at 40 MHz (see e.g. Figure 6.1). For frequencies higher than 200 MHz, Jack Piddington and Harry Minnett led the research, while the low frequency region below 60 MHz was the domain of Alex Shain, Charles Higgins and others. These frequency ranges were not rigid and changed over time.

A key feature of the Radiophysics group was the number of field stations to which the Lab had access, some of them (such as Dover Heights) former wartime radar sites (see Figure 5.3). These sites enabled the rapidly growing group to split up into a number of small and independent teams, each pursuing a particular line of investigation. On a practical level this had the advantage that one group carrying out observations would not be disturbed by another group needing, for example, to start up electrical machinery to carry out maintenance work. On another level, this relative isolation promoted a healthy degree of self-reliance and inventiveness. Each group had essentially a free hand in dealing with their day-to-day problems and, in the long

Figure 5.2. (above) Paul Wild at the Dapto field station south of Sydney and (below) Chris Christiansen at the Potts Hill field station in suburban Sydney. Wild's group studied short-lived phenomena such as violent flares in the solar atmosphere, while Christiansen led the group studying radio emission from the 'quiet' Sun and slowly varying features such as sunspots. [courtesy: RAIA]

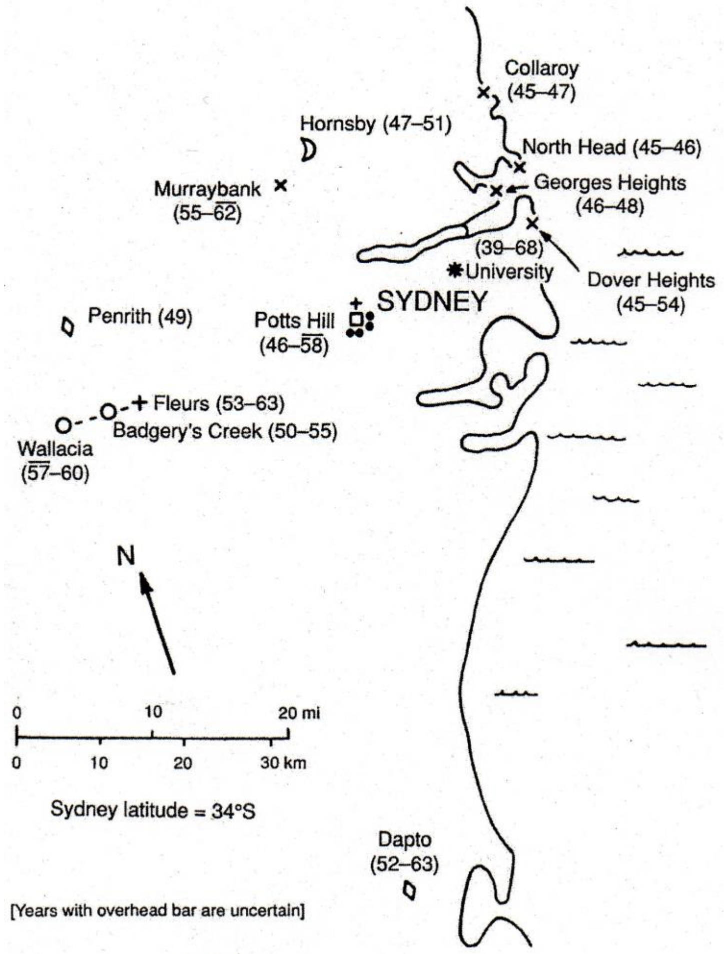


Figure 5.3. The field stations used by the Radiophysics Lab for radio astronomy during 1945–60. [courtesy: Woody Sullivan]

term, in determining the direction their research would take. A large part of the time at these field stations was spent outdoors, so the new radio astronomers felt like pioneers in the physical sense as well. Chris Christiansen recalled [12]:

> ‘Each morning people set off in open trucks to the field stations where their equipment, mainly salvaged and modified from radar installations, had been installed in ex-army and navy huts. At the field stations the atmosphere was completely informal and egalitarian, with dirty jobs shared by all. Thermionic valves were in frequent need of replacement and old and well-used coaxial connectors were a constant source of trouble. All receivers suffered from drifts in gain and ‘system-noise’ of hundreds or thousands of degrees represented the state of the art. During this period there was no place for observers who

> were incapable of repairing and maintaining the equipment. One constantly expected trouble.'

The radio astronomers joked that for them the letters PhD stood for Post-hole Digger. Joe Pawsey oversaw the whole operation. He had effectively sacrificed his personal research career in order to guide and coordinate the activities at these various sites. He suggested research projects, helped in the design of equipment, advised on the most suitable observational methods, assisted with some observations and, most importantly of all, became a tough and dependable critic when it came to analysing the data and writing it up for publication. Paul Wild wrote [13]:

> 'Pawsey's role at this time was quite central. Most people of his group – though perhaps there were a couple who liked to think themselves self-sufficient – looked to him for advice, encouragement and inspiration, which were freely and selflessly given. About once a fortnight the research staff would meet together with Pawsey in the chair. Each person or group would report their progress and Pawsey would ask questions and make suggestions. At other times when one ran into problems, half-an-hour's discussion with Joe tended to be both soothing and rewarding. Then on some days he would arrive unexpectedly at one's field station, usually at lunch time (accompanied by a type of sticky cake known as the lamington, which he found irresistible) or else infuriatingly near knock-off time. During all such visits one had to watch him like a hawk because he was a compulsive knob-twiddler. Some experimenters even claimed to have built into their equipment prominent functionless knobs as decoys, especially for Pawsey's benefit.'

Pawsey provided the guidance and inspiration during the formative years of the radio astronomy group. During the 1950s the group would steadily grow and consolidate its position at the cutting edge of the new astronomy.

5.3 A Rather Distant Outpost: The Radiophysics and Cavendish Labs

The Australian historian Geoffrey Blainey coined the term 'tyranny of distance' to describe how the distance and isolation from the mother country Britain has done much to shape the course of Australian history [14]. The same is also true for Australian science. Very few Australian scientists could make a name for themselves internationally without spending much of their career working at the main centres of science in Europe or North America. The University of Melbourne was the first

Australian university to offer a PhD program in 1948, but until then the common practice had been for young researchers to carry out their PhD research at a British university, with the two most prestigious destinations being Cambridge and Oxford. Many of the most talented scientists never returned. Woody Sullivan has described how the 'tyranny of distance' affected the Radiophysics Lab [15]:

> 'The early Radiophysics years are rife with examples of things that would have gone differently if RP had not been located 10,000 miles from its sister institutions, but instead 100, or even 1000. The best airline connections to Europe required a gruelling three days (or a civilised week) and more common passage by ship took about four weeks; moreover, the cost of a ship's berth amounted to one or two months' pay for an RP staff member. The RP staff (and Australian science in general) were constantly bedevilled by their inability to have frequent contact with colleagues from other institutions, the long interval before learning about research conducted elsewhere, the delays (sometimes inordinate) in publishing Australian results in the prestigious British journals, and the lack of foreign readership of Australian journals.'

The distance and isolation worked in the other direction too. Until the international URSI Congress held in Sydney in August 1952 (see next chapter), there is no record of a single radio astronomer from overseas visiting the Radiophysics Lab, despite it being the world leader in most areas of radio astronomy [16]. If not for the tyranny of distance, Radiophysics might have become a mecca for young researchers from other countries eager to break into the new and fast-moving branch of astronomy.

In the late 1940s the main rival to the Radiophysics Lab was the Cavendish Laboratory in Cambridge (the Jodrell Bank group published its first radio astronomy paper in 1950 and soon joined Sydney and Cambridge as one of the top three centres internationally – see later). The contrast between the Radiophysics and Cavendish Labs could hardly have been more extreme. As we see in the next section, in contrast to the isolation of Radiophysics, the Cavendish complained of just the opposite problem – too many visitors wanting a tour of the Lab and causing too much distraction for its researchers. Until 1945 Radiophysics did not officially exist and in the years following WWII it was virtually unknown in scientific circles in the northern hemisphere. In complete contrast, the Cavendish Lab since its foundation in

1874 had long been considered the finest centre for physics in the English speaking world. In 1919 its reputation received a further boost when the New Zealander Ernest Rutherford replaced J. J. Thomson as head of the Cavendish. Rutherford focussed the research effort into nuclear physics. The 1920s was the decade of atomic physics and the foundation of quantum mechanics, but in the 1930s the new glamour field became nuclear physics. As a powerful illustration of the Cavendish's pre-eminence, the staff photo in 1932 (with the tall graduate student Joe Pawsey in the back row) included nine current or future Nobel Laureates [17].

After Rutherford's premature death in 1937, the Adelaide-born Lawrence Bragg was appointed the new head of the Cavendish. In 1915 he and his father William Bragg were awarded the Nobel Prize for Physics for their development of the new field of crystallography [18]. Bragg foresaw correctly that with the advent of large and expensive particle accelerators, the Cavendish would be unable to compete against the growing number of nuclear physics centres in the United States. Against considerable opposition, Bragg decided to diversify the research program into new areas, such as his own field of crystallography. His decision paid handsomely in 1953 when Cavendish crystallographer Francis Crick and visiting American James Watson announced the double helix structure of DNA, one of the most important discoveries of the twentieth century.

At the end of WWII Bragg also supported the formation of a small radio astronomy group under the supervision of the ionospheric physicist Jack Ratcliffe. Ratcliffe had been a leading authority on the physics of the upper atmosphere before spending the war years engaged in radar research at the Telecommunications Research Establishment. On returning to Cambridge he recruited several young radar scientists to his department at the Cavendish Laboratory, among them Martin Ryle (see Figure 5.4), and then later Graham Smith and Antony Hewish. The Cavendish group began by making observations of the Sun and was able to confirm the discovery by Pawsey's group that sunspots were a source of intense radio emission. The early Cambridge work provided a depressing example of how the Radiophysics Lab was disadvantaged by the 'tyranny of distance' referred to above. The paper by Pawsey's group reporting the discovery of sunspots as the source of intense radio emission had been submitted to the prestigious *Proc. Roy. Soc. London*. The English referee 'sat' on the paper for months and it was over a year before the paper got into print. In the meantime the Cavendish group made the same discovery and rushed into print within two weeks, their *Nature* paper appearing six months before the Pawsey paper. The Cambridge group was widely credited for making the discovery even though their observations were made six months after those at Radiophysics [19].

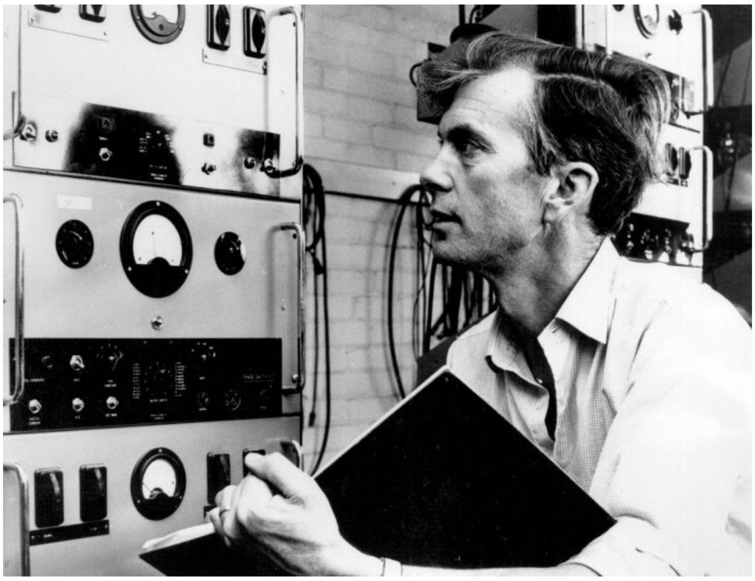


Figure 5.4. Martin Ryle founded the radio astronomy group at the Cavendish Laboratory in Cambridge. In 1974 he and Antony Hewish received the Nobel Prize for Physics, the first occasion it was awarded to radio astronomers. [courtesy: Cavendish Laboratory]

Early in 1948 Ryle's interests turned from solar radio astronomy to cosmic radio astronomy. His change of interest was probably reinforced by Joe Pawsey who spent May 1948 at the Cavendish during his world tour as the guest of Jack Ratcliffe, his former PhD supervisor. Pawsey reported at length on the success of the Dover Heights group, including Bolton's solo paper listing seven discrete sources which had been submitted to *Nature* the previous month (see Table 4.1). In the same month as Pawsey's visit, Ryle and Graham Smith built a four-Yagi antenna operating at 80 MHz and were able to detect Cygnus A on their first attempt. They also showed that its angular size was less than 6′, confirming the point-like size of the source. On the same night they detected a second source in the Cassiopeia constellation that was an even stronger source of emission than Cygnus A, making it therefore (apart from the Sun) the most powerful of the known discrete sources. Cassiopeia A was later identified with a supernova remnant (see Section 6.1), joining the Crab Nebula as the second example of how these objects can be powerful radio emitters [20]. Solar observations continued at Cambridge for several years, but from May 1948 the course of the Cavendish group was firmly set on cosmic radio astronomy.

During the period September 1946 to December 1949 well over thirty letters were exchanged between Pawsey and Bolton in Sydney and Ratcliffe and Ryle in Cambridge, many of them quite detailed (and some unfortunately that have not survived). At face value this would suggest a fruitful and cooperative collaboration between the two groups which were, at this stage in the development of radio astronomy, the two most important. There were also the personal ties – Pawsey to his PhD supervisor Ratcliffe and Bolton to his *alma mater* where he had completed his Bachelors degree in 1942 [21]. However, as we see in the next section, the relationship between Radiophysics and the Cavendish turned out to be far from harmonious.

The first exchange between the two groups came after Pawsey received a reprint of the Cavendish paper reporting the sunspot radiation which, as mentioned above, was based on observations made six months after the original discovery by Pawsey's group [22]:

> 'I got rather a shock when I received Ryle's note enclosing a copy of the letter to 'Nature' contributed by himself and Vonberg. As you will see from the paper describing our work … the Cavendish and Radiophysics Laboratories have unfortunately succeeded in duplicating a very considerable part of the work. … I do not know what we can do about this duplication or how we can avoid it in the future.'

Ratcliffe replied that some amount of duplication may not be such a bad thing:

> 'As you know, we have embarked on a big program of this kind, and, as you mentioned in your letter, there has been, and probably will be, a certain amount of overlap between us. I do not think there is any harm in this. The methods which we are using are in many respects very different. … I do not view with any more dismay the possibility of overlap here than I do in the case of ionospheric research, for example. Now that the air mail works so quickly … we will make a special attempt to keep you fully in touch with what we are doing.'

After the initial detection of the Cygnus source by Ryle and Smith in May 1948, the main point of contention between the two groups was the position of the source. In their discovery paper Bolton and Stanley (1948) gave a position which they claimed was accurate in right ascension to ±10 sec and in declination to ±7′. In stark contrast, the Cambridge position was a full 2° away from the Dover Heights position. After Pawsey's visit, Ryle informed Bolton [23]:

> 'We have had lengthy discussions with Pawsey on the possibility of systematic errors in either of our methods of determining declination, but have failed to think of anything which could account for the large discrepancy. However it is clear that one of us must be wrong – unless the source has moved. … It is obviously very important to see whether the source has moved, and we are wondering if you will be able to make another measurement soon. If you still get your original figure we will have to work out which of our systems is giving the wrong answer, but if you find it has moved – then the astrophysicists must think again!'

Pawsey also commented on the worrying discrepancy [24]:

> 'Ratcliffe, Ryle and I have talked it over and reached the following conclusion. We could not find the reason for the difference, so have no justification for saying that either Ryle or Bolton is wrong. It seems to be something which can best be resolved by direct discussions between Bolton and Ryle. … I have no clues. It is up to Bolton and Ryle to *sort it out*. I wish them luck.' [his italics]

Over the next few months both Bolton and Ryle seriously considered the possibility that Cygnus was moving, i.e. undergoing proper motion so that its apparent celestial position changes over time. As mentioned in Chapter 4, at the Pakiri Hill site Bolton and Stanley had obtained good records for Cygnus on thirty nights. However, there was a substantial scatter in the records, not seen in the records for the other three sources Taurus, Centaurus and Virgo. As one example, the scatter in the rising times for Cygnus was up to 7 or 8 minutes, whereas the rise times for the Taurus source hardly showed any scatter. Bolton began to consider that the amplitude fluctuations in intensity in Cygnus might somehow be the result of the source moving. For his part, Ryle became convinced that Cygnus moved and that it tended to be at either of two distinct positions. By early November 1948, Bolton had almost completed his analysis of the New Zealand data. His new position for Cygnus was the average of the thirty Pakiri records, as he reported to Ryle [25]:

> ‘Subject to arithmetical errors undetected as yet, the ‘mean apparent position’ for some six weeks of June and July was:
>
> RA: 19h 58m 14s Dec: 40° 36´.
>
> Statistically the errors are only ±7 sec and ±2´ but I think the source probably lies within 1 deg of this position! You will note that the declination is half way between your two groups although I have no evidence of the two distinct groups you speak of. However, observing for some seven hours per night the source wanders off the ‘mean apparent path’ up to about a degree for periods varying between a few minutes and a few hours. I have no evidence of two sources as suggested by your beats.’

The new position reduced the discrepancy between the Cambridge and Dover positions from 2° to less than 1°, but it still could not rule out the possibility that the source was moving. Bolton also commented on the amplitude variations in the same letter:

> ‘A further result of the New Zealand Expedition is that the variations are ‘local’ – there was no correspondence between Dover Heights and NZ records. I am beginning to wonder whether there might be some hard radiation from the source in addition to RF [radio frequency] which affects the ionosphere particularly along the line of sight.’

By ‘hard radiation’ Bolton presumably meant that Cygnus might emit high energy particles or photons that interact with the ionosphere in such a way as to cause the large amplitude fluctuations at radio frequencies. Although Bolton soon abandoned the idea, it was one that was in keeping with the times. In the early post-war years there was considerable interest in ultra-high energy cosmic rays that collide with particles in the atmosphere and produce extensive showers of charged subatomic particles. The Nobel Prize for Physics in 1948 was awarded to Patrick Blackett at the University of Manchester for his studies of nuclear reactions and cosmic rays. Blackett was a mentor to Bernard Lovell and he encouraged Lovell to investigate the use of radar to track the paths of cosmic ray showers. The project at the Jodrell Bank field station in Cheshire was unsuccessful, though radar did prove to be an effective way of detecting the paths of meteors. In 1948 Lovell and his group made the transition from radar research to radio astronomy (see next section) [26].

By November 1948 Pawsey felt that the time had come to publish the results of the two groups, as he wrote to Ratcliffe [27]:

> ‘It seems to me that Ryle and Bolton have uncovered a major mystery and it is worth raising the question of publication at this stage. Bolton’s present thought is that it might be best for Ryle and him to publish detailed observations separately but that it might be appropriate for them to send a joint letter to ‘Nature’ describing the peculiar property of the Cygnus source. What do you think it would be best to do?’

Ratcliffe turned down the suggestion of a joint letter, noting that Ryle wanted to complete an extended series of observations before publishing [28]:

> ‘These extended results would of course contain *his* discovery [my italics] that the source in Cygnus moves. You say that Bolton has also found out this point. Of course it is never profitable to ask who got it first, but you will recall that when I questioned you here you were quite satisfied that the source had not moved in the last six months, and I think you thought that Ryle’s experimental results were due to an error in his apparatus. Is not the proper procedure for each to go ahead in his own way and to publish his results when he feels they justify it? … You will see therefore that I am inclined to accept Bolton’s attitude to the subject, i.e. that they should both publish separately.’

Ratcliffe’s disingenuous remark that ‘it is never profitable to ask who got it first’ was at odds with his claim that Ryle deserved priority for the discovery. If Ratcliffe had supported the idea of a joint paper it would have, presumably, led to the first internationally co-authored paper in radio astronomy.

Nevertheless, Pawsey persisted and argued that something needed to be published to avoid the possibility of another group making the same discovery [29]:

> ‘The question arises as to whether some interim note should be published primarily guarding against the discovery of the peculiar behaviour of this source by perhaps an American observer. I myself think that the discovery is sufficiently unusual to warrant a

> note to ‘Nature’ and was rather favouring the suggestion that Bolton and Ryle should combine in a note which would be very brief and would state the fact that the apparent position varies, and perhaps add the details – (a) that the variations are different when observed at places 2000 miles apart and (b) that the variations in position are absent on about 200 Mc/s. This seems to be a reasonable balance between the contributions of the two people.’

On this occasion, Ryle replied to Pawsey, rather than Ratcliffe [30]:

> ‘I have had a very full discussion with Ratcliffe on the question of the early publication of the results on Cygnus. … Your point about publication by some American observer is a very strong argument! We did not feel very happy about a joint letter to ‘Nature’, both because of the complications of writing a co-operative account by remote control and also because of inevitable differences in belief (e.g. we are not yet convinced that the fluctuations we observe in Cygnus are due to local effects).’

After further correspondence a compromise was finally reached, as Bolton wrote to Ryle [31]:

> ‘Many thanks for your recent letters. I think your proposal of simultaneous letters to ‘Nature’ is an excellent one. I have roughed out my contribution. This will have to be sent on to CSIR Executive in Melbourne for approval. After that I will forward it to you to send on to ‘Nature’ when convenient.’
>
> ‘The outline of my letter is as follows: (1) The new mean position from NZ observations. (2) Short period variations in position on individual nights. (3) Differences in position between individual nights. (4) No correspondence in amplitude between NZ and Sydney observations. (5) Certain considerations which may invalidate (4) such as low angle effects, interference method etc. (6) A mention of Taurus-A observations between NZ and Dover as a partial ‘control’ in (4). All observations were made on 100 Mc/s.’

Despite the numerous letters on the publication issue over a four-month period, the proposal to have back-to-back letters in *Nature* came to nothing. In December 1948 Ryle and his group installed a new array at their Grange Road field station, known as the Long Michelson interferometer (see Figure 5.5). Ryle informed Pawsey in February 1949 [32]:

> ‘I am still not happy about our experimental evidence for the movement of the source in Cygnus and I have delayed replying until we had carried out a re-analysis of some of our old records. Since we have had our new aerial in operation (December) we have obtained a large number of observations of the position of the source (and of that of Cassiopeia) on 80 Mc/s. The measurements have generally been of considerably greater accuracy than our previous ones … The results obtained show that during this period the source in Cygnus has remained stationary to within ±20′ in declination and ±½ minutes in R.A. … [From] observations during this period we would not have concluded that Cygnus moves. … The question now arises as to whether our earlier measurements were as accurate as we thought …’

Ryle’s assertion of a moving Cygnus source was quietly buried.

It took most of 1949 before the two groups agreed on the origin of the amplitude fluctuations in Cygnus. As seen in the correspondence above, on at least two

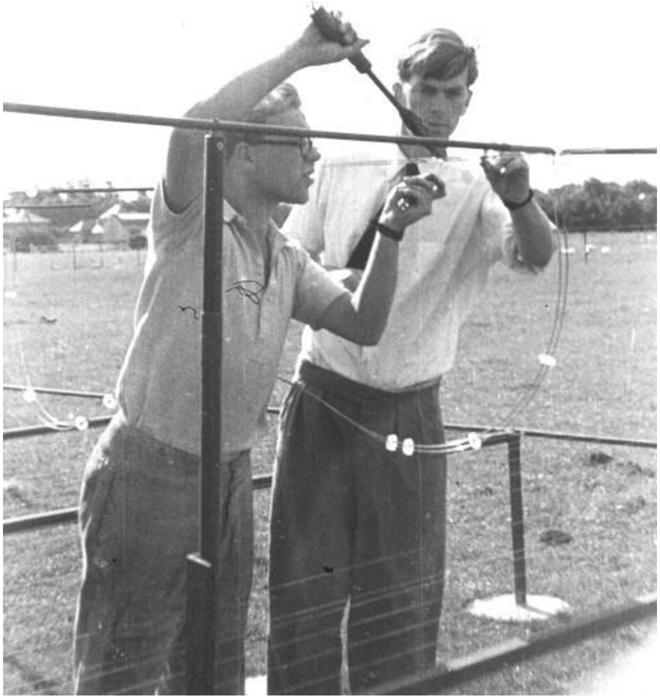


Figure 5.5. Graham Smith (left) and Martin Ryle working on the Long Michelson interferometer at their field station outside Cambridge. The interferometer was used to compile the first Cambridge catalogue listing 50 discrete sources. [courtesy: Woody Sullivan; credit: Bruce Elsmore].

occasions Bolton informed Ryle that there was no correlation between the Cygnus fluctuations observed simultaneously in New Zealand and in Sydney. In the previous chapter, we noted that simultaneous observations of the fluctuations at Dover Heights and Long Reef in January 1948, at a separation of 15 km, appeared to show a reasonable correlation between the two sites. Before publishing the New Zealand–Sydney finding, Bolton wanted to have independent confirmation of the lack of correlation and so he encouraged Ryle to carry out simultaneous observations of Cygnus with Lovell's group at Jodrell Bank. If there was no significant correlation over the Cambridge–Manchester distance of 210 km, then it would confirm why there was no correlation over the Tasman Sea baseline of 2100 km. In January 1949 Ryle wrote to Pawsey [33]:

> 'I am very anxious to know your views on the New Zealand results. As I said in my last letter to Bolton, the results, if true, are most significant. The possibility that fluctuations are introduced by tropospheric or ionospheric refraction seems so important that we would like to see some similar experiments carried out … I have suggested to Lovell that we might carry out such experiments jointly. Although the distance is only … 130 miles, any local effects (whether tropospheric or ionospheric) should be different at that distance.'
>
> 'I should be very glad to have your comments on the desirability of doing this experiment as soon as possible as it will involve Lovell in the construction of a new aerial if we do decide to do it. If you feel that your New Zealand results may be due to local refraction effects, but that there are also genuine sudden fluctuations inherent in the radiation from the source, then we might not think it worth doing the experiment. If you think that *all* the fluctuations are due to local effects we would want to try a normal-incidence experiment.' [his italics]

Four months later Ryle reported: 'We have so far obtained no conclusive results either way in our experiment with Lovell on the short period variations.' In addition to the observations at 81 MHz in cooperation with Lovell, the Cavendish group carried out independent observations at 45 MHz using aerials spaced up to 180 km from Cambridge. Similarly, the Jodrell Bank group carried out independent observations at 81 MHz with aerial spacings of 100 m and 4 km. By September 1949

Ryle could confidently claim to have confirmed the New Zealand–Sydney finding [34]:

> ‘The main conclusion so far is that the greater part of the recent fluctuations is different, and therefore agrees with your New Zealand–Australia results; we must therefore conclude that some of the fluctuations are caused by some relatively local effect. … There is no doubt that your original experiment was most important in shewing the existence of an uncorrelated component – I think otherwise everyone would have assumed that it must be due to the source.’

We return to the Cygnus fluctuations in the next section.

5.4 A Tour of Radio Astronomy Centres

In the previous section we noted how the ‘tyranny of distance’ made it difficult for the Radiophysics radio astronomers to interact with the other radio astronomy groups emerging in Britain and elsewhere. Taffy Bowen and Joe Pawsey realised very early that the best way to counteract the isolation of the Radiophysics Lab was to send staff on fact-finding, intelligence-gathering tours of the research centres in the northern hemisphere. Bowen was the first to go in 1946, sending back lengthy letters summarising the work at various centres including, as noted earlier, an early alert of Hey’s discovery of the intensity fluctuations in Cygnus. Pawsey was the next to go, embarking on a marathon 13-month tour in September 1947. Pawsey established personal contacts with a number of prominent astronomers in the US and Europe and gave first-hand accounts of the research at Dover Heights.

Late in 1949 Bowen decided that Bolton would be the next to go, partly as a reward for his achievements over the previous three years and partly because he was the best qualified to assess the progress of radio astronomy centres elsewhere. The centrepiece of the tour would be for Bolton to represent the Radiophysics Lab in Zurich at the general assembly of the peak international body for radio science, known by its French name Union Radio Scientifique Internationale (URSI). In November 1949 Bowen sought support for Bolton’s trip from the CSIRO Executive, requesting five months in Europe, followed by three months in North America [35].

> 'I would like now to recommend that Mr John Bolton should proceed overseas in some months' time in connection with his work on radio astronomy. As you are aware Bolton came into the Laboratory soon after the war without much previous experience but in the last four years has developed into a first class researcher with a number of completed pieces of work to his credit. …'
>
> 'During his visit overseas a year ago Dr Pawsey found that while experimental work in radio astronomy was further advanced in England than in the United States there was much greater interest in the implications of the work of astronomy in the Observatories in America such as Harvard, Yerkes, Mount Wilson, Michigan, and Princeton. Dr Pawsey was invited to describe the Australian work at each of the above Observatories and I feel sure that in view of Bolton's recent work they would be just as interested in hearing from him. In view of these facts I would like to recommend most strongly that in addition to proceeding to England and Switzerland for the URSI Conference Bolton should proceed to America for a period of approximately three months.'

The CSIRO Executive closely vetted all overseas travel requests by its officers, wary that the new organisation could not risk a repeat of the political attacks that had brought down its predecessor CSIR. In turn, the Executive requested ministerial approval for Bolton's trip. Its letter was promptly returned with a handwritten annotation by no less than the prime minister: 'Yes, Robert G. Menzies, 28 January 1950' [36].

Before we describe Bolton's tour in some detail, it will be useful to return to Dover Heights and another research project carried out during 1949. After submitting the *Nature* letter on the possible optical identifications of Taurus, Centaurus and Virgo in May 1949, Bolton returned to a project he and new recruit Kevin Westfold (Figure 5.6) had begun earlier in the year, a project independent of the hunt for more discrete sources. Earlier, Grote Reber in the US and Stanley Hey and his group in England had carried out surveys of the northern sky, producing contour maps of radio strength at the frequencies of 160 and 480 MHz (Reber) and at 64 MHz (Hey) [37]. Bolton and Westfold aimed to carry out the first southern survey and then combine the results with the Reber and Hey maps to produce the first all-sky survey. To carry out the survey the Dover group constructed a new array consisting of nine Yagi aerials

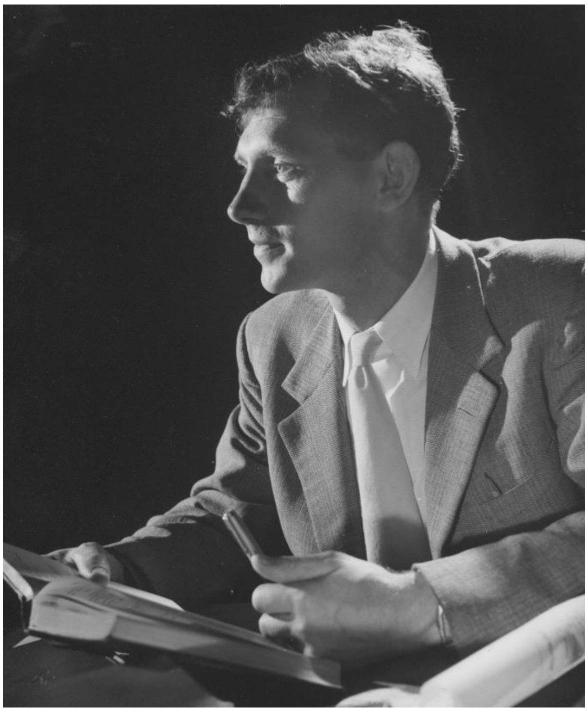


Figure 5.6. Kevin Westfold became the fourth member of the Dover Heights team in December 1948. He joined the Radiophysics Lab after receiving a Bachelors degree from the University of Melbourne and then a Masters degree from the University of Tasmania. [courtesy: Woody Sullivan]

and operating at 100 MHz (see Figure 5.7). Rather than pointing the aerial to the horizon to operate as a sea interferometer, the array was on an equatorial mount so that it could be swept across the sky, recording for each sweep the radio strength along a thin strip of sky.

As expected, the dominant feature in the southern map was the strong radio emission from along the Galactic plane. The Galactic centre passes almost overhead at Sydney’s latitude, but is low on the horizon in the northern hemisphere, and so this strong emission did not feature as prominently in the Reber and Hey maps (see Figure 5.8). Bolton and Westfold noted that the emission reached a maximum in the direction of the Galactic centre but then moving outwards from the centre, along the Galactic plane, the intensity fell away to just one-fifth of the maximum. On the assumption that the radio intensity was proportional to the amount of Galactic material along the line of sight, their results were consistent with the Solar System being located in a spiral arm somewhere in the outer regions of the Milky Way. Looking along the spiral arm to the crowded Galactic centre would produce a

Figure 5.7. The nine-Yagi array was the first of the purpose-built radio telescopes at Dover Heights. (left) The array on its equatorial mounting was used to carry out the first survey of the southern sky at 100 MHz. (right) The array in its sea interferometer mounting. [courtesy: RAIA]

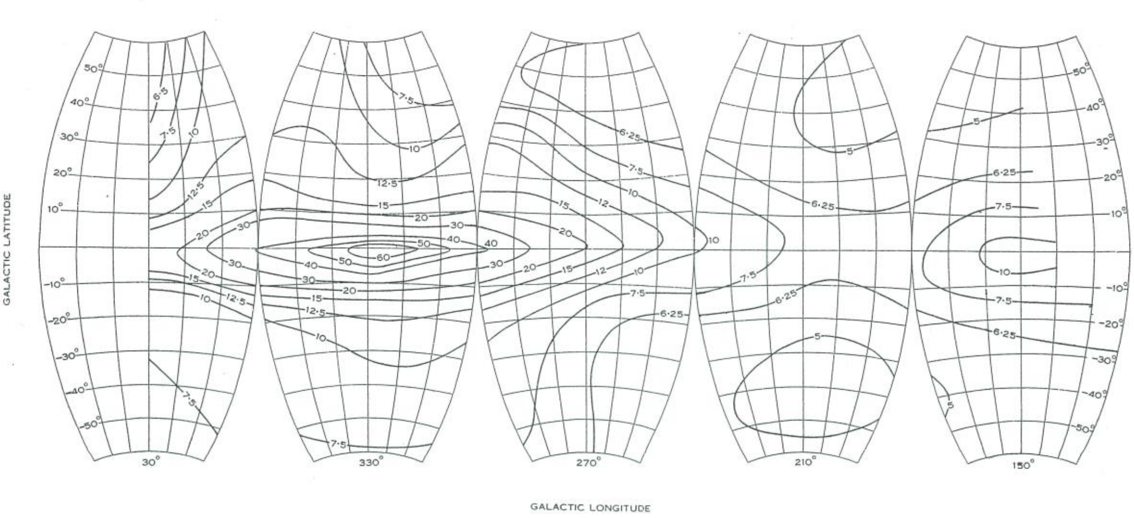


Figure 5.8. Equal-area charts of equivalent black-body temperature at 100 MHz over the celestial sphere. The contours are labelled in units of 100 K in brightness temperature. The Galactic centre features prominently in the chart for galactic longitude 330°. [after Bolton and Westfold (1950a), Fig. 5A]

maximum intensity, while looking out at right angles into the sparsely populated dark alley separating two spiral arms would produce a minimum intensity.

Before publishing the results Bolton wrote to Jan Oort at the Leiden Observatory, an authority on the structure of the Galaxy, who replied [38]:

> ‘The extension of surveys of the distribution of galactic noise in the southern hemisphere is in my opinion one of the most important jobs that can be undertaken. And it is a very happy circumstance that in this branch of astronomy the southern hemisphere is competing so beautifully with the northern. This cannot be said of most other parts of astronomy where our knowledge of the southern skies remains very far behind. I am looking forward very intensely to the details of your investigation.’

Following the usual Dover Heights practice, Bolton and Westfold sent an announcement letter to *Nature* and two detailed papers to the *Australian Journal of Scientific Research* [39]. The first Australian paper presented the observational data, while the second Australian paper compared their observations with those by Hey and Reber in the region of sky where the southern and northern surveys overlapped. The second paper also discussed the evidence for a spiral structure and also the sense of rotation of the Galaxy. The *Nature* letter noted:

> ‘These observations can be interpreted as placing the Sun in or near the arm of a spiral galaxy, this arm extending from Carina through the region of the Sun to Cygnus. … The direction of rotation of the Galaxy is known from astronomical observations of the apparent motion of stars and star clusters, and if the radio observations can be interpreted in terms of a spiral structure with an arm opening out in the direction of Cygnus, the sense of rotation is that of a spiral unwinding. This sense of rotation has not been previously established.’

The conclusive proof of the spiral structure would follow shortly after with the discovery of the 21 cm hydrogen line (see below).

*****

Bolton and his wife Letty boarded the *Himalaya* in late February 1950 and arrived at Tilbury dock in London a month later. Bolton’s first priority was to catch a train to Sheffield and spend a week with his father, John Bolton, senior. Although they corresponded from time to time, he had not seen his father for six years, not since he had signed on to the *Unicorn* as its radio officer. After John's mother died in 1942, his father had remarried a younger woman but their relationship broke down and they separated after just three years. His father had then employed a live-in housekeeper who had her own daughter. It was the last time Bolton saw his father. The following year he was diagnosed with cancer. Despite three operations he continued teaching mathematics, stoically refusing to take extended sick leave, but died shortly after, aged 58.

The Boltons were struck immediately by the austere conditions in England. In contrast to Sydney's booming economy in 1950, life remained difficult for most people. On his first day in Sheffield Bolton had collected a ration card. Although the war had ended five years earlier, the British economy took many years to recover. Rationing actually became stricter after the war and was at its harshest during 1949–50 [40].

Bolton spent a day in the Sheffield Public Library catching up on the latest publications. The most recent *Nature* issue contained his letter with Westfold on Galactic structure. Bolton was surprised to see in the same issue two back-to-back letters reporting the results of the spaced aerial experiment between Cambridge and Jodrell Bank. The first letter by Graham Smith reported the Cambridge observations, while the second by Bernard Lovell and his graduate student Gordon Little reported the Jodrell Bank results [41]. Smith noted:

> 'In a private communication, Dr J. L. Pawsey has described some experiments by Bolton, in which the source in Cygnus was observed simultaneously from sites in Australia and New Zealand. The records of fluctuations obtained in these experiments were markedly different at the two sites, and therefore suggested a comparatively local origin.'

Smith also noted that the Australia–New Zealand records were for Cygnus very low on the horizon and so it was important to make observations for Cygnus near to normal incidence (12° from the zenith). After his analysis of the observations, he concluded:

> ‘It therefore seems likely that two separate mechanisms are responsible for the observed fluctuations. One appears to be related to variations of the emission from the sources; the brief duration of these ‘bursts’ suggests that the sources are of stellar dimensions. The other appears to be due to diffraction in a comparatively local region.’

The Jodrell Bank letter by Little and Lovell made no mention of the Australian work, even though Pawsey had informed Lovell over a year earlier that [42]: ‘… observations taken simultaneously in Sydney and New Zealand which show amplitude variations [are] uncorrelated at the two places.’ In contrast to Smith’s letter, Little and Lovell concluded correctly that the fluctuations were *solely* the result of terrestrial causes:

> ‘It therefore seems likely that these fluctuations in the received intensity of the radio waves from the galactic sources are introduced in a local terrestrial medium, and are analogous to the twinkling of stars on optical wavelengths.’

Initially, Bolton was unperturbed by the two letters to *Nature*. He informed Bowen [43]: ‘There appears to be ample acknowledgment of our own efforts in this direction.’ Later, after visits to Cambridge and Jodrell Bank (see below), Bolton’s attitude hardened. Lovell told him that he was not aware that the idea for the joint Cambridge–Jodrell Bank observations had come from Radiophysics – Ryle had not told him. Bolton explained that he had held off publishing the Sydney–New Zealand results until the Cambridge–Jodrell Bank observations were completed, so that both findings could be published together. Later, at the URSI Congress in Zurich, Lovell publicly apologised to Bolton for the oversight [44].

As we saw in the previous section, there were numerous letters over several months between the Radiophysics and Cavendish Labs, discussing what form their joint publications would take, but they were now irrelevant. Six months after the two *Nature* letters, Gordon Stanley and Bruce Slee published the Sydney–New Zealand results in the Australian journal [45], but by then the priority for the discovery of the nature of the Cygnus fluctuations had gone to Cambridge and Jodrell Bank. As we saw earlier with the case of Pawsey and the discovery of sunspot radiation, this was the second occasion that Radiophysics had missed out on priority for an important discovery and a further illustration of the ‘tyranny of distance’ discussed in the previous section.

Figure 5.9. The Boltons and Westfolds on a bicycle tour at Bridge of Ray near Oxford (from left): John, Joan, Letty and Kevin. [courtesy: Bolton family]

Oxford was to be home base for the Boltons during their stay in England (see Figures 5.9 and 5.10). Kevin Westfold had been awarded a prestigious CSIRO studentship and he decided to do his PhD under the distinguished Oxford astrophysicist Edward Milne. Westfold and his wife Joan were housesitting for an Oxford professor who was on sabbatical in the United States. The house was a converted hotel and could easily accommodate two couples [46]. Bolton’s first official visit was to the physics department at the University of Birmingham, where Marc Oliphant (see note [17]) and his group were building one of the world’s first synchrotrons. Bolton gave a talk on the research at Radiophysics, concluding with his own work at Dover Heights.

Next was a visit to Stanley Hey at the Army Operational Research Group at Byfleet, west of London. Bolton was disappointed by what he found. Hey had been appointed superintendent of the group and was completely preoccupied with administrative duties. Galactic observations had stopped two years ago and, although solar observations were in progress, Bolton estimated that they were about eighteen months behind Paul Wild’s group. Hey had even lost his two principal collaborators. John Parsons had joined an electronics firm, while James Phillips had decided that managing an orchard would provide a more rewarding career. Hey was however still well connected to the astronomical community and he arranged for Bolton to give a talk the following month to the Royal Astronomical Society in London [47].

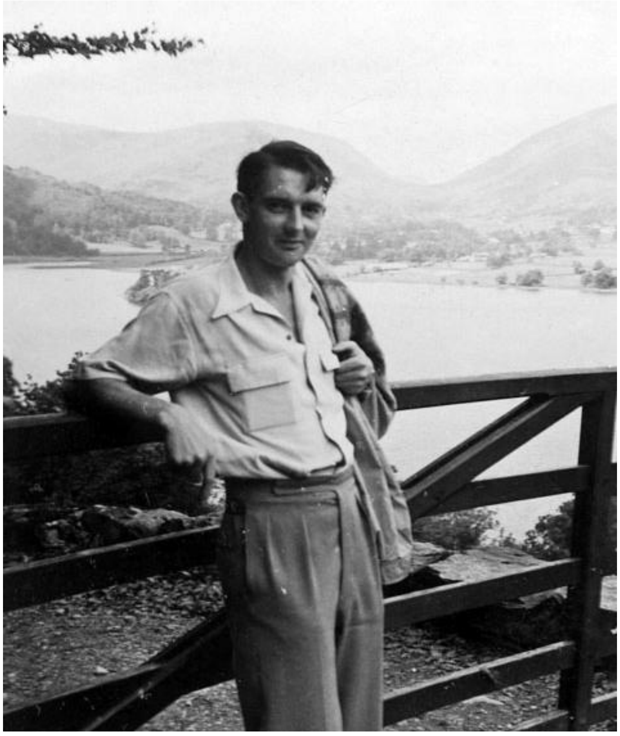


Figure 5.10. Bolton near Keswick during a tour of the Lake District in August 1950. [courtesy: Bolton family]

A visit to Cambridge was the most eagerly anticipated event in Bolton's itinerary. As a teenager Cambridge had been Bolton's ticket out of Sheffield and, though the lifestyle at Trinity College had been spartan, he had fond memories of the two years studying for his bachelor's degree. He had been bitterly disappointed in 1945 when his application to do postgraduate study at Cambridge had been turned down (see Chapter 2, note 18), but in retrospect the rejection seemed to have turned out for the better. Now, happily married, and with a well paid and exceptionally fulfilling job, the cards had certainly fallen his way since arriving in Sydney.

On his way to Cambridge Bolton visited the Australian Scientific Liaison Office in London to check his mail. ASLO had been established to assist Australian scientists travelling and working in Europe and was the place to go to receive letters, to get letters and manuscripts typed, to make travel bookings, and to browse through recent issues of the journals. There was a letter from Lawrence Bragg, the Australian-born director of the Cavendish, which Bolton assumed would discuss a few housekeeping details for the three-week visit he had arranged with Ryle. However, he was shocked to read [48]:

> ‘The number of visitors to the Cavendish is very large indeed. If I do not try to ration them somewhat, the research men spend all their time showing people round and the interruption to work is very great. … The difficulty is greatest when a visitor proposes to spend two or three weeks here, because it means effectively a research man looking after him for all that time … Ryle has had a particularly heavy burden lately because his work has aroused general interest and many have wished to include it in their tour of the laboratory. At the same time, his work, just because it is at an exciting and formative stage, ought to be free from such interruptions.’

Bragg made it clear that Bolton was welcome to visit for a day or two, or even spend a year working in the Cavendish as a research fellow, but a three-week visit was an unacceptable distraction to Ryle and his group. Bolton forwarded Bragg’s letter to Taffy Bowen who was furious at the rejection. He replied [49]:

> ‘I have just seen the letter from Bragg in response to your request to Ratcliffe and Ryle to visit the Cavendish in a few days’ time. I am terribly sorry that Bragg and presumably Ratcliffe have taken this point of view and the only suggestion which I can make at this stage is to say with some regret that, as we cannot agree to your staying in Cambridge for a whole year, you had better confine yourself to one day. I feel that Bragg ought to be reminded of Kettering’s dictum that in closing the doors of the laboratory they shut out more than they shut in.’

In typically colourful language Bowen informed Fred White at CSIRO head office [50]:

> ‘I find it hard to comment on this letter in a dispassionate way and my first reaction as a Welshman was to throw things and make loud noises. On sober reflection it is quite clear that Bragg has a right to run his laboratory in any way he chooses and there is little or nothing we can do about it. I have therefore written to Bolton saying how sorry I am that

> his old University has treated him in this way and, as we cannot agree to his staying at the Cavendish for a year, he had better confine his visit to a single day.'
>
> 'Bragg's letter raises one issue as far as CSIRO is concerned. It is that overseas visits are an important way of maintaining contacts with scientists in England and America and in keeping our own work in proper perspective with respect to work done overseas. CSIRO goes to considerable trouble and expense to support such visits but clearly a good case could not be made for an officer travelling 12,000 miles to spend one day only at a laboratory he hopes to visit. You may therefore want to discuss this letter with your colleagues on the Executive and you may decide that some action should be taken.'

Bowen was puzzled why the Australian-born Bragg had not gone out of his way to make Bolton welcome. Based on his Cavendish visit two years earlier, Pawsey believed Bragg wrote the letter without being properly briefed by Ryle [51]:

> 'May I add the following comments from my own experience. Ryle is egotistical, impetuous and superficially at any rate, extremely confident of his own work. He is an excellent experimenter but not so good at interpretation – I think he is immature as yet. Nevertheless quite likeable. Ratcliffe has all the balance which Ryle lacks but, when I was there, he left Ryle to run the cosmic and solar noise work with very little supervision. My guess is therefore that … Bragg acted with insufficient knowledge having too great confidence in Ryle.'

Bolton spent three days in discussion with Ryle and his group, but kept the visit to minimum. As he reported home, Ryle was guarded in the information he was prepared to share [52]:

> 'There is undoubtedly a visitors' problem at the Cavendish but in spite of this they are both jealous and scared of Radiophysics. Ryle himself said that he could make some suggestion as to an experiment he could make – I could write back to RP and have it done and the results published before even he built the equipment. I said that such a situation was quite unthinkable – we had quite enough to do without resorting to dishonesty!'

There was however one unexpected and beneficial outcome of the brief visit. Bolton got to know the astrophysicist Fred Hoyle who had read the *Nature* article on the optical identifications of the first three discrete sources and realised the importance of the work. Hoyle introduced him to his colleagues Herman Bondi, Tom Gold and Ray Lyttleton and invited him to spend time at his home base in St Johns College. Hoyle and his colleagues were developing the steady state theory of the Universe, a cosmology that would rival the big bang theory and spark a fierce controversy later in the 1950s. It was the beginning of a long friendship between the two [53]:

> ‘During my last week I spent two days with Hoyle and one with Gold and got on extremely well with both of them. Hoyle is short, rather tubby, has curly black hair, wears horn rimmed spectacles and speaks with a strong Yorkshire accent. He would look more at home in a north country saleyard than in St Johns. He has wide interests outside his own subject and is very keen on cricket. Most of our discussions were held in the members stand at Fenners!’

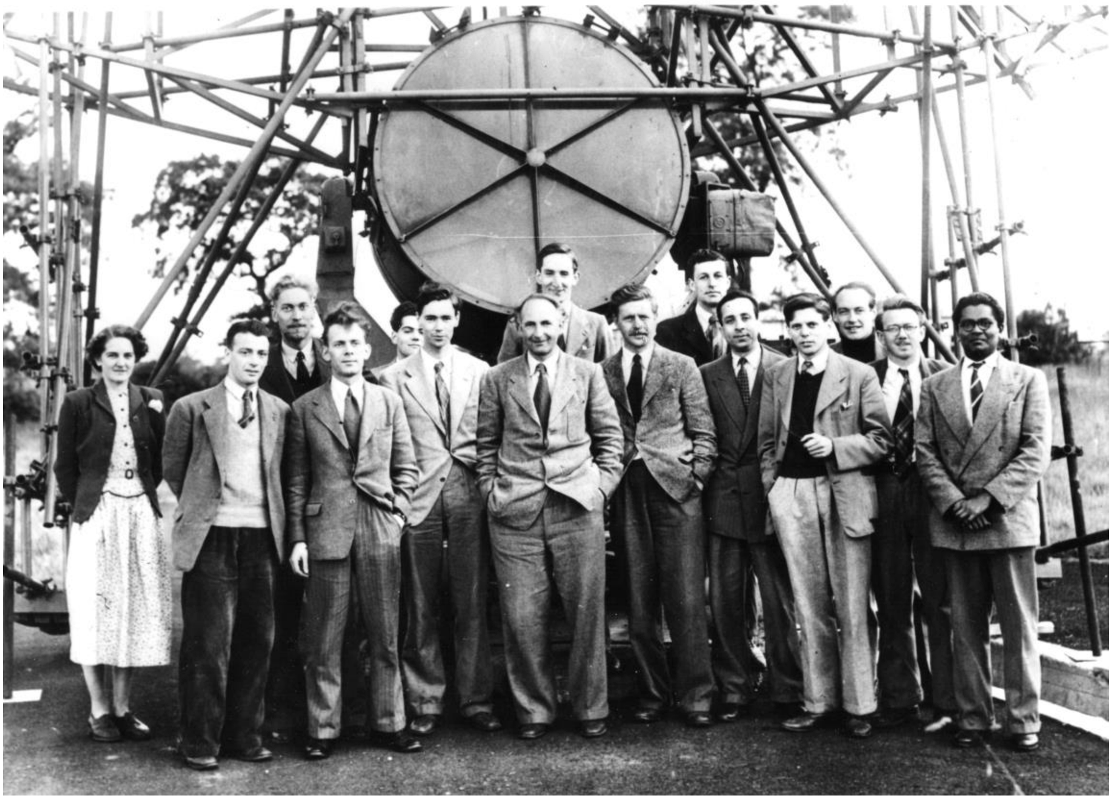


Figure 5.11. The Jodrell Bank group in 1951 with Bernard Lovell (centre front row). In 1950 Cyril Hazard (second from left) and Robert Hanbury Brown (absent) detected radio emission from the Andromeda (M31) galaxy, leading to the second radio astronomy paper by the group. In 1963 Hazard played a major role in the discovery of quasars (see Section 7.2). [courtesy: Woody Sullivan]

Bolton’s reception at the University of Manchester was as warm as the Cavendish had been frosty. Bernard Lovell’s career in radio astronomy began in December 1945 when a trailer loaded with ex-Army radar gear was towed onto the university’s horticultural field station, known as Jodrell Bank (see Figure 5.11). As noted in the previous section, Lovell’s first experiment was an attempt to detect radio waves reflected from the trails of cosmic rays. Instead of cosmic rays, Lovell inadvertently succeeded in detecting meteors, which produce a similar but much larger trail of ionised particles in the atmosphere, and so confirmed the discovery made by Stanley Hey’s group a year earlier of the radar echoes produced by meteor trails. In 1947 Lovell and John Clegg constructed a fixed parabolic aerial 220 feet (67 m) in diameter consisting of a spider’s web of wire suspended on upright tubular supports. Although initially intended for radar studies of cosmic rays and meteors, the 220 ft aerial was used increasingly as a radio telescope to study cosmic emissions [54, 55].

When Bolton visited in June 1950, Robert Hanbury Brown and Cyril Hazard had begun an ambitious attempt to detect radio emission from the Andromeda (M31) galaxy. They reasoned that if Andromeda emitted radio energy with a strength comparable to our own Galaxy, it should be possible to detect the emission even at this vast extragalactic distance. Although the observations were seriously hampered by radio interference from a nearby motorway (made worse by the recent lifting of petrol rationing), the data obtained over 90 nights confirmed that Andromeda was indeed a radio emitter similar in strength to the Milky Way. Andromeda was the first extragalactic object to be positively identified as a radio source [56, 57]. However, the fact that Andromeda was approximately 10,000 times less luminous than Centaurus (NGC 5128) and Virgo (M87) threw further doubt on whether these two Dover Heights sources could in fact be extragalactic objects. As we saw in Chapter 4, in the 1949 *Nature* paper Bolton had argued that it was far more plausible to reclassify NGC 5128 and M87 as Galactic objects, rather than claim them to be immensely powerful radio sources at extragalactic distances.

In July Bolton and Westfold made the first of two tours to radio astronomy centres on the Continent. Their first stop was to northern Germany with Albrecht Unsöld and his group at the University of Kiel, which was temporarily housed in an old factory. Bolton was shocked by the scale of the Allied bombing which had destroyed almost the entire centre of the city, including the old university and observatory. Because of a lack of funds, the emphasis at Kiel was on theoretical work and a few simple solar observations. At the Leiden Observatory in Holland he met Jan Oort who, as we saw earlier, gave his enthusiastic support for the work at Dover Heights on the structure of the Galaxy [58].

Oort and his colleague Henk van de Hulst were primarily interested in the structure and dynamics of the Milky Way and were eager to discuss the Bolton–Westfold paper on the evidence for a spiral structure. During WWII, van de Hulst had predicted that interstellar hydrogen emits radiation at a wavelength of 21 cm (or frequency 1420 MHz). For many years astronomers had theorised that a significant fraction of the total material in the local Galaxy consists of atomic hydrogen, left in interstellar space after the earlier formation of stars. Some of this hydrogen in the vicinity of very hot stars becomes ionised and can be observed optically, but the vast bulk remains as a cold, neutral and extremely rarefied gas dispersed throughout the Milky Way and invisible to optical telescopes. If van de Hulst's prediction was correct, the 21 cm radiation would provide a way to map the distribution and density of this interstellar hydrogen.

Oort and Alex Muller began the search for the 21 cm line but suffered a setback early in 1950 when most of their receiving equipment was lost in a fire. In the meantime Edward Purcell at Harvard and his PhD student Harold 'Doc' Ewen began their own search and were able to announce the detection of the hydrogen line in March 1951. Two months later the Dutch group were able to confirm the discovery. When news of the discovery reached Radiophysics, Chris Christiansen and Jim Hindman set aside their solar work and embarked on a crash program to assemble the necessary equipment at the Potts Hill field station. They were able to confirm the discovery, the product of almost two years work by the Harvard group, in a little over two months. At Purcell's suggestion the first papers from Harvard and Leiden on the hydrogen line were published in the same issue of *Nature*, accompanied by a cable from Pawsey announcing Sydney's confirmation. In contrast to the rivalry we have seen between the Radiophysics and Cavendish labs, the collaboration between the American, Dutch and Australian groups proved to be the first example of international cooperation in radio astronomy [59].

The discovery was a golden opportunity missed at Radiophysics. Pawsey learnt of van de Hulst's prediction while visiting Washington early in January 1948, as he reported to Bowen [60]:

> 'Mr Reber gave me some very valuable information. He tells me that there is an absorption line of hydrogen atoms on a frequency of 1420 MHz … This is derived from theory and from laboratory work which he thinks is published, but which I have not yet seen. It may be in the *Physical Review* and is probably by the Columbia University people. If this is correct, there may be very considerable interest in searching for either cosmic or solar noise absorption or emission bands at this frequency.'

However, both Bowen and Pawsey believed the detection of the hydrogen line was too much of a longshot to justify diverting resources away from other Radiophysics projects. They were proved wrong when Christiansen and Hindman were able to confirm the Harvard discovery in just two months. After such an illustrious start, this was the first major mistake, or rather major misjudgment, made by the Radiophysics group.

After visits to Utrecht and Eindhoven, the next stop for Bolton and Westfold was Paris where groups at the Ecole Normale Superieure and at the Institut d'Astrophysique were concentrating on solar observations. Most of the centres they visited had one or more Würzburg reflectors, former radar dishes which had been abandoned by retreating German forces near the end of the war (see Figure 6.2). The precision-engineered dishes could easily be converted from radar to radio astronomy at very little cost. Returning to Oxford, Bolton reported [61]:

> 'As regards publications – my trip so far has convinced me that in work done and in work being done we still have a considerable lead. But in work published and distributed to those who are most interested in it – we occupy a very bad last place. … Most important is to realise the great interest of the ordinary astronomer in the radio observations. This is quite clearly brought out in the Royal Astronomical Society's support for Lovell and Ryle and also in Holland where a national effort is being made in radio astronomy. … Our recent visit to Germany, Holland and France was I think a success from both the

> propaganda point of view and information gained. The greatest interest is quite definitely in Paul Wild's work – discrete sources are now taking a back seat!'

Westfold was also impressed by the reception they had received [62]:

> 'As Bolton has told you, we have just returned from an interesting and stimulating tour of Kiel, Leiden and Paris. All the astronomers in these countries are very keen on the prospects of radio astronomy and gave us some pretty strenuous sessions on what is being done in Australia and where things are going. We ourselves got great benefit from discussions on astronomical questions. I was encouraged to find some people interested in theoretical aspects of radio astronomy.'

Two months later Bolton and Westfold made their second tour of the Continent, beginning with the URSI General Assembly in Zurich. Founded in 1919, URSI consisted of six commissions each dealing with a particular branch of radio science and its applications. At its previous assembly in Stockholm in 1948 URSI decided to form a new commission with the title 'Extraterrestrial Radio Noise'. In recognition of Australia's major contribution to the field, David Martyn (Commonwealth Observatory at Mt Stromlo) was appointed inaugural president of the commission, with Joe Pawsey as secretary. At the Zurich meeting the name of the commission was changed to 'Radio Astronomy' and use of the word 'noise' was officially discouraged because of its misleading acoustic connotation. No doubt Pawsey lobbied delegates for the name change. As we saw earlier, Pawsey coined the term 'radio astronomy' in January 1948 and was eager to see its use widely adopted [63].

After Zurich, Bolton and Westfield toured Scandinavia, visiting Bengt Strömgren in Copenhagen, Hannes Alfvén and Bertil Lindblad in Stockholm, Svein Rosseland in Oslo and Olof Rydbeck in Göteborg [64]. Westfold recalled [65]:

> 'We chose those places because most of our understanding of astronomical matters had come from the writings of people in these institutions. We were gratified by the intense interest that was shown in our work, and the work of the Radiophysics Lab in general which, in many areas, seemed to be in advance of theirs. Indeed, we got the impression that the optical astronomers on the Continent were taking radio astronomy rather more seriously than their counterparts in England and Australia.'

At the end of October 1950 Letty Bolton boarded a ship to Australia, while Bolton began the North American leg of his tour. Originally, Bowen wanted him to spend three months in North America but this was cut back to a month, partly because the European leg had been extended by three months from the original plan and partly because currency restrictions in the US limited the travel funds available to about a month. Bolton's first stop was at the National Research Council in Ottawa (the Canadian equivalent of CSIRO), where Arthur Covington led a small group monitoring the Sun at centimetre wavelengths. After visits to Harvard, Cornell and Washington, Bolton flew to Pasadena on the west coast for the last stop of his tour where he met Walter Baade and Rudolph Minkowski at the Mt Wilson and Palomar Observatories. In 1948 the MWPO had commissioned the 200-inch Hale telescope, the largest and most powerful instrument in the world and, as we shall see in the next chapter, one that would play an important role in the further development of radio astronomy. Bolton could not have foreseen that, in exactly four years time, Pasadena would be his new home [66].

Notes to Chapter 5

[1] Stanley's personal notes, 12 March 1994, Kellermann papers, NRAO.

[2] Collis (2002), p. xv. See also the biography of Rivett (1972) by his son Rohan Rivett, and Chapter 9 of Schedvin (1987). It is interesting to note that David Rivett's father-in-law was Alfred Deakin, prime minister of Australia on three separate occasions.

[3] Rivett to Bowen, 22 September 1948, NAA file E2/3A.

[4] Quoted in Rivett (1972), p. 188.

[5] Bowen to Rivett, 1 October 1948 – see note [3]. See also Rivett (1972), p. 12.

[6] Westfold to Harrison, 24 November 1948, Westfold papers, Monash University Archives, MON 642, CSIR to CSIRO (1948–49) [1986/01 (8)].

[7] See Collis (2002), p. xvi.

[8] See e.g. O'Dea (1997). The Radiophysics Lab was one of 13 divisions within CSIRO. In 1951 it accounted for 7% of CSIRO's total budget [see *Aust. J. Science* **15** (1953) 164].

[9] See Robertson (1992), p. 31. Taffy Bowen noted: 'Finally, in our practical work we have just achieved a gratifying success in the design of a radar distance measuring equipment for civil aviation. This has been adopted for use on the Australian airlines and it is going into manufacture locally to the tune of three-quarters of a million pounds.' Bowen to Edward Appleton, 20 March 1950, NAA file F1/4/BOL/1. In 1954 the DME was made compulsory on all passenger-carrying aircraft in Australia, about ten years before similar systems were adopted in the United States and elsewhere. Research on air navigation at Radiophysics continued in the Microwave Navigation Group until 1955.

[10] Robertson (1992), p. 32. CSIRAC was used to generate astronomical tables, but there is no evidence that the Dover Heights or the other radio astronomy groups at Radiophysics made any significant use of the computer – see Wendt (2009), pp. 155–56.

[11] See Collis (2002), pp. 365–75, and Home (2005) for the science and politics of rainmaking in Australia.

[12] Christiansen in Sullivan (1984), p. 113.

[13] Wild (1972), p. 54. Pawsey lived in the suburb of Vaucluse, next door to Dover Heights, and occasionally dropped in on his way home – as Wild notes – infuriatingly near knock-off time.

[14] See Blainey (1966).

[15] Sullivan (2009), p. 143.

[16] A possible exception was Robert McNicol who gave a talk at the Radiophysics Lab in June 1949 entitled 'Radio work in Cambridge'. McNicol had returned to Australia after completing his PhD in ionospheric physics at the Cavendish Laboratory, but he was not a visitor nor a radio astronomer. RPL memo to staff, 15 June 1949, NAA file A1/1/1.

[17] Robertson (2010). Besides Pawsey, there were three other Australians in the 1932 Cavendish staff photo: Courtney Mohr, Harrie Massey and Marc Oliphant. Pawsey, Mohr and Massey were all graduates from the School of Physics, University of Melbourne, and Oliphant from the University of Adelaide. Courtney Mohr returned to Australia in 1947 where he later became the inaugural professor of theoretical physics at the University of Melbourne (and the graduate supervisor of this author). Unlike Mohr, Harrie Massey stayed in England and became a very influential figure in the British science establishment. The Massey Medal is awarded jointly every two years by the UK Institute of Physics and the Australian Institute of Physics. Mark Oliphant possibly had the most illustrious career of the four Australians. He rose to become Rutherford's right-hand man, before moving to the University of Birmingham. In 1948 he returned to Australia where he became the inaugural director of the Research School of Physical Sciences at the Australian National University. Oliphant ended his career as governor of the state of South Australia.

[18] See note [18] in Chapter 2. For a history of the Cavendish Laboratory see Crowther (1974).

[19] See McCready *et al.* (1947), *Proc. R. Soc. London* **A190**, 357, and Ryle and Vonberg (1946), *Nature* **158**, 339. See also Goss and McGee (2010), p. 104. The Radiophysics group suspected that Edward Appleton was the referee responsible for the delay of their paper. Appleton had been Taffy Bowen's PhD supervisor at Kings College in London in the early 1930s. In 1947 he won the Nobel Prize for Physics for his discovery of the ionosphere in the 1920s. Although a pillar of the British science establishment, Appleton was not held in high regard at Radiophysics. He was widely suspected of plagiarism and of obstructing other people's research in favour of his own – see Orchiston (2005b), p. 83.

[20] Ryle and Smith (1948), *Nature* **162**, 462–63. The Cassiopeia source was too far north to be observed from Sydney's latitude. The source was later identified with an unrecorded supernova that exploded in about 1700 AD. After leaving Cambridge Pawsey reported: 'Probably the chief thing of most immediate interest to you is that Ryle has just commenced taking observations of discrete sources of cosmic noise using his spaced aerial technique. He has shown that the source in Cygnus is unpolarised and he has discovered an equally intense source just below your northern horizon.' Pawsey to Bolton, 9 June 1948, NAA file C4659, Pawsey correspondence, part 8.

[21] Another connection was Ron Bracewell a young Radiophysics staff member who had been awarded a prestigious CSIR studentship in 1947 to study for his PhD under Ratcliffe. Bracewell volunteered to be the unofficial 'go-between' the two groups for exchanging information and news – see e.g. Goss and McGee (2010), p. 178. On returning to Radiophysics, Bracewell collaborated with Pawsey to produce the first textbook on radio astronomy – see Pawsey and Bracewell (1955).

[22] For the two letters quoted see Pawsey to Ratcliffe, 10 September 1946, and Ratcliffe to Pawsey, 17 September 1946, NAA file A1/1/1.

[23] Ryle to Bolton, 22 June 1948, NAA file F1/4/PAW, part 1. Bolton received the letter while at Pakiri Hill in New Zealand. Bolton briefly considered that the discrepancy might be caused by parallax due to Cambridge and Sydney being on opposite sides of the Earth: 'One rather fantastic possibility is that both measurements are correct and Cygnus is very close. It would however in that case be too small for a body of the required density to possess gravitational stability.' Bolton to Bowen, 15 July 1948, NAA file A1/3/14A.

[24] Pawsey to Bowen, 24 June 1948, NAA file A1/3/14A. Bowen forwarded Pawsey's letter to Bolton and urged him: 'As Pawsey says, the discrepancy in your and Ryle's

declination for the Cygnus source is somewhat disturbing and it is up to you to sort it out with Ryle as best you can.' Bowen to Bolton, 9 July 1948, same file.

[25] Bolton to Ryle, 12 November 1948, NAA file A1/1/1. See Sullivan (2009), p. 319 for a discussion of the Bolton–Ryle debate on the nature of Cygnus.

[26] In 1947 Cecil Powell at Bristol University discovered a new subatomic particle in cosmic ray showers known as the π meson. The particle had been predicted earlier by the Japanese theorist Hideke Yukawa, who proposed that the π meson mediates the strong interaction between protons and neutrons. Yukawa was awarded the Nobel Prize in 1949 for his prediction, followed by Powell in 1950 for his discovery of the particle.

[27] Pawsey to Ratcliffe, 12 November 1948, NAA file A1/1/1.

[28] Ratcliffe to Pawsey, 30 November 1948, NAA file A1/1/1.

[29] Pawsey to Ratcliffe, 17 December 1948, Sullivan papers, NRAO Archives.

[30] Ryle to Pawsey, 12 January 1949, NAA file A1/1/1. In the same letter Ryle noted: 'The problem is further complicated by Lovell's recent work and his wish to publish some of his results. While these do not relate directly to the Cygnus source it brings up the question of whether some account of recent work should not be published by all three teams.' Despite Ryle noting that Lovell's results had little relevance to Cygnus, he continued: 'The suggestion that we should like to make is that in the near future all three teams should write short separate notes for publication in 'Nature'. The three contributions should then be forwarded together for simultaneous publication in the same issues. It seems that apart from describing the work in the two hemispheres such a procedure would have the advantage that three independent observers using quite different techniques could give their own accounts of the phenomena and thus produce a more convincing story of the effects than if combined in a single account. In addition to being a convincing story (e.g. for the astronomers) it would make it clear that all three teams were obtaining important results (thus guarding against the hypothetical American).'

[31] Bolton to Ryle, 17 February 1949, NAA file A1/1/1.

[32] Ryle to Pawsey, 24 February 1949, NAA file A1/1/1.

[33] See note [30]. Significant parts of Ryle's handwriting in this letter are illegible. In contrast to Sydney's latitude, Cygnus passes almost directly overhead at Cambridge and Manchester, leading Ryle to refer to the observations as a 'normal-incidence experiment'. In his letter to Lovell proposing a joint experiment, Ryle stated: 'I do not believe [the Australian] result.' See Sullivan (2009), p. 325, note [34].

[34] See Ryle to Bolton, 17 May 1949, Sullivan papers, NRAO Archives, and Ryle to Pawsey, 28 September 1949, NAA file A1/1/1. See also Lovell (1984), p. 203. Pawsey replied (file A1/1/1) on 12 October: 'Bolton has been carrying out spaced receiver experiments on Cygnus similar to yours and his results so far are similar to yours, i.e. substantial differences in records at spaced sites. It looks like some relatively local effect. I do not think he has so far recognised a type of disturbance common at two sites though the type of fluctuations are similar at one time.' Ryle's final letter on the Cygnus fluctuations to Radiophysics appears to have been an undated handwritten note early in December 1949: 'We have now got some quite nice results in on spaced-aerial observations of the fluctuations in Cygnus.' Ryle to Bolton, Sullivan papers, NRAO Archives.

[35] Bowen to G. A. Cook, 8 November 1949, NAA file PH/BOL/5B, part 1.

[36] Secretary CSIRO to Minister-in-Charge CSIRO, 26 January 1950, NAA file PH/BOL/5B (travel), part 1. The Menzies government had been in office just over a month. In March 1950 Richard Casey was appointed Minister-in-Charge of CSIRO, a portfolio he held for ten years. Casey was arguably the best minister CSIRO has had in its history. Former CSIRO chairman Fred White has noted: ‘Casey, in the years between 1950 and 1960, became a patron and advocate for CSIRO to a degree quite beyond that normally to be expected of a Minister’ (White 1977, p. 67).

[37] See Hey *et al.* (1948), *Proc. R. Soc. London* A **192**, 425–45, and Reber (1948), *Proc. Inst. Radio Eng.* **36**, 1215–18.

[38] Oort to Bolton, 17 October 1950, Oort papers, Leiden.

[39] See Bolton and Westfold (1950a, 1950b, 1950c). It was Bolton’s fifth *Nature* letter in less than three years. The Australian papers had the title ‘Galactic radiation at radio frequencies: Part I. 100 Mc/s and Part III. Galactic structure’. A further six papers, Parts II and IV–VIII, with the same generic title were published over the period 1950–54. These papers reported most of the remaining research output by the Dover Heights group and will be examined in detail in the next chapter.

[40] At the time a widespread practice by Australian families was to post food parcels to their relatives and friends in Britain. In the correspondence between Radiophysics and the Cavendish (see previous section), Pawsey and Bolton noted on several occasions that they had posted food parcels to Ratcliffe and Ryle. Ryle in particular came from a wealthy and influential family, so the Radiophysics parcels were really more a goodwill gesture. See e.g. Pawsey to Ryle, 17 December 1948, NAA file A1/1/1.

[41] See Smith (1950), *Nature* **165**, 422–23, and Little and Lovell (1950), *Nature* **165**, 423–24. The latter was the first radio astronomy publication by the Jodrell Bank group.

[42] Pawsey to Lovell, 7 February 1949, NAA file A1/1/1.

[43] Bolton to Bowen, 1 April 1950, NAA file F1/4/BOL/1.

[44] Bolton (1982), p. 352.

[45] See Stanley and Slee (1950), Section 5. They submitted their paper to the Australian journal in November 1949, a month before the two English groups submitted their letters to *Nature*, but the Australian journal took six months longer to publish the paper.

[46] The house belonged to the geophysicist Sydney Chapman who was spending a sabbatical year at Caltech. Milne was best known for his model of an expanding Universe that differed from the standard (Einstein) model, in that the model did not assume the Universe began with a homogeneous distribution of matter. Following Milne’s sudden death in September 1950, Chapman was appointed as Westfold’s supervisor. Westfold to Pawsey, 23 October 1950, NAA file F1/4/WES.

[47] Bolton to Bowen, 14 April 1950, NAA file F1/4/BOL/1. Bowen replied on 10 May (same file): ‘Your letter about Hey prompts me to raise with him the question of whether he would like to come out to work in Australia. Both Joe and I have approached him before without success but from what you say we might succeed if we tried again …’.

[48] Bragg to Bolton, 2 May 1950, NAA file F1/4/BOL/1. Earlier, Ryle had written to Pawsey: ‘We are very much looking forward to seeing Bolton, and to hearing about some of

the more recent work at Radiophysics.' Ryle to Pawsey, 21 March 1950, NAA file A1/1/1. Bolton replied to Bragg who, in turn, agreed to extend Bolton's visit to three days. Bolton to Bowen, 18 May 1950, NAA file F1/4/BOL/1.

[49] Bowen to Bolton, 10 May 1950, NAA file F1/4/BOL/1.

[50] Bowen to White, 12 May 1950, NAA file PH/BOL/5B, part 1. A copy of Bragg's letter was sent to former CEO David Rivett who made clear his displeasure at Bolton's treatment. In White's view: 'I would feel inclined myself not to do anything about the matter. It would be better to suffer some injustice rather than to cause a permanent breach with the Cavendish.' White to Bowen, 30 May 1950, same file.

[51] Pawsey to White, 6 June 1950, NAA file PH/BOL/5B, part 1. White replied on 13 June (same file): 'I felt right from the beginning that Ratcliffe would have handled the matter otherwise. Ryle seems to be a very funny sort of chap.'

[52] Bolton to Bowen, 18 May 1950, NAA file PH/BOL/5B, part 1. Bolton gathered enough material to write a detailed report covering the Cavendish research on solar noise and the discrete sources. On leaving Cambridge, Bolton noted: 'I didn't get the opportunity of a private talk with Ratcliffe, in fact I didn't say goodbye to either Ratcliffe or Bragg. This may have been a mistake but I could hardly thank them for their kind reception and hospitality etc. after what had happened!' Bolton to Pawsey, 17 July 1950, NAA file F1/4/BOL/1.

[53] Bolton to Bowen, 31 May 1950, NAA file F1/4/BOL/1. Fenners is the home of the Cambridge University Cricket Club. Hoyle and Ryle had developed an intense dislike of each other. In his autobiography Hoyle (1994, p. 268) wrote of Bolton's visit: 'But it is an ill wind that blows nobody any good. I owed the start of a lifelong friendship with the Australian radio astronomer John Bolton to Ryle's acute dislike of anybody from outside visiting his own tightly controlled group.'

[54] It is interesting to note that in May 1947 Lovell was offered a chair in physics at the University of Sydney, with a salary more than double his Manchester one. Lovell turned down the offer and also a similar one from the University of Adelaide the following year. Radio astronomy at Jodrell Bank may have never developed if Lovell had accepted either offer – see Saward (1984), p. 135.

[55] See Lovell (1968) for the history of Jodrell Bank. Bolton made two lengthy visits to Jodrell Bank: 'When I arrived on my first visit, Bernard Lovell handed me a dog-eared school exercise book containing the mathematical formulation of the Hanbury Brown–Twiss intensity interferometer and asked me to see if I could find any errors. After a week of very long evenings I reported back that I could find no errors, but was at a loss for any physical understanding. The experimental proof of validity came later that year when the diameter of the Sun was measured …'. See Bolton (1982), p. 353.

[56] Hanbury Brown and Hazard (1951), *Mon. Not. R. Astron. Soc.* **111**, 357–67. Hanbury Brown joked about the radio noisy site at Jodrell Bank: 'In radio astronomy it is only too easy to ascribe cosmical significance to what is, in effect, activity in the local tramway system.' Hanbury Brown to Bowen, 30 April 1950, NAA file A1/1/1.

[57] See Hanbury Brown's autobiography (1991, p. 102). During the war Hanbury Brown had been a member of Bowen's airborne radar group. Bowen had a high opinion of him and tried unsuccessfully to recruit him to Radiophysics. Bowen to Bolton, 3 April 1950, NAA file F1/4/BOL/1. Hanbury Brown eventually came to Australia in 1962, though it was to the University of Sydney where he built the first full-scale intensity interferometer (see note [55]).

[58] At the time Oort had correctly predicted that comets originate from a reservoir of debris lying far beyond the Solar System. The reservoir is now known as the Oort cloud – see e.g. Katgert-Merkelijn (1997), p. xxiii.

[59] See Robertson (1992), p. 81. For an account of the detection of the 21 cm hydrogen line at Radiophysics see Wendt *et al.* (2008b).

[60] Pawsey to Bowen, 23 January 1948, F1/4/PAW, part 1. Several Radiophysics staff became interested in the 21 cm prediction, including Paul Wild who wrote two theoretical internal reports on the subject, but no attempt was made to detect the line.

[61] Bolton to Pawsey, 17 July 1950, NAA file F1/4/BOL/1. Bowen's predecessor as chief of Radiophysics, John Briton, had enquired about bringing a Würzburg aerial to Sydney late in 1945: 'We understand that there is a good possibility of sidetracking one of the German Würzburg equipments from the Royal Air Force. We would be very glad indeed to acquire one of these. We would set it up at our new field testing site at Georges Heights, Sydney, where it would be very useful for a number of purposes …'. Briton to G. B. Gresford, 6 November 1945, NAA file A1/1/1 [see Figure 3.2 for the location of the Georges Heights site]. However, nothing came of the proposal.

[62] Westfold to Pawsey, 18 July 1950, NAA file F1/4/WES.

[63] See Section 3.2. As well as Martyn, Pawsey, Bolton and Westfold, Jim Roberts from Radiophysics was the fifth Australian at the Zurich congress. Roberts was studying for his PhD at Cambridge, supervised by Fred Hoyle and supported by a CSIRO studentship. Later, he became one of Bolton's principal collaborators at Caltech and Parkes (see Chapter 7).

[64] For an account of early Swedish radio astronomy see Radhakrishnan (2006). A brief report and photo of the visit by Bolton and Westfold appeared in a Göteborg newspaper under the heading [my translation]: 'Researchers from Australia with Swedish radio astronomers' [NLA papers, Series 3, Press clippings]. Bolton reported: 'Since leaving Zurich I seem to have spent half my time giving talks and half in railway trains.' Bolton to Pawsey, 2 October 1950, NAA file F1/4/BOL/1.

[65] See Westfold (1994), p. 538.

[66] After his return to Sydney, Bolton became critically ill and was rushed to hospital. At first it was thought that he had contracted tuberculosis, but the diagnosis was changed to an acute bladder infection [Letty Bolton to author, 1 October 2009]. His lengthy illness delayed plans to build the so-called hole-in-the-ground telescope at Dover Heights – see Section 6.3.

Chapter 6

Consolidation and Competition: The Dover Heights Years 1951–54

In this chapter we examine the second half of the Dover Heights years, covering the period 1951–54. It was a time of consolidation that built on the successes of the late 1940s. A succession of larger Yagi arrays and improvements to receivers and electronics led to a significant improvement in the sensitivity and resolution of the sea interferometers. Similarly it was a period of increasing competition from other groups, both from within the Radiophysics Lab and from a number of emerging groups overseas.

In Section 6.1 we return to the source Cygnus A which, as we saw in Chapters 3 and 4, was the primary focus of the Dover Heights group during 1947–49. Unlike Taurus A, Centaurus A and Virgo A, all attempts to identify Cygnus A with an optical object turned out to be frustrating failures. Increasingly accurate positions for the source derived by Bernard Mills at Radiophysics and then Graham Smith at Cambridge finally led astronomers at Mt Wilson–Palomar to identify the source with a distant object that appeared to be two galaxies in collision.

In Section 6.2 we briefly examine the relationship between the Radiophysics radio astronomers and the outside world of media and public relations. In the late 1940s the Radiophysics Lab shunned any publicity, a legacy of its secret wartime activities. By about 1950 this attitude began to change when it was realised that the Lab’s achievements were being overlooked both in Australia and internationally. A new approach to promote and publicise the Lab’s activities reached its zenith at a major international congress held in Sydney in 1952. The congress made clear to the international delegates that Radiophysics was the world’s premier radio astronomy group.

Until the early 1950s the Dover Heights observing program was based largely on the technique of sea interferometry. As we see in Section 6.3, in 1952 the group branched out by building a large parabolic dish in the sandy surface of the field station. The dish was used to discover the exact position of the Galactic nucleus, an achievement that had been beyond the power of traditional astronomy. The discovery later helped to prompt the International Astronomical Union to define a new set of Galactic coordinates based on the new position.

Finally, in Section 6.4 we see that by 1953 the technique of sea interferometry had been exploited to its limit. The Dover Heights group needed to develop a new direction, but there was increasing competition from the other Radiophysics groups, all wanting to build new and increasingly expensive instruments.

*****

In Section 5.4 we described how early in 1949 Bolton and Westfold carried out a 100 MHz survey of the southern sky using the aerial system in Figure 5.7, producing a contour map of radio strength over the declination range +30° to –90°. A valuable byproduct of the survey was the discovery of a further six discrete sources. During Bolton's absence overseas in 1950, Gordon Stanley and Bruce Slee published [1] a summary of the data on the known discrete sources, which now numbered 22 (see Table 6.1). The positions and source fluxes for the four strongest sources Cygnus A, Taurus A, Virgo A and Centaurus A differed significantly from the crude values Bolton had published in 1948 (see Table 4.1), a result of the more accurate observations made during the New Zealand expedition. Approximate positions were given for most of the other weaker sources with right ascensions known to 1 minute accuracy and declinations to 1° accuracy. As can be seen from the last column in Table 6.1, the four strongest sources had been studied extensively. Some of the weaker sources were first detected during the few hours before dawn when levels of background interference were at their lowest and not all could be easily confirmed. As a result, sources with less than four records available were omitted from the table (numbers 3, 13, 14 and 16). The Stanley–Slee paper also broke new ground by publishing the first spectra of the four strongest sources over the range 40–160 MHz (see Figure 6.1). The spectra for Cygnus A, Virgo A and Centaurus A show a steep fall in intensity with increasing frequency. The fall is steeper than a similar fall for the unresolved background radiation. In sharp contrast Taurus A shows a very flat

Table 6.1: List of confirmed discrete sources detected at Dover Heights between June 1947 and October 1949 [adapted from Stanley and Slee (1950) p. 238]

Number & year of discovery [A]	Temporary designation	Intensity at 100 MHz [B] (Jy)	Angular width (arcmin)	Coordinates (epoch 1948)		Number of observa-tions
				RA	Dec	
1 – 1946	Cygnus A	12500	<1.5	19h 58m 14s	+40° 36´	320
2 – 1947	Taurus A	1850	< 6	05h 31m 30s	+22° 10´	80
4 – 1947	Virgo A	1250	< 5	12h 28m 06s	+12° 41´	100
5 – 1947	(Centaurus)	800	<30			10
6 – 1947	Centaurus A	1850	< 7	13h 22m 20s	–42° 37´	50
7 – 1948	Hercules A	200	<30	16h 50m	+05°	30
8 – 1948	Taurus C	300	<15	04h 38m	+28°	15
9 – 1948	Taurus B	600	<30	05h 32m	+24°	15
10 – 1948	Fornax A	200	<15	03h 11m	–36°	15
11 – 1948	Serpans–Cauda A	300	<15	18h 43m	+05°	6
12 – 1948	(Centaurus)[C]	200	<30			4
15 – 1948	(Leo) [D]	100	<30	11h 52m	+17°	5
17 – 1949	Scorpius A	200	<30			5
18 – 1949	Serpans–Cauda B	200	<30	18h 11m	–15°	5
19 – 1949	Sextans A	200	<30	09h 55m	–05°	4
20 – 1949	(Columba–Caelum)	200	<30	05h 01m	–36°	10
21 – 1949	Puppis A	300	<30	08h 18m	–42°	8
22 – 1949	Pictor A	300	<30	05h 18m	–44°	6

[A] Sources 3, 13, 14 and 16 are unconfirmed.

[B] Original units used were (watts m^{-2} (c/s)$^{-1}$) × 10^{-24} ≡ 100 Jy.

[C] Rises before Centaurus A, almost circumpolar at Dover Heights latitude.

[D] Rises just before Virgo A.

spectrum, which was later shown to be a feature of radio emission from a small class of supernova remnants. The paper gave the ‘possible’ optical identifications for Taurus A, Virgo A and Centaurus A, but otherwise made no attempt to suggest identifications for the other sources.

To conclude the paper, belatedly, Stanley and Slee commented on the Cygnus fluctuations and what they had known before anyone else:

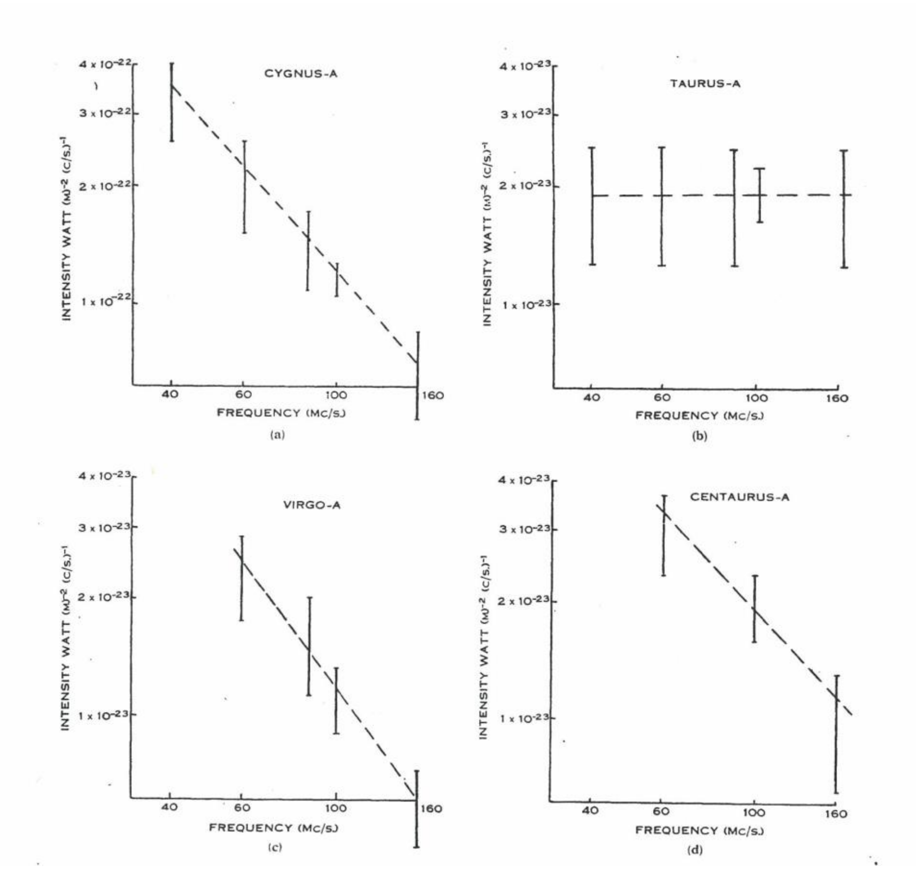


Figure 6.1. Spectra of the four strongest discrete sources where the error bars indicate the range of observed intensities. Measurements were made on Cygnus A and Taurus A at the five frequencies 40, 60, 85, 100 and 160 MHz. The measurements on the sources Virgo A and Centaurus A were made during daylight when the terrestrial noise fluctuations were too great to obtain results at 40 MHz. [after Stanley and Slee (1950), Fig. 4]

> ‘There are four features of the fluctuation phenomenon which would suggest an origin in the ionosphere:
>
> (1) The spaced aerial observations on Cygnus.
> (2) The annual variation in the Cygnus fluctuations.
> (3) The increasing degree of fluctuation with decreasing frequency.
> (4) Marked fluctuations in most cases at low altitude.
>
> The absence of fluctuations in some of the minor sources may be due to angular width. If the fluctuations are due to irregularities in the ionosphere it is likely that the effect would be more pronounced in the case of sources of small angular width. Recent measurements indicate that the source in Cygnus has an angular width of less than 1′ 30″ whereas the angular widths of a number of the minor sources are believed to be several minutes of arc. This suggestion may be compared with the “twinkling” of stars and the steady appearance of planets.’

6.1 Cygnus A Revisited: Galaxies in Collision?

As we saw in Chapter 4, in July 1949 Bolton, Stanley and Slee published optical identifications for three of their strong sources, but the identity of the strongest source Cygnus A had remained a mystery. The identifications created a fair amount of interest, but did not set the astronomical world on fire. The event that really caught the attention of astronomers was the identification of Cygnus A. In May 1949 Bernard Mills took up the challenge of measuring a more accurate position for the source. Mills had joined the Radiophysics Lab in 1942 after completing a degree in electrical engineering at the University of Sydney. After the war he spent time working on CSIRAC, Australia's first digital computer (see Section 5.2), but in 1948 Mills was forced to take extended leave after contracting tuberculosis. On his return to Radiophysics, Mills was persuaded by Pawsey to transfer to the radio astronomy group and to consider two possible projects – an attempt to detect the 21 cm hydrogen line predicted by van de Hulst (see Section 5.4) or to investigate the nature of the discrete sources, independent of the Dover Heights group. Mills recalled [2]:

> 'If I had been a trained astronomer and therefore aware of the possible great importance of the H line no doubt this would have been my choice, but I looked on it as merely a technical challenge, whereas I was intrigued by the mystery of the discrete sources and had no hesitation in choosing this option. This did ensure some friction within the group as John Bolton had made discrete sources his own, following his use of the sea interferometer to discover the first such source and to establish the existence of this class of object by finding several others.'

Mills and fellow electrical engineer Adin Thomas began observations on Cygnus in May 1949 at the Potts Hill field station (Figure 5.3). They used an interferometer, previously built for solar work, consisting of three Yagi aerials mounted at approximately 300 metre intervals in an east–west direction. Each aerial was connected through a coaxial switch to a pre-amplifier and then by cable to the main receiver. The operating frequency of 97 MHz was in the range of 40–200 MHz assigned to the Dover Heights group, but Pawsey thought that the two interferometer techniques were sufficiently different to justify the overlap.

Over a six-month observing period Mills and Thomas took painstaking care to minimise all sources of error. The position measured was a significant improvement on the Dover value, derived after the New Zealand expedition, with a reduction by a factor of 4 in the area of the error box:

Dover Heights:	RA	19h	58m	16s	Dec	+40°	36′
Potts Hill:	RA	19h	57m	36s	Dec	+40°	31′

Next Mills examined photographs of this region of the sky that Bolton had earlier received from Rudolph Minkowski, taken with the 100-inch Hooker telescope on Mt Wilson. Mills found a faint nebulous object very close to the measured position, which he assumed was probably a nearby object in the local Galaxy. The radio position differed from the object's position by only 2 sec in RA and 2′ in Dec. Before announcing a possible identification, Mills wrote to Minkowski to inform him of the close coincidence of the radio and optical positions and noted the previous discrepancy between the positions measured by the Dover and Cavendish groups [3]:

> 'For some time my colleagues and I have been observing the discrete source of radio noise in the Cygnus region, using a double aerial interferometer similar to that of Ryle. As you know a number of different positions have been quoted for this source in the past, illustrating the difficulty of making accurate measurements at radio frequencies … Mr Bolton has shown us your photographs of the region and we find that the source can quite reasonably be identified with an object which you have marked as an extragalactic nebula … How certain is it that the object in question is extragalactic?'

Mills hoped that Minkowski would re-examine the nebulous object, possibly with the new and more powerful 200-inch Hale telescope which had been commissioned the year before. To Mills' disappointment, Minkowski replied that on the evidence available the object appeared to be an external galaxy at great distance. He firmly advised against announcing the object as the Cygnus source [4]:

> 'It is gratifying to see the gradual improvement of the determination of position. Ultimately, this should make it possible to investigate the spectra of the brighter stars within the area outlined by the probable errors. But, in a field as rich as the Cygnus field

> this does not yet seem to be a reasonably promising method of attack. From the astronomical side, the most useful bit of work would be the search for a star with high proper motion … I do not think that it's permissible to identify the source with one of the faint extragalactic nebulae in the area. These nebulae are undoubtedly extragalactic, at a distance of the order 10^7 parsec or more … This leaves either a bright star at a very large distance or an intrinsically faint star nearby. The search for a proper motion star should be the best way to decide between the alternatives.'

Mills was now confronted with the same dilemma that Bolton had faced early in 1949 with the Centaurus and Virgo sources. It seemed highly improbable that a galaxy at such a great distance could radiate such an extraordinary amount of radio energy. Mills decided against publishing such a claim. In December 1950 Mills and Thomas submitted their results to the Australian journal and played safe by concluding [5]: 'On the evidence presented it would seem most likely that the source is located in some nearby faint star of abnormal properties. A proper-motion search of the field would therefore be of the greatest interest.'

Radio astronomers elsewhere were now on the track of the elusive source. At Jodrell Bank, Hanbury Brown and Hazard used the above-ground 67 m paraboloid (Section 5.4) to measure a position for Cygnus, but the errors bars were too large for the position to be of interest to Minkowski. In August 1951 Graham Smith, carrying out research for his doctorate at Cambridge, announced new positions for the four sources Cygnus, Cassiopeia, Taurus and Virgo (Centaurus was too far south to be observed from Cambridge). Smith made observations with two interferometers: the Long Michelson interferometer used to conduct the first Cambridge sky survey (see Figure 5.5) and a second consisting of two parabolic Würzburg dishes operating at 80 and 215 MHz (see Figure 6.2). In the meantime Mills had moved to the Badgery's Creek field station (Figure 5.3), south–west of Potts Hill, where he established a new form of broadside interferometer (see Figure 6.3). Mills used the array to measure accurate positions for Cygnus and the five sources in Centaurus, Virgo, Hydra, Taurus and Fornax [6]. The Radiophysics and Cavendish positions for Cygnus were now in close agreement:

Figure 6.2. Graham Smith with the Cambridge interferometer, consisting of two former wartime Würzburg dishes. Smith used the interferometer in 1951 to measure a precise position for the Cygnus A source as part of his PhD thesis. It was the beginning of a distinguished career for Smith. In 1982 he was appointed Britain's Astronomer Royal. [courtesy: Graham Smith; credit: Bruce Elsmore]

Revised Mills: RA 19h 57m 44±2.5s Dec +40° 34±1.5′

Smith: RA 19h 57m 45.3±1s Dec +40° 35.0±1′

More importantly, the error box for Smith's position was almost twenty times smaller than the Mills–Thomas one that had originally been sent to Minkowski. Smith wrote to Walter Baade at Mt Wilson (Minkowski's close colleague), encouraged by Roderick Redman, director of the Cambridge University Observatory [7]:

> 'I have just completed a series of measurements of the positions of four major radio stars, and I have been discussing with Professor Redman the problem of attempting to identify them with visible objects. The accuracy of location has been considerably improved by new interferometric techniques, and he suggested that you might consider it worth while to investigate those positions with the 200-inch telescope.'

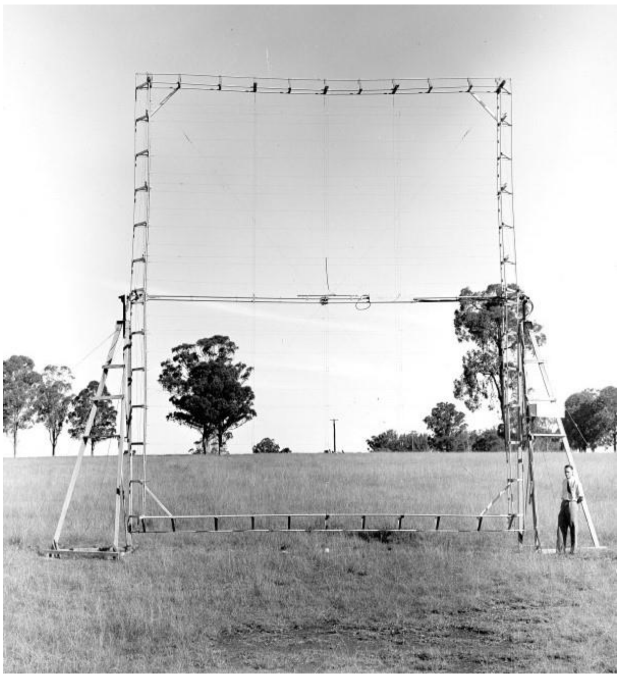


Figure 6.3. One of the three broadside antennas erected at the Badgery's Creek field station in late 1949. The three-element interferometer operated at 101 MHz and was positioned along an east–west baseline. In 1950 Mills used the interferometer with baselines of 60 and 270 m to obtain the positions of 77 discrete sources, including a new and more accurate position for Cygnus A. Each of the broadside antennas could be rotated in elevation on its horizontal axis, allowing a transit survey of the whole sky. [courtesy: RAIA]

Baade replied [8]: 'Your latest measures have reduced so much the uncertainties in the positions of the radio stars in Cygnus and Cassiopeia that a serious effort should be made to identify them, if possible, with visible stars.' Baade did not include Taurus or Virgo in this 'serious effort' because he believed that the identifications made by the Dover Heights group two years earlier were correct for Taurus and probably correct for Virgo:

> 'Regarding the Taurus source I have no doubt that the identification with the Crab nebula – the remnant of the supernova of 1054AD – is the correct one. Not only is the Crab nebula astrophysically in a class by itself but it also seems to differ from the common radio sources in respect to the wavelength dependence of its radiation (Bolton).'
>
> 'The radio source in Virgo coincides with one of the brightest galaxies of the Virgo cluster of nebulae, NGC4486 + Messier 87. This coincidence could of course be accidental. But Messier 87, a giant ellipsoidal galaxy, is unique among all the galaxies of its kind on account of a most unusual feature: a huge, thin jet of matter emanating from

> its nucleus. The nature of this jet is a complete mystery at present. Nonetheless, one begins to wonder whether the coincidence of the radio source and Messier 87 is merely accidental.'

Baade noted that he would examine the colour of stars in the vicinity of the radio positions, particularly their behaviour in the infrared, while Minkowski would take spectrograms of the same stars in the hope that the radio star might show an unusual spectrum: 'Both lines of attack are of course straight gambling and there is every indication that the identification of the radio sources with visible stars may be very difficult.'

Two months later Baade could report [9]:

> 'I would like to let you know that my search for the Cassiopeia radio source at the 200 inch has turned up an exceedingly interesting object close to your measured position. It is an emission nebulosity 2.8 minutes of arc long of a most abnormal type. In fact the only nebulosity with which it can be compared in its intricate structure is the well known Crab nebula! … Although the present data do not yet establish the identity of radio source and nebulosity the coincidence of the radio source with a very abnormal astronomical object appears certainly suggestive.'

Cygnus remained the only one of Smith's four radio sources with accurate positions yet to be identified. After many hours of observation with the 200-inch Hale telescope, Baade and Minkowski became convinced that the Cygnus source was the very same nebulous object proposed by Mills and Thomas two years earlier and which Minkowski had dismissed. Next came the major surprise. An analysis of the faint light from the object showed sharp emission lines greatly shifted towards red wavelengths, indicating that the Cygnus source was at the extraordinary distance of 1000 million light-years. The Mills–Thomas identification had been correct all along. If Minkowski had trusted their Cygnus position, the credit for this remarkable discovery might well have gone to them. Later, in their paper giving the optical identification, Baade and Minkowski added a footnote justifying their actions [10]:

> 'This coincidence was already noted in 1951 by Mills and Thomas … but it seemed unlikely at that time that a distant galaxy could be the radio emitter. Moreover, the

> coincidence established by them was not convincing, since, besides the nebula in question, three of the brighter members of the cluster fall into the area defined by the uncertainty of the position. Minkowski therefore wrote Mills that he did not think it was permissible to identify the source with one of the faint extragalactic nebulae in the area and emphasized that what was wanted was a more accurate radio position. The accuracy of Smith's position was needed to make the identification among the cluster members unambiguous.'

In his later years Mills did not hold a grudge [11]:

> 'I could not really blame Minkowski for dismissing our result, because three positions of the source had been published previously, all in wild disagreement and in disagreement with ours; the radio measurements of obviously ignorant newcomers were clearly not taken seriously, especially when in conflict with the conventional wisdom. However, the whole episode marked the beginning of my development of a healthy scepticism toward authoritative pronouncements and the confidence to rely on my own judgment …'.

The Palomar observations continued and by May 1952 Baade and Minkowski were able to resolve the object into two bright condensations consisting of a bright central region surrounded by much fainter outer parts of elliptical outline. If the distance to the object provided an extraordinary surprise, so too did the apparent nature of the Cygnus source [12]:

> 'At first sight, this nebula is a very curious object which seems to defy classification. The clue to a proper interpretation lies in the fact that it has two nuclei which are tidally distorted and that hence we are dealing with the superimposed images of two galaxies. Both are late-type systems, judging by the low density gradients … Actually, the two systems must be in close contact because of the strong signs of tidal distortions which the nuclei show. This suggests that we are dealing with the exceedingly rare case of two galaxies which are in actual collision.'

An astronomical traffic accident of such violent proportions had never been detected before. Baade and Minkowski explained how the collision could generate intense radio emission [13]:

> ‘As far as the stars of the colliding systems are concerned, such a collision is an absolutely harmless affair. The average distance between two stars is so large that the two galaxies penetrate each other without any stellar collisions. The situation is very different for the gas and the dust imbedded in the two systems. Because of the much shorter free paths of the gas and the dust particles, the collision of the two galaxies means a real collision of the imbedded gas and dust, which are heated up to very high temperatures, since the collisional velocities range from hundreds to thousands of kilometres per second. It is obvious that this behaviour of the gas and dust provides a beautiful test of our hypothesis that the two galaxies which we identify with the radio source Cygnus A are actually colliding …’.

Knowing the distance to Cygnus and the flux received, and assuming the emission is isotropic, Baade and Minkowski were able to calculate the total energy emitted in the radio region as 8×10^{42} ergs/sec. They concluded: ‘The source of energy for the radio emission may be the relative kinetic energy of the colliding nebulae, which is of the order of 10^{59} ergs for a relative velocity of 500 km/sec.’

As we noted in Chapter 2, Karl Jansky and Grote Reber suggested that the Galactic radio emission arose from the scattering of energetic charged particles – electrons and positive ions – moving freely in interstellar space. With the discovery of the first discrete sources, Bolton had speculated that much of the radio emission might come from pre-main sequence or post-main sequence stars. During the late 1940s and early 1950s a number of theoretical papers attempted to explain the mechanism responsible for the radio emission from discrete sources. A survey of these theories is beyond the scope of the present thesis [14]. However, we can note that none of these theories seemed capable of explaining the prodigious amount of radio energy emitted by peculiar extragalactic objects such as Cygnus.

The collision theory was widely adopted as the correct mechanism for other extragalactic sources such as Centaurus and Virgo. Some astronomers, including Martin Ryle, claimed that the theory provided strong evidence in favour of the big bang cosmology. Soon after the big bang, when the Universe was in a very compact state, collisions between pairs of galaxies were probably commonplace. It was argued that the current population of extragalactic sources was providing a ‘window’ back to the very early epoch of colliding galaxies. However, the idea was soon shown to be untenable. Not even the energy generated by galactic collisions seemed enough to account for the intense radiation. By 1955, three years after the announcement by Baade and Minkowski, most astronomers had abandoned the collision theory of distant radio sources [15].

The mechanism to emerge to account for the intense emission from radio sources was named after a new type of laboratory particle accelerator – the synchrotron which accelerates charged particles to relativistic energies, confined by a strong magnetic field. In 1947 a synchrotron designed by the General Electric Company in the US produced a new and unexpected blue light emitted by the electron beam. In 1950 the physicists Hannes Alfvén and Nicolai Herlofson in Stockholm, and independently Karl-Otto Kiepenheuer in Freiborg, suggested that synchrotron radiation was the principal mechanism for radio emission from discrete sources [16]. The idea did not find much immediate support because astronomers were convinced that the correct mechanism must involve some form of interaction between pairs of charged particles, rather than the interaction of individual particles with a magnetic field. The idea was however taken up in the early 1950s by the Russian theorists Vitaly Ginzburg and Iosif Shklovsky who independently worked out the theoretical formalism of the synchrotron mechanism. Whereas the Alfvén–Herlofson theory had been applied to stars, the Ginzburg–Shklovsky theory applied to galaxies. Their papers were published in Russian in relatively obscure journals which significantly delayed their arrival and acceptance in the West. It is interesting to note that both Alfvén and Ginzburg were subsequently awarded the Nobel Prize for Physics, in 1970 and 2003 respectively, though there was no mention of synchrotron radiation in either of their citations [17].

Caltech theorist Jesse Greenstein dated a conference at Jodrell Bank in June 1955 as the time when consensus was finally reached that synchrotron radiation was the correct mechanism [18]:

> ‘The 1955 IAU Symposium was probably radio astronomy’s coming-of-age party. It was quite an international meeting which brought definitive agreement that non-thermal, electron-synchrotron radiation dominated strong radio sources. The Ginzburg–Shklovsky

> model triumphed. Cosmic-ray electrons at relativistic energies (although rare in our Galaxy) radiated copiously in the magnetic fields of radio sources, from X-rays to radio frequencies … Thermal radiation from ionised gas clouds, or galaxies in collision, proved too small. Thus, 1955 marked the realisation that enormous violence dominated the cosmos.'

Although the galactic-collision mechanism turned out to be incorrect, the optical identification of Cygnus in 1952 by Baade and Minkowski proved to be a major milestone in the development of radio astronomy. After the Sun and the supernova remnant Cassiopeia, by astronomical standards our near neighbours, Cygnus is the next strongest radio source, even at the extraordinary distance of 1000 million light-years. Much weaker sources could easily be detected with the simple aerials in use during these early days of radio astronomy. As we noted at the end of Chapter 4, the identification of the Centaurus and Virgo sources with extragalactic objects by Bolton, Stanley and Slee in 1949 opened up the possibility of radio astronomy being able to reach much further out into the Universe than traditional astronomy. Baade and Minkowski clearly recognised this possibility [19]:

> 'Cygnus A is without doubt an object of exceedingly rare type. But its intensity is so high that at a ten times larger distance it would still be an easily observable source. At such a distance it would cease to be an optically observable astronomical object; and even at a distance of only twice that of Cygnus A recognition as a peculiar nebula and observation of the spectrum would become very difficult. Thus a large volume of space is easily accessible to radio observations but is practically or entirely beyond the limit of astronomical work, even with the largest telescope. The number of observed or observable sources in this volume cannot be determined. It may be sizable, and it would be no contradiction to any known fact if the majority of the unidentified sources should turn out to be of this type. Whether this is so, only the future can decide.'

Their prediction turned out to be correct. The discovery during the early 1960s of remote quasi-stellar sources (quasars) – in which John Bolton played a leading role (see next chapter) – pushed back the known boundaries of the Universe and led to a revolution in modern cosmology.

6.2 Coming of Age – The 1952 URSI Congress in Sydney

In Chapter 4 we noted that, during the expedition to New Zealand in mid-1948, Bolton and Stanley had shunned the interest in their work by the local press. The visits by reporters to the site at Pakiri Hill were seen as an unwelcome distraction and disruption. Talking to the press was considered equivalent to bragging about the importance of their research, not the sort of behaviour expected of a scientist. Bolton went so far as to refer to the reporters as 'a menace' [see note 12 in Chapter 4]. In this section we briefly review how this attitude at Radiophysics to the press and other media changed during the late 1940s. By 1952, when Sydney hosted the General Assembly of the Union Radio Scientifique Internationale (URSI), the Radiophysics Lab was actively encouraging media stories about its radio astronomy and its other research programs.

The relationship between the Radiophysics Lab and the British scientific establishment did not get off to a good start. As discussed in Section 3.1, the first radio astronomy paper from Radiophysics was a letter to *Nature* in February 1946 by Joe Pawsey, Ruby Payne-Scott and Lindsay McCready reporting that sunspots were the source of intense bursts of radio emission from the Sun. As an indication of how radio astronomy was still in its infancy, the letter contained just four references to earlier work – the papers by Jansky and Reber, and the wartime reports by Stanley Hey in England and Elizabeth Alexander in New Zealand. Several newspaper reports of the Radiophysics discovery appeared in England and the United States, including mention of the confidential reports by Hey and Alexander. However, there was a problem – even though the war had ended and the contents of the two confidential reports were widely known, both reports were still classified secret. Sir Edward Appleton wrote from London to CSIR head office condemning the disclosure of the two reports and requested an apology. It was left to Taffy Bowen to humbly write to Archibald Hill, a senior figure at the UK Department of Scientific and Industrial Research [20]:

> 'We have just had a note from Sir Edward Appleton referring to the fact that in a recent letter to 'Nature' from this Laboratory reference was improperly made to two confidential reports. We regret very much that this has occurred and wish to apologise for not seeking prior permission from the authorities concerned.'

> ‘Our excuses if they can be given at this late stage are that, on the one hand, we were most anxious to acknowledge the priority of the British and New Zealand work, and, on the other, we were misled by the fact that while the contents of the two reports had become common knowledge, the reports themselves remained classified. I sincerely hope that this omission on our part can be overlooked and I will see that it does not occur again.’

A similar incident occurred late in 1947. A year earlier, radar operators in Hungary and the United States had been the first to detect radar signals bounced off the Moon, however it was a Radiophysics group that achieved the first results of significant scientific value. Frank Kerr, Alex Shain and Charles Higgins began their own radar experiments using a powerful transmitter installed at the overseas broadcast station ‘Radio Australia’ at Shepparton in Victoria, in conjunction with a receiving station at Hornsby near Sydney (Figure 5.3). The group succeeded in registering echoes from the Moon and, by analysing the modulation of the return signal, were able to deduce some of the properties of the lunar surface (later confirmed during the Apollo 11 mission).

A reporter in Shepparton picked up the story and several newspaper reports appeared in November 1947, some containing a number of factual errors. Rather than welcoming the publicity, the CSIR chief executive David Rivett was scathing in his criticism of the reports [21]:

> ‘Don’t worry about the news hawks. After all, people probably think it is a matter of tremendous scientific importance to get an echo from the Moon. If only the reporters had described it as noises from the Moon, created, presumably, by the tom toms of its inhabitants, you would all have been regarded as really great men. Has anybody, by the way, yet asked you who makes the noises in the Sun?’

In contrast to the unwelcome intrusion of the popular press, the Radiophysics Lab faced the opposite problem in the professional literature. In another illustration of the ‘tyranny of distance’ noted earlier, the Radiophysics contributions were often overlooked or devalued. As one example, early in 1948 the prestigious British journal *Proceedings of the Institution of Radio Engineers* published a review of progress in radio science the previous year, including solar and galactic noise, but failed to make a single reference to Radiophysics. Similarly, a popular account of radio astronomy by the Cambridge astronomer Michael Ovenden, published in the widely read *Science Progress*, made no mention of the work at Dover Heights. Bowen expressed his frustration [22]:

> ‘I realise that there is nothing worse in scientific work than cries of ‘we did it first’, but I am sure you will understand that we are having a difficult time keeping radio work going in this rather distant outpost and it is a bit hard to find later work elsewhere getting the credit. I realise that distance and the difficulties of publication are the basic reason for this but we are attempting to overcome it by giving as wide a distribution as possible to our papers.’

‘Personally I think we are pestered by enough radio stars on this earth without the CSIR finding others in the skies. But I must admit I like the discovery that the heavenly one is hissing the earthly ones. I’ve often felt that way myself.’
— Columnist in the *Sydney Morning Herald*, October 1948.

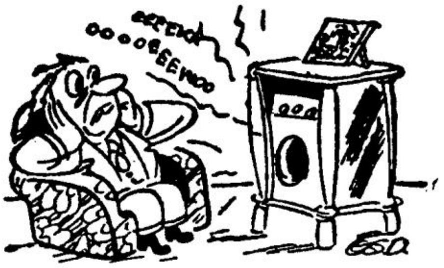


Figure 6.4. A composite image where the text is from the *Sydney Morning Herald* in October 1948, the first Australian newspaper to regularly publish articles on radio astronomy. The sketch is from the periodical *Smith’s* in a December 1948 article on the ‘Sad fate of radio stars’. The article noted that Cygnus could be a star near the end of its life, no longer visible in the optical, but still emitting radio: ‘Maybe the big noise in the Swan is really only a little chap, beyond telescope or photography, but still able to kick up a noise on the radio before he passes out.’ [courtesy: Bolton papers, National Library of Australia]

The earlier reluctance to publicise the activities at Radiophysics now gave way to active promotion of its research (see e.g. Figure 6.4). In 1949 Bowen commissioned an 18 minute documentary showcasing eight main research areas, including moon echoes, rain making, electronic computing, radar aids to air navigation and, of course, radio astronomy. Radiophysics staff travelling overseas were encouraged to take along a copy of the film. Bowen himself showed the film at a meeting in June 1951 of the British Astronomical Association in London. Feature articles on radio

Figure 6.5. Two photos from the series taken by *Life* magazine photographer Fritz Goro during his visit to Sydney in July 1951: (above) At Dover Heights with the 4.8 m dish on its equatorial mount. A colour version with a red dawn sky in the background was the main image used in the *Life* feature article on radio astronomy. (below) John Bolton inside the blockhouse (the photo was not included in the article). [courtesy: *Life* magazine]

astronomy also began to appear in popular magazines, both local and overseas. The highlight was a feature in September 1951 in the leading American *Life* magazine, under the title ‘New “Ears” are Huge and Costly’, which included photos of Potts Hill and Dover Heights (see Figure 6.5) [23].

The event that really boosted the growing public profile of the Radiophysics Lab was the Tenth General Assembly of the Union Radio Scientifique Internationale (URSI) held in August 1952. As we saw in Section 5.4, a principal aim of Bolton’s tour of Europe was to represent Radiophysics at the URSI General Assembly in Zurich in August 1950. At the meeting David Martyn (Commonwealth Observatory at Mt Stromlo) was the president of the newly-formed commission on Radio Astronomy, with Joe Pawsey as its secretary. At the Zurich meeting Martyn and Pawsey successfully lobbied to have the next general assembly held in Sydney. It was a coup of great significance, the first time any major international scientific organisation had decided to meet outside Europe or North America. The decision was a tribute not only to Australia’s leadership in radio astronomy, but also to the strength of Australian radio science as a whole.

Over sixty delegates from thirteen countries attended the congress, with a large number of local delegates (see Figure 6.6). Although radio astronomy was only one of seven URSI commissions, about one third of the delegates signed up for the radio astronomy program. Radiophysics hosted the event, while the meeting itself took place in the nearby Department of Electrical Engineering which had a sufficient number of lecture theatres to accommodate the various sessions. A concert by the Sydney Symphony Orchestra in the university’s Great Hall opened the proceedings and over the next two weeks the delegates were treated to a round of official receptions, a tour of the city and its beaches and, of course, a harbour cruise. Official tours were arranged to Potts Hill and to Dapto on the south coast (see Figure 5.3), while other smaller informal visits were made to other field stations (though there is no record of a visit to Dover Heights). A weekend trip to Canberra included a visit to the fledgling Australian National University and to the Mt Stromlo Observatory, with Martyn acting as proud host [24].

Figure 6.6. The URSI General Assembly held in Sydney in August 1952 was the first international scientific conference held outside Europe and the United States. (above) Joe Pawsey (right) and Taffy Bowen extend a shipboard welcome to Sir Edward Appleton, the president of URSI. (below) Bolton with Robert Hanbury Brown (right) from Jodrell Bank and two other delegates. [courtesy: RAIA]

The radio astronomy program was divided into four sections dealing with solar studies, the physics of ionised gases, the 21 cm hydrogen line, and the discrete sources. The five talks on discrete sources were given by Graham Smith (Cambridge), Robert Hanbury Brown (Jodrell Bank) and, from Radiophysics, Bernie Mills, Alex Shain and Bolton. The optical identification of Cygnus with a distant extragalactic object had radically altered the landscape for discrete sources. Bolton no longer felt compelled to argue that the objects identified with Centaurus (NGC 5128) and Virgo (M87) must be within the local Galaxy. Both were now considered 'provisional' extragalactic objects, in line with increasing evidence from optical astronomers that they were indeed, like Cygnus, pairs of colliding galaxies. The prevailing view that the discrete sources were a new class of radio 'star' – optically dim and relatively close – was changing fast. There were now (see note [12]) seven sources where the optical identifications were fairly certain: three supernova remnants in the Galaxy, three peculiar galaxies, and one 'normal' galaxy. Bolton was given the task of summarising the radio astronomy program in an article written for the British astronomy magazine *The Observatory*. For the section on discrete sources he concluded: 'It seems that the term radio "star" may be a misnomer' [25].

The success of the URSI Congress was very much a coming of age for the Radiophysics Lab. The international delegates were impressed by the size and calibre of its staff, the well-equipped laboratories and workshops, and the breadth of its research program at the various field stations in and around Sydney. Bowen basked in the Lab's achievement [26]:

> 'We are going round with something of a glow at the present time as a result of the stream of letters that are coming in from departing delegates expressing their appreciation of the show that was put on. It is quite clear that they will remember it for a long time to come and we will benefit immeasurably as a result of it.'

For most of the delegates, the scale of the activities at Radiophysics dwarfed their own small university or observatory programs, which operated on shoestring budgets during the postwar years of austerity in Europe. One of the most senior delegates to make the voyage to Australia was Jack Ratcliffe who, as we saw in the previous chapter, was the nominal head of the Cambridge radio astronomy group. Ratcliffe was so impressed by the Radiophysics facilities that he was concerned that Australians would no longer be interested in coming to the Cavendish Lab [27]:

> ‘I do hope that you can continue to spare an occasional man to come and work with us. We value our Australian contacts very much and it does us good to have people from overseas in the Laboratory. Without the help of the Dominions’ students we should not be able to keep our work, and particularly our ionospheric work, running at its present level. Please help us with an occasional PhD student for three years, or a more senior man for a shorter time.’

The tide was turning from when it had been almost mandatory for a young Australian scientist to spend time studying at a British university. Bowen sent an extract of Ratcliffe’s letter to Fred White, who commented:

> ‘I can well imagine, now that he [Ratcliffe] has seen Radiophysics, he perhaps wonders why we bother to send our students to Cambridge or, in fact, to any other centre in the United Kingdom interested in radio. I know that he was very much impressed with your facilities and said quite frankly they exceed his. However, there are many other virtues in a young man having experience in England and in one of the older universities, and I for one would certainly advocate sending our younger men to Cambridge occasionally.’

At a business meeting during the congress the URSI Executive Committee called for special reports to be prepared on four subjects – meteors, the distribution of radio emission across the solar disc, interstellar hydrogen, and the discrete sources. For the fourth subject, the Executive appointed a sub-committee consisting of the four ‘young Turks’ – Smith, Hanbury Brown and Mills, with Bolton as chair. The fifty-six page report was completed just over a year later, in September 1953. Although it was published by the URSI General Secretariat in Brussels, rather than in a peer-reviewed journal, the report was the first comprehensive review of the field. The report was divided into eight sections dealing with a historical overview; optical identifications; source surveys and the general background radiation; scintillations and refraction; the detection of sources and the problem of confusion; the determination of positions of sources; and the determination of angular widths. The introduction began with a generous acknowledgment [28]:

> 'The discovery by Hey, Parsons and Phillips (1946) of short period fluctuations in the intensity of extra-terrestrial noise from a small region in the constellation of Cygnus opened a remarkable chapter of modern astronomy … The fluctuations, or scintillations as they are now called, which led to the discovery of the first discrete source, have since been shown to be due to irregularities in the ionosphere. Thus Hey's pioneer discovery had led not only to knowledge of new types of astronomical objects, but has provided new methods of investigating the conditions in the ionosphere.'

As a clear indication of how the three main centres dominated the field, the report's bibliography listed a total of 63 papers published by: the Radiophysics Lab (38% of all papers), the Cavendish Lab (30%), Jodrell Bank (23%) and Other groups (9%). Similarly, the British and Australian journals accounted for the great majority of papers: *Nature* (30%), *Aust. J. Scient. Res.* (30%), *Mon. Not. R. Astron. Soc.* (10%), *Proc. R. Soc. London* (8%) and Others (22%) (see [29]).

6.3 A Hole-in-the-Ground: Discovery of the Galactic Nucleus

Late in 1951 the Royal Society of New South Wales, Australia's oldest learned society (founded 1821), awarded Bolton its Edgeworth David Medal, citing 'his outstanding contributions in the field of radio astronomy'. Named after the prominent Australian geologist and Antarctic explorer, the medal was awarded to promising scientists under the age of 35 and would be the first of many Bolton received over his career. Joe Pawsey wrote the nomination [30]:

> 'Australian research in radio astronomy over the past few years has represented a major contribution to the science of astronomy. In this Bolton has played an outstanding part. I consider his scientific contributions over the past few years to be materially greater than any other young Australian physicist, mathematician, astronomer or meteorologist of whom I know.'

Bolton expressed his gratitude to Fred White at CSIRO head office [31]:

> 'Thank you very much for your letter of congratulation which I value as much as the award of the medal itself. I should like to say that I regard the award as an award to a team as I have been extremely fortunate in having as assistants two very able men to

> whom a forty hour week means nothing. Our results have been mainly due to Stanley's initial design of equipment and to Slee's persistence in improving equipment performance and making tedious observations. I hope that we shall be able to continue the past standard of research.'

Bolton's research was also gaining recognition where it mattered most. When he joined Radiophysics in September 1946, Bolton began on the lowest rung of the research officer level, but with a series of double and triple annual increments he had rocketed up the research ladder. In July 1952 Bolton was promoted to the grade of Senior Research Officer (SRO) at a salary more than double that from September 1946. Barely 18 months after his promotion, Bolton was again promoted to the next grade of Principal Research Officer (PRO). At the age of 31, he became the youngest officer to be appointed to this grade in CSIRO [32].

After returning from his overseas trip in 1950, Bolton decided on a new line of attack. As we have seen, the observational program at Dover Heights since 1946 had been based on the technique of sea interferometry. The one exception was the sky survey carried out by Bolton and Kevin Westfold in 1949 using the nine-Yagi array mounted on the roof of the blockhouse (see Figure 5.7). During his visit to Jodrell Bank, Bolton had been greatly impressed by the 67 m (220 ft) diameter above-ground parabolic dish. Bernard Lovell had built the dish in 1947 with the aim of using radar to study the showers of charged particles produced by cosmic rays, but then converted the instrument to radio astronomy. In 1950 Robert Hanbury Brown and Cyril Hazard used the dish to detect radio emission from the Andromeda galaxy.

Bolton decided to build a similar radio telescope, but rather than suspending the aerial above ground using steel poles and guy ropes, the dish would be dug into the sandy soil at Dover Heights. Bolton decided to carry out the work in secret, fearing Joe Pawsey would disapprove and veto the project. A site at the northern end of the field station was chosen, out of view to any casual visitor. Over a three-month period late in 1951 the Dover team spent their free time with shovels and wheelbarrows digging over 1500 cubic metres from the hole, with the spoil used to build up the outer rim. With no budget for the unofficial project everything had to be done on the cheap. Several truckloads of unwanted ash from a nearby power station were used to stabilise the sandy surface. The 22 m (72 ft) diameter reflecting surface of the dish consisted of discarded steel strips used for binding packing crates, scavenged from the docks at Botany Bay. Finally, a mast was installed at the centre of the dish to carry a dipole feed to a receiver operating at 160 MHz at the base of the mast (see Figure 6.7) (for previous accounts of the hole-in-the-ground telescope see [33]).

Figure 6.7. The 22 m parabolic 'hole-in-the-ground' antenna excavated in the sand at Dover Heights by Bolton, Slee and Stanley. Shown are the packing case metal strips used for the reflecting surface, the catwalk that provided access to the centre of the antenna, the aerial mast and dipole, and the instrument box at the base of the mast that contained part of the 160 MHz receiver. This novel radio telescope had a beamwidth of 6° and was used in late 1951 and early 1952 to generate a preliminary isophote map of the Galactic centre region. [courtesy: RAIA]

Similar to other transit telescopes, the hole-in-the-ground relied on the rotation of the Earth to map along a narrow strip of sky. By progressively altering the tilt of the receiver mast, successive strips of the sky could be built up. Early in 1952 the Dover group completed a survey at 160 MHz of the region between declinations –20° and –47°, which included the Galactic plane and the Galactic centre. The survey showed a considerable improvement on the earlier one at 100 MHz with the nine-Yagi array, with a three-to-one reduction in the aerial bandwidth producing a three-to-one improvement in resolution.

Although Taffy Bowen knew of the hole-in-the-ground telescope, and was given a guided tour when the excavation was in progress, it was only after the preliminary 160 MHz results had been obtained that Pawsey was informed of the project. Far from disapproving, Pawsey gave his full support and immediately provided funds to upgrade the dish. Pawsey's support was a surprise and made Bolton's original decision to carry out the project in secret difficult to justify. The preliminary results at 160 MHz were towards the upper limit of the frequency range (40–200 MHz) assigned to the Dover Heights group by Pawsey. Bolton's clear intent was to push to higher frequencies which he suspected would meet with Pawsey's disapproval. Nevertheless, even though Pawsey gave his support, he would have been keenly aware of Bolton's challenge to his authority, especially when it had Bowen's tacit approval. It was a preview of further trouble ahead [34].

In upgrading the 22 m hole-in-the-ground Bolton aimed for a further three-to-one improvement in the resolution of the dish, which required a more accurate surface and an increase in the aperture diameter. The surface was concreted using a rotating parabolic template and short lengths of galvanised wire were left protruding from the concrete to secure the final wire-mesh surface. Aluminium tubes at the perimeter and annular tension wires extended the diameter from 22 to 24 m (see Figure 6.8). The greater accuracy of the new surface meant the dish could operate at the higher frequency of 400 MHz, giving the desired factor of three improvement in the resolution. The preamplifier and associated electronic items were located in a waterproof box at the base of the aluminium mast, while the main receiver, amplifier and chart recorder were housed in a small hut near the southern rim of the dish. The upgrade of the dish took most of the second half of 1952 to complete.

As with the first hole-in-the-ground, the primary aim of the upgraded dish was to survey the Galactic plane and the region surrounding the Galactic centre. At Sydney's latitude of 34°S, the Dover Heights site was an ideal location for the survey, with the Galactic centre passing within 5° of the zenith. In 1918 Harlow Shapley, then at the Mt Wilson Observatory, was the first to determine an approximate position for the Galactic centre, based on a study of the distribution of globular clusters. Shapley concluded that the centre lies near the border of the Sagittarius and Scorpius

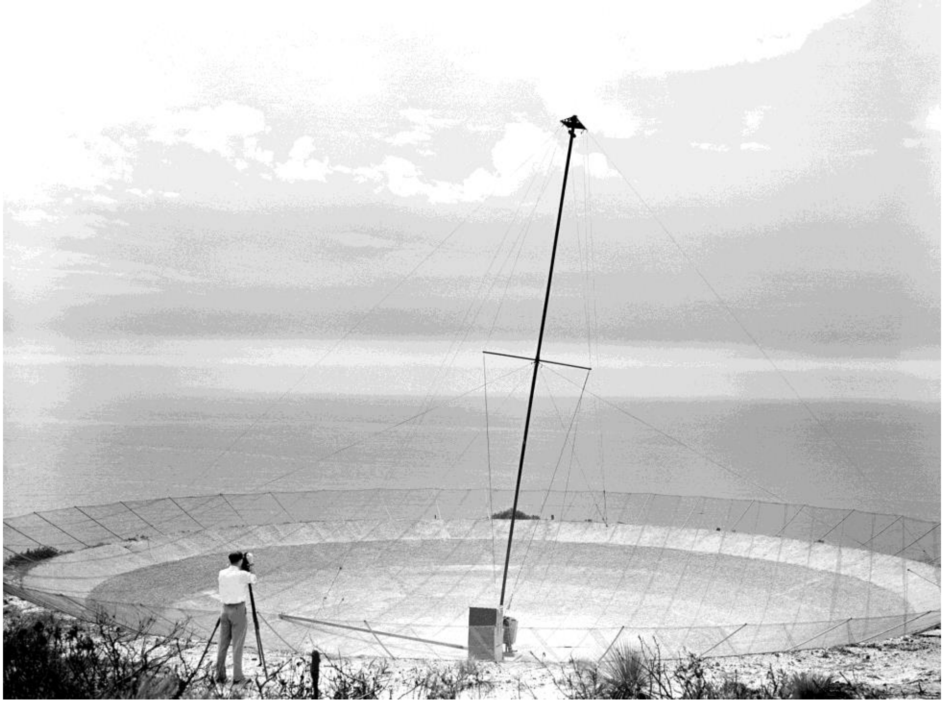


Figure 6.8. Upgrading the hole-in-the-ground telescope: (above) In February 1953 a concrete surface was added and the diameter extended from 22 to 24 m. The rotating wooden jig was used to position formwork for the concrete and also to finish the parabolic surface. (below) The completed dish showing the addition of the wire-mesh surface, the receiver mast, and the housing for the second stage of the receiver at the vertex. Gordon Stanley uses a theodolite to measure the angle of tilt of the mast. [courtesy: RAIA]

Figure 6.9. The 4.9 × 5.5 m parabolic antenna at the Radiophysics field station at Potts Hill. In 1950 Jack Piddington and Harry Minnett used the antenna to discover the strong radio source Sagittarius A. [courtesy: RAIA]

constellations at a distance from the Sun of approximately 4×10^4 light-years (the currently-accepted distance is 2.7×10^4 light-years).

The Dover Heights group was not the first to carry out a radio survey of this region. In 1950 senior Radiophysics staff Jack Piddington and Harry Minnett carried out a similar survey at the high frequencies of 1210 and 3000 MHz at the Potts Hill field station, in south–west Sydney (see Figure 6.9). They found a very strong source which they named Sagittarius A and noted that the source lies in the Galactic plane and ‘also lies very close to the centre of the Galaxy’. However, Piddington and Minnett hesitated in claiming Sagittarius A to be the Galactic centre, probably for two reasons. The first was the prevailing view that it seemed highly improbable that strong radio sources could be at great distances, a view that had held back both Bolton and Mills in their attempts at optical identifications. The second reason was that astronomers only had a very approximate idea of the location of the Galactic centre. Dense dust clouds in this direction block out the visible light by factors of 10^6 or greater, which made it almost impossible to determine an exact position.

Similarly, observations in the infrared had been unable to penetrate the dust clouds; however, the clouds are transparent to radio waves. Instead, Piddington and Minnett suggested that Sagittarius A might coincide with a nebula located somewhere between the Sun and the Galactic centre [35]:

> ‘Although … the accuracy of location of the source is not high, it may be significant that the position found almost coincides with that of the Galactic nebula NGC 6451, a loose cluster of about 70 stars extending over 15 minutes of arc. A much more accurate determination of position is required, however, before the coincidence is given serious consideration.’

Figure 6.10. Dick McGee working on the feed of the 4.8 m dish on top of the blockhouse (see Figure 6.5). After serving in the army and airforce during WWII, McGee joined the Radiophysics Lab in 1949 and was transferred to the Dover Heights group late in 1952. [courtesy: McGee family]

Late in 1952 Richard (‘Dick’) McGee joined the Dover Heights group, effectively replacing Kevin Westfold who had taken up an academic position at the University of Sydney (see Figure 6.10). McGee recalled [36]:

> ‘When I found out that Pawsey was posting me out there a few people at Radiophysics said, ‘Bad luck mate’. Some considered John to be a typical pommy bastard. You had to

> get to know him. Once you did, John would do anything to stick up for you, to defend you. When I arrived they were upgrading the hole-in-the-ground, concreting the surface. I offered to solder together the wire mesh making the reflecting surface. What I didn't know is that this is what appealed to John. If you were prepared to work, you were accepted.'

The group spent most of 1953 using the upgraded dish to carry out a new survey of the Galactic plane and Galactic centre. McGee did most of the observing and data reduction, while Bolton, Stanley and Slee concentrated on completing a sky survey for discrete sources using a new 12-Yagi sea interferometer (see next section). Pawsey, who lived in the neighbouring suburb of Vaucluse, visited late one afternoon just as McGee had completed sketching the intensity contours in pencil. Pawsey realised immediately the significance of the intense source Sagittarius A that McGee had shaded in black. He arranged for a photograph to be taken of the sketch and mailed copies to a number of astronomers overseas, including Walter Baade at the Mt Wilson–Palomar Observatories in Pasadena. Baade replied immediately [37]:

> 'Now to the object in the centre of the Galaxy, the contour diagram of which you kindly included in your letter. Frankly, I jumped out of my chair the moment I saw what it meant. I have not the slightest doubt that you finally got the nucleus of our Galaxy!! Visually one can see nothing in this region since the obscuration by dark clouds … Altogether I concluded about two years ago – after a careful examination of my 48 inch Schmidt plates of the nuclear region of our Galaxy and thorough checking of all suspicious objects at the 200 inch – that there was positively no chance whatsoever to detect the nucleus of our Galaxy in the optical range and that we had to await what you radio people could do about it. … <u>It is very improbable that the coincidence between inferred and observed position of the nucleus is accidental.</u>' [Baade's underline]

At this time the Dutch astronomer Henk van de Hulst was visiting Pasadena, who had predicted the existence of the 21 cm hydrogen line in 1944 (see Section 5.4). After the initial detection of the line by a Harvard group, van de Hulst, Jan Oort and the group at Leiden Observatory followed up the discovery by mapping the distribution of hydrogen along the Galactic plane. A study of the Doppler shift of the hydrogen line in gas clouds close to the Galactic centre led the Dutch group to conclude that the position of the Galactic nucleus appeared to closely coincide with the position of Sagittarius A. Pawsey had also written to van de Hulst, who replied [38]:

> 'Baade got really excited about your fine observations of the Galactic nucleus and shows your plot to anybody who comes near his office. The position agrees quite well with the best we can do on the basis of the 21 cm observations …'

Baade also sent the contour diagram to Jan Oort who enthusiastically noted [39]:

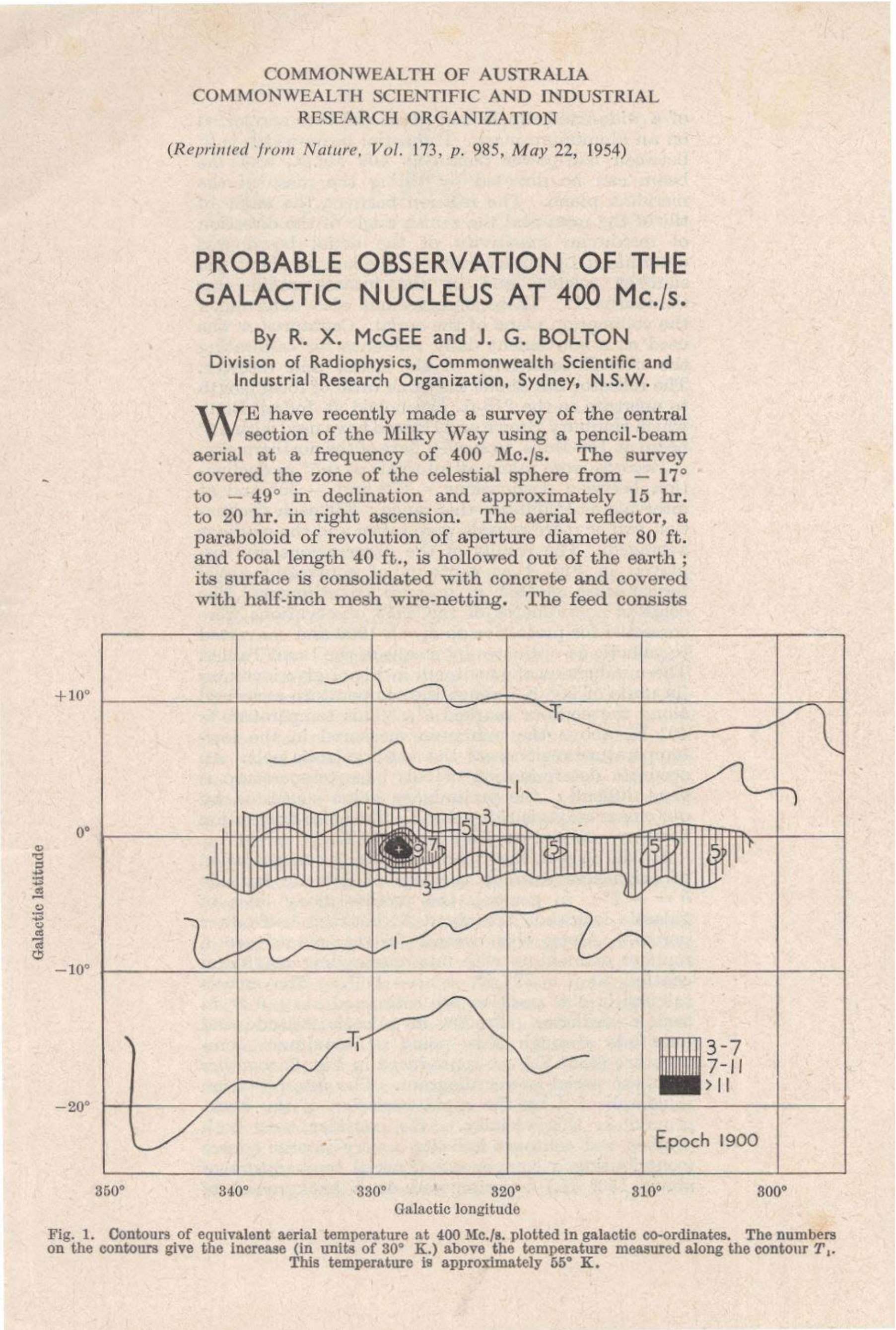
> 'I have been excited by Pawsey's diagram that I received from you this morning. The longitude of the concentration which the Sydney observers have found coincides exactly with the longitude of the centre that Mr Westerhout has now deduced with considerable accuracy from the 21 cm observations. The angular velocity of the Galactic system keeps on increasing up to very small distances from the centre, and then reverses sign so sharply that an accurate determination of the longitude of the centre is possible.'

In keeping with the standard Radiophysics practice, McGee drafted a paper to *Nature* with the title 'The Galactic Nucleus' to announce the discovery. Pawsey then extensively rewrote the paper with a new title 'Radio Observation of the Galactic Nucleus'. Before the paper could be submitted to the journal it needed the approval of the Radiophysics publications committee, chaired by Frank Kerr. The internal peer review system at Radiophysics was more rigorous than most journals, with the result that it was relatively uncommon for a Radiophysics paper to strike trouble with journal referees. McGee recalled [40]:

> 'There was some skepticism in the Lab as to whether our analysis was correct and whether we had found the Galactic centre. This happened with most of the work that came from the Lab and at times the criticism could be quite vicious. One of the reasons our work was so well received overseas is that it had gone through this internal criticism. I used to think that if you could get your paper past Pawsey, you were safe. You had to get it past him before it went out the door.'

One of the internal referees maintained that, since the distance to Sagittarius A was unknown, it was not possible to rule out a chance alignment of the source and the Galactic nucleus. As a compromise Pawsey settled on the final title 'Probable

Observation of the Galactic Nucleus at 400 Mc/s'. The three-page paper was published in *Nature* on 22 May 1954 (see Figure 6.11), followed by a detailed paper in the *Australian Journal of Physics* which contained the full results of the Galactic survey [41].



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PROBABLE OBSERVATION OF THE GALACTIC NUCLEUS AT 400 Mc./s.

By R. X. McGEE and J. G. BOLTON
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WE have recently made a survey of the central section of the Milky Way using a pencil-beam aerial at a frequency of 400 Mc./s. The survey covered the zone of the celestial sphere from − 17° to − 49° in declination and approximately 15 hr. to 20 hr. in right ascension. The aerial reflector, a paraboloid of revolution of aperture diameter 80 ft. and focal length 40 ft., is hollowed out of the earth; its surface is consolidated with concrete and covered with half-inch mesh wire-netting. The feed consists

Fig. 1. Contours of equivalent aerial temperature at 400 Mc./s. plotted in galactic co-ordinates. The numbers on the contours give the increase (in units of 30° K.) above the temperature measured along the contour T_1. This temperature is approximately 55° K.

Figure 6.11. A three-page paper by McGee and Bolton on the Galactic nucleus was published in *Nature* in May 1954. After rigorous internal refereeing at Radiophysics, the word 'probable' was added to the title to cover the possibility of a chance coincidence. [courtesy: *Nature*]

McGee and Bolton reported the following position for the source:

Galactic longitude $l = 327.9°$ Galactic latitude $b = –1.0°$,

with uncertainties estimated to be ±0.2° in each coordinate. Although the analysis was complicated by the rapidly varying background in the region of the nucleus, McGee and Bolton estimated a flux density for the source of 1400 Jy at 400 MHz, the sameorder as the flux density from Cygnus A at this frequency. They also noted that the angular size of the object appeared to be less than the hole-in-the-ground beamwidth of 2°.

In August 1955 at the general assembly of the International Astronomical Union in Dublin, Bolton put forward a proposal for the IAU to introduce a new system of Galactic coordinates to replace the existing system introduced in 1932. A subcommission was appointed consisting of Joe Pawsey, the young Australian astronomer Colin Gum, and the two Dutch astronomers Adrian Blaauw and Gart Westerhout. The brief of the subcommission was to study the results of the Sydney and Leiden groups and 'to investigate the desirability of a revision of the Galactic pole and of the zero of Galactic longitude' [42]. The recommendations of this subcommission were reported and then adopted at the next IAU general assembly held in Moscow in 1958. The point of zero longitude and latitude in the new system was designated $l^{\mathrm{II}} = 0$ and $b^{\mathrm{II}} = 0$, while the old Galactic coordinates of the nucleus were given as $l^{\mathrm{I}} = 327.69°$ and $b^{\mathrm{I}} = –1.40°$, based on the most recent 21 cm observations (compare with the McGee–Bolton position given above).

In Section 6.1 we saw how the identification of the Cygnus A source with an object that appeared to be two galaxies in collision proved to be a major milestone in the development of radio astronomy. Astronomers realised that the new astronomy would be able to study the distant reaches of the Universe, beyond the range of the most powerful optical telescopes. Similarly, the discovery and identification of the Galactic nucleus by radio methods proved to be another major milestone. The dark dust clouds blocking visible light from the Galactic centre made it highly unlikely that optical astronomers could determine an accurate position for the Galactic centre.

Radio astronomy had again demonstrated its power to investigate and solve problems beyond the reach of traditional astronomy.

6.4 The Struggle for Resources: The Final Years at Dover Heights

Earlier we noted how the Dover Heights group published a series of eight papers over the period 1950–54, each with the generic title of ‘Galactic radiation at radio frequencies’ (see note [39] in Chapter 5). The first four parts were published in the *Australian Journal of Scientific Research* during 1950–51. As noted at the beginning of this chapter, part II of the series consisted of the sky survey carried out by Stanley and Slee in 1949 which catalogued a total of 22 discrete sources (Table 6.1). Parts I and III of the series by Bolton and Westfold described the sky survey of continuum radiation at 100 MHz using the nine-Yagi array at Dover Heights (see Figures 5.7 and 5.8). In particular, part III presented evidence that the Sun is located in an arm of a spiral and that the sense of rotation of the galaxy is that of the spiral unwinding.

A further paper by Bolton and Westfold (1951, part IV) analysed the distribution of radio stars in the Galaxy (the paper was based on the talk Bolton gave at the URSI meeting in Zurich in September 1950). The paper referred to the discrete sources as *radio stars* with the property of high radio and low optical emission. Using the data from part I, the paper assumed that the background continuum radiation was the aggregate emission from a distribution of radio stars typified by the discrete sources already known. Bolton and Westfold then estimated the local number density, the flux from a typical radio star, and the probable distances of some of the known discrete sources.

The remaining four papers V – VIII were published over the period 1953–54 with the authors being Bolton and various permutations of Slee, Stanley and Westfold. It is worth while giving a brief summary of each.

Part V. The Sea Interferometer

Bolton and Slee summarised their knowledge of the technique that had served the Dover Heights group so well since 1947. They began by discussing the advantages of the sea interferometer over a two-aerial interferometer. Twice the sensitivity is achieved with a single aerial and no interconnecting cables or pre-amplifiers are required. The most important advantage is due to the 'cutoff' of the sea's horizon. The interference pattern commences sharply as a source rises above the horizon, in contrast to a gradual 'fading in' with the two-aerial interferometer. This feature was particularly valuable in resolving two or more close sources. (This problem, known as 'confusion', plagued the operation of the early two-aerial interferometers at Cambridge – see note [11] in Chapter 7.) However, most of the paper was an analysis of how to minimise the disadvantages of the sea interferometer. For example, the sea interferometer is adversely affected by the curvature of the Earth which leads to divergence or 'smearing' of the reflected beam, resulting in less signal power and therefore incomplete interference between reflected and direct beams. More serious are the adverse effects of atmospheric refraction and scintillation, where sources in sea interferometry are observed low on the horizon with the signal passing through a longer column of the atmosphere.

Although it was the first detailed study of the technique, Part V did not provide a blueprint for the future use of sea interferometry. On the contrary, the technique had effectively run its course and was about to be overtaken by other forms of radio telescopes. It is interesting to note that no other radio astronomy group adopted sea interferometry. Curiously, the only radio astronomer to show an interest in the technique was none other than the early pioneer Grote Reber. In 1947 he accepted an invitation to start a radio astronomy group at the National Bureau of Standards in Washington, DC. Reber lobbied the NBS to fund a 60 m diameter dish, but was unsuccessful. Disillusioned, he decided to return to radio astronomy the way he had started – as a lone individual. In 1951 he moved to the island of Maui in Hawaii where he set up a sea interferometer on top of Mt Haleakala. At an elevation of 3000 m the site dwarfed the clifftops at Dover Heights. However, Reber had only limited success, as noted by his biographer [43]:

> 'By replacing the fixed antenna design used by the Australians with one that rotated in azimuth, and by working on the top of a mountain, he could observe sources both rising in the east and setting in the west with an interferometer that had an effective baseline of 6 km. In principle, his sea interferometer had a resolution of about 1′, but he

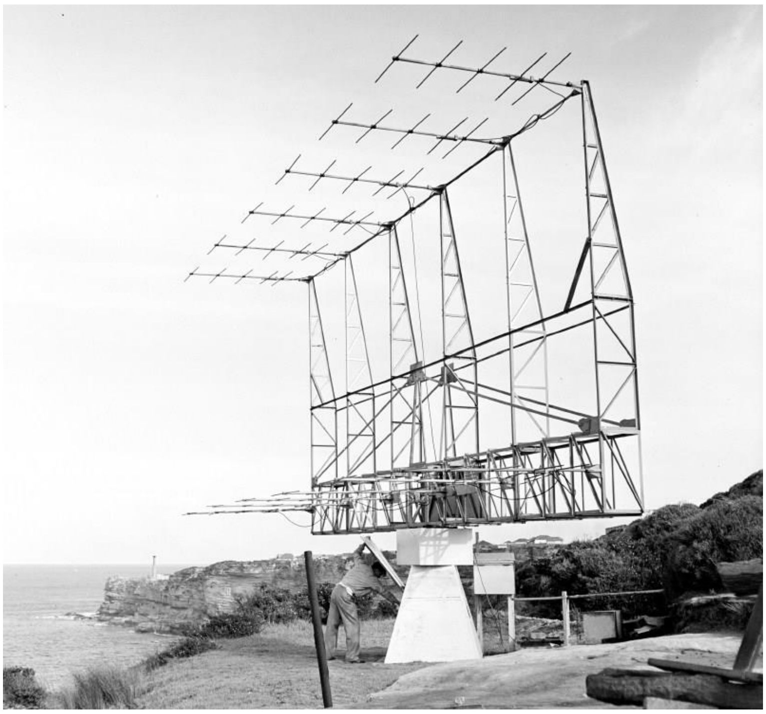

Figure 6.12. Bolton working on the 12-Yagi array at Dover Heights: (above) the view to the south and (below) the view to the north. This array began as an eight-Yagi array in 1951 and in early 1952 was up-graded using cannibalised elements of the earlier nine-Yagi array erected on the roof of the blockhouse (see Figure 5.7). The 12-Yagi antenna was used to carry out the last major source survey at Dover Heights, cataloguing a total of 104 discrete sources. [courtesy: RAIA]

> was plagued by ionospheric refraction and terrestrial interference and was only able to obtain useful results for a few of the strongest radio sources. He finally concluded that mountaintops were not suitable for radio telescopes.'

Part VI. Low Altitude Scintillations of the Discrete Sources

As discussed in Chapter 4, an important outcome of the New Zealand expedition in 1948 were the simultaneous observations of Cygnus A at Pakiri Hill and Dover Heights, two sites over 2000 km apart. The observations showed there was no correlation in the fluctuations of the source at each site, providing strong evidence that the fluctuations are not intrinsic to the source but are caused by the Earth's atmosphere. Bolton, Slee and Stanley carried out a systematic study of these fluctuations, or scintillations as they became known, based on about 2000 records of the four strong sources Cygnus, Virgo, Taurus and Centaurus over the period 1948–51. They showed that the correlation between individual scintillations at two sites disappeared for distances greater than about 5 km. The study found that for the scintillation index, a measure of the amplitude of the scintillations: (1) the index increases with increasing wavelength; (2) decreases rapidly with increasing altitude of the source; and (3) shows seasonal and diurnal variations, with the seasonal component having minima near the equinoxes and the diurnal component near dawn and sunset. The paper concluded by establishing a strong correlation between the occurrence of the scintillations and an effect known as sporadic E – irregular and transient ionisation disturbances in the E layer of the ionosphere at a height of about 100 km.

Part VII. Discrete Sources with Large Angular Widths

Bolton, Westfold, Stanley and Slee used three types of radio telescope to reveal the existence of a number of sources of angular width more than 1°. The first was the 22 m hole-in-the-ground telescope operating at 160 MHz, before its upgrade to 24 m diameter. The second was the 12-Yagi sea interferometer (see Figure 6.12) fitted with automatic control of the receiver gain, a technique devised by Bruce Slee. The technique suppresses the slowly varying components in the receiver output which drown out faint sources in regions near the Galactic plane. The third was a new instrument known as an azimuth interferometer, consisting of two sea interferometer aerials spaced at variable distances along the cliff-top. Combining the fringes from

Table 6.2: List of extended sources at 100 MHz
[adapted from Bolton *et al.* (1954b) p. 103]

Source	Position [A] Galactic coordinates *l*	*b*	Estimated flux density (10^2 Jy)	Estimated angular size [B]	Equipment used [C]	Remarks
A	206°	–56°	6	½–1°	AzI	Probably Fornax A
B	145°	–16°	20	10×5°	AGC	Lies along a parallel of Galactic latitude
C	215°	–35°	15	1–2°	AzI	Possibly Pictor A
D	173°	–14°	15	10×5°	AGC	Lies along a parallel of Galactic latitude
E	227°	–2°	15	1–2°	AzI	Source Puppis A
F	230°	–2°	70	5°	HitG, AzI AGC	–
G	210°	+27°	>10	–	AzI	Possible position error of several degrees
H	270°	+69°	25	4°	AzI	Possible position error of several degrees
J	274°	+20°	50	2°	AGC, AzI	Concentric with Centaurus A
K	309°	–2°	350	10×6°	AzI, HitG	Lies along a parallel of Galactic latitude
L	329°	0°	>>300	12×2°	AzI, HitG	Lies along the Galactic equator

[A] Approximate position of apparent centroid [B] To ~20% of central brightness

[C] AzI, azimuth interferometer; AGC, automatic gain control on 12-Yagi array; HitG, 22 m diameter hole-in-the-ground

both sea interferometers produces a third azimuth fringe system. The azimuth fringes reveal the presence of extended sources, which do not appear in the individual sea interferometer fringes [44].

Bolton *et al.* claimed the existence of over 20 extended sources and presented data for 11 of them, most of which had been detected by the azimuth interferometer (see Table 6.2). In their discussion of each of the 11 sources they noted:

Sources A and C. These sources appear to coincide with the discrete sources Fornax A and Pictor A, respectfully, catalogued by Stanley and Slee (1950).

Source E. As noted above in Section 6.1 (note [12]), the coordinates for the Puppis A source had been sent to the Mt Wilson–Palomar astronomers: 'The new determination of position and observation of angular width have led to the identification of this source by Baade and Minkowski (personal communication) with a network of gaseous filaments similar to that which coincides with the Cassiopeia source.' After Taurus A and Cassiopeia A, Puppis A became the third radio source identified with a supernova remnant.

Source J. Previous work had established that the angular diameter of Centaurus A is less than 7′, which is less than the visible extent of the galaxy. 'It is possible that the small source is associated with the nucleus of the Galaxy and the extended object with its outer regions. It would be a remarkable coincidence if these two bright sources had no physical connection.'

Source L. The authors noted that the centre of this extended source is close to the accepted position of the Galactic centre. 'We are left with the inference that there is an extended physical object at the centre of the Galaxy, which is an unusually intense source of radio noise.' The subsequent observations with the 24 m hole-in-the-ground (Section 6.3 above) would prove them correct.

Part VIII. Discrete sources at 100 Mc/s between declinations +50° and –50°

In mid-1953 Bolton, Stanley and Slee completed a sky survey with the 12-Yagi array at Dover Heights (Figure 6.12). It catalogued 104 sources, more than any of the five major surveys previously published (see Table 6.3). The survey covered approximately 70% of the celestial sphere, less than the survey by Mills (50° to –90°). However, the 104 sources reported exceeded the 77 in the Mills survey because of the greater resolving power of the 12-Yagi array. The published catalogue contained the following information on each source: the constellation in which it was found; its position in both equatorial and galactic coordinates; errors in time of rising and in azimuth; the flux density; and, where appropriate, whether the source appears in any of the surveys 2–5 in Table 6.3.

After a detailed comparison of the Dover Heights survey with surveys 2–5, Bolton *et al.* could confidently claim that 73 of their 104 sources were confirmed by one or more of the previous surveys. They concluded: 'The agreement between the individual sources of the various surveys has been found to be quite high after due allowance has been made for factors such as the different sensitivities of the instruments and conditions of the surveys.' Finally, tentative optical identifications were made for ten of the sources – seven with extragalactic objects of photographic magnitude about 12.5 and three with the galactic nebulae NGC 6445 and 2792 and the expanding shell of Nova Aquila 1918.

Table 6.3: Surveys of discrete radio sources 1950–54
[adapted from Bolton *et al.* (1954c) p. 111]

Survey number	Observers (publication year) [A]	Field station	Frequency (MHz)	Limit of sensitivity (Jy)	Survey region (Dec.)	Number of sources
1	Stanley–Slee (1950)	Dover Heights	100	100	50° to –50°	22
2	Ryle–Smith–Elsmore (1950)	Cambridge	81	30	90° to 10°	50
3	Mills (1952a, b, c)	Potts Hill NSW	100	50	50° to –90°	77
4	Hanbury Brown –Hazard (1953)	Jodrell Bank	158	5	70° to 40°	23
5	Shain–Higgins (1954)	Hornsby NSW	18	3000	10° to –90°	37
6	Bolton–Stanley–Slee (1954c)	Dover Heights	100	50	50° to –50°	104

[A] Stanley–Slee (1950), *Aust. J. Scient. Res.* **A3**, 234–50; Ryle–Smith–Elsmore (1950), *Mon. Not. R. Astron. Soc.* **110**, 508–23; Mills (1952a, b, c), *Aust. J. Scient. Res.* **A5**, 266–87; **A5**, 456–63; *Nature* **170**, 1063–64; Hanbury Brown–Hazard (1953), *Mon. Not. R. Astron. Soc.* **113**, 123–33; Shain–Higgins (1954), *Aust. J. Phys.* **7**, 130–49; and Bolton–Stanley–Slee (1954c), *Aust. J. Phys.* **7**, 110–29.

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A search through the Radiophysics files covering the early 1950s reveals almost as many proposals for new radio telescopes as there were radio astronomers. With the completion of the sky survey with the 12-Yagi array in mid-1953, the Dover Heights group had several ideas on how to proceed next. Bolton suggested a second hole-in-the-ground, but tilted at an angle of 25° to the south so that it could continue the sky survey at 400 MHz between declinations –50° and –90°. Another possibility was to build a second hole-in-the-ground at the opposite end of the Dover site and connect the two as an interferometer, enabling a survey of the Galactic plane with unprecedented resolution. Gordon Stanley was in favour of another type of interferometer known as the rolling barrels, consisting of two cylindrical parabolas mounted on tracks to vary the distance between them. However, Bolton’s first choice was to build a new type of sea interferometer, one that did not involve an array of Yagis. The interferometer would consist of a 6 m high wall 60 m in length and curved into the shape of a parabola. Viewed from above, the parabolic wall would face out to sea with a focal length of 45 m fed by a vertical stack of dipoles. The wall would consist of steel poles and wire mesh and resemble the fence around a tennis court. With tennis courts springing up all over Sydney at this time, there would have been no shortage of contractors and the cost would be relatively modest [45].

The Dover designs were in direct competition with a range of proposals by other Radiophysics groups, both solar and non-solar. Despite long and at times heated discussions over the relative merits of particular designs, in the event an entirely new type of radio telescope emerged triumphant. As we saw in Section 6.1, Bernard Mills carried out a series of observations on Cygnus A, first at Potts Hill and then at Badgery's Creek, trying out a number of interferometers with aerials spaced up to 10 km apart. This period of experimentation impressed on Mills that to achieve a high resolution the collecting areas of the aerials were relatively unimportant in comparison with the spatial extent of the array. Mills investigated a number of aerial systems before hitting on the idea of having two long arrays of small dipole aerials lying north–south and east–west along the ground in the form of a cross. The key feature was that each arm of the cross would produce a fan-shaped beam which could be fed to the central receiver through a switch which, in turn, would join the two beams alternately in and out of phase. Combining the two signals in this way would lead to a relatively narrow 'pencil' beam which would be far more effective in resolving closely-spaced radio sources than other types of interferometers. The great promise of the cross was that its resolving power would be roughly equal to a parabolic dish with a diameter equal to the length of the cross arms. Because the working components housed in each arm would be inexpensive and involve no complex engineering, it seemed possible to build a cross of very large dimensions.

The theory of the cross was not exactly simple. The initial reaction to the proposal prepared by Mills in March 1953 proved far from positive, as he recalled [46]:

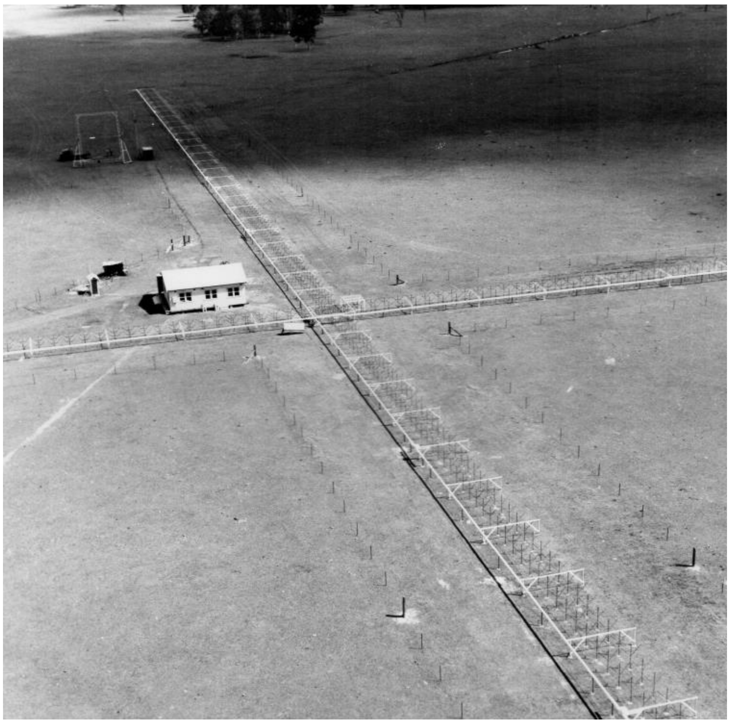


Figure 6.13. (above) The first full-scale cross telescope devised by Bernard Mills and built at the Fleurs field station in 1954. (below) Mills (right) with Alec Little who supervised the construction of the cross. [courtesy: RAIA]

> ‘There was opposition to the idea in the Laboratory for some technical reason that I never really understood, and perhaps a political reason which I could well understand. However, Pawsey supported me and gave approval for the construction of a small experimental model to explore the technique.’

The pilot model with arms 36 m in length and operating at a frequency of 100 MHz was constructed at the Potts Hill field station. The trials not only showed that the idea worked but also turned in some useful astronomy, including the first detection of continuum radiation from the Large Magellanic Cloud. The results convinced the radio astronomy group that, among the range of competing proposals for new telescopes, a full-scale cross was worth supporting.

First, a new field station had to be found because Potts Hill did not have an adequate area of flat land. A disused airstrip further west was leased and christened the Fleurs Radio Observatory; the new site became the main field station used by Radiophysics for the rest of the 1950s (Figure 5.3). The full-scale cross consisted of two arms 455 m (1500 ft) in length, each housing two rows of 250 dipole aerials tuned to receive at 85 MHz. Mills spent much of 1953 visiting astronomy centres in the United States, leaving Alec Little to supervise the construction of the cross (see Figure 6.13). By the middle of 1954 the full-scale cross began producing its first data. Detailed studies were made of a select number of radio sources but by far the richest scientific yield came from the program for which the cross had been designed – the most extensive survey yet of the southern sky.

The Mills Cross telescope and variations in its design dominated research in cosmic radio astronomy by the Radiophysics group for the rest of the 1950s. The principle found application in other areas such as solar studies (the Chris Cross named after Chris Christiansen) and in radio emission at very low frequencies (the Shain Cross after Alex Shain). The principle was also widely adopted internationally with versions built at various new radio centres, including the Department of Terrestrial Magnetism (Washington, DC), the University of Bologna (Italy) and the Lebedev Institute of Physics (Serpukhov, Russia). The construction of these crosses marked a transition from what Paul Wild [47] has called the period of ‘little’ science in the postwar years of radio astronomy, characterised by its small, inexpensive and experimental radio telescopes, to a period of ‘middle’ science which saw the introduction of larger and more complex equipment and more refined observing techniques. The cross telescopes could, however, still be wholly designed, constructed and financed with the resources available to Radiophysics. The 455 m Mills Cross, for example, took ten men about nine months to build and the materials cost about £5000. The project remained an in-house one, though this limited the possibility of backing other proposals for large instruments for cosmic work put forward in the early 1950s.

Early in 1953 Bolton arranged a meeting at the Radiophysics Lab with Joe Pawsey in a last ditch attempt to get support for a large new sea interferometer at Dover Heights. The competition for limited resources and the view that sea interferometry was coming to an end both counted against Bolton. A heated argument broke out and both men went to see Taffy Bowen in his office. Shortly after Bolton emerged and went to find Gordon Stanley. Bolton announced ‘I’m out of radio astronomy’ and promptly left the building [48].

There were two further papers produced by the Dover Heights group, both published after operations were shut down at the field station late in 1954. The first was a solo paper by Bruce Slee reporting variations in the flux density from the strong source Hydra A. Slee observed the source over a period of a year, first with the 12-Yagi sea interferometer and then with the Mills Cross at Fleurs. The observations showed that the flux density could vary in strength by up to 30% on successive nights, though no periodic changes were detected. Cygnus-like scintillations in the ionosphere could be ruled out and the mechanism causing the variation remained unknown [49].

The final paper from Dover Heights was authored by Gordon Stanley and Robert Price, a visiting post-doctoral fellow from the Massachusetts Institute of Technology. Following the discovery of the interstellar 21 cm hydrogen line in 1951, astronomers speculated on whether line radiation might also be detected from its isotope, atomic deuterium. The following year the Russian theorist Iosif Shklovsky predicted an emission line for deuterium at 327 MHz (compared with 1420 MHz for hydrogen). Even though the terrestrial abundance of deuterium is only 0.015% that of hydrogen, the strong 21 cm emission suggested that it might be possible to detect the much weaker deuterium line. Stanley and Price spent much of 1954 making lengthy observations at 327 MHz using the hole-in-the-ground telescope. Rather than searching for the emission line, they attempted to detect the corresponding absorption line along the line of sight to the strong sources Sagittarius A and Centaurus A. Although their attempt failed, Stanley and Price were able to place an upper limit on the deuterium abundance of 0.1% compared to interstellar hydrogen. To end a fine tradition, their null result was published in *Nature* – the swansong publication of the Dover Heights team [50].

Notes to Chapter 6

[1] See Stanley and Slee (1950). The paper was published at the same time as the first Cambridge survey, which listed fifty radio 'stars' in the Northern Hemisphere (Ryle *et al.* 1950, *Mon. Not. R. Astron. Soc.* **110**, 508–23). The Stanley–Slee paper was the first of the Dover Heights papers without Bolton as a coauthor (nor is he acknowledged at the end of the paper). The paper was submitted in November 1949, before Bolton's departure overseas, and there is no doubt that he contributed significantly to the work. This was characteristic of Bolton later in his career. He occasionally omitted his name from research papers, presumably so that his junior colleagues would receive more credit and exposure. A classic case is the 1963 paper announcing the discovery of the first quasar (see next chapter). Bolton had done more than any of the paper's three authors to prepare the Parkes telescope in NSW for the observations and ought to have been named as the senior author. Elsewhere, I have speculated that Bolton's sometimes casual attitude to publishing may have cost him a Nobel Prize in physics – see Robertson (2016), ch. 15.

[2] Mills (2006), p. 3. This personal memoir was written by Mills after receiving the honour of being invited by the *Annual Review of Astronomy and Astrophysics* to introduce its annual volume for 2006. For a detailed history of the Potts Hill field station see Wendt (2009).

[3] Mills to Minkowski, 16 December 1949, NAA file A1/1/1, part 4.

[4] Minkowski to Mills, 29 December 1949, NAA file A1/1/1, part 4.

[5] Mills and Thomas (1951), *Aust. J. Scient. Res.* **A4**, 158–71. Very little is known of Adin Thomas. It appears he may have left Radiophysics at this time and returned to his native England.

[6] See Mills (1952), *Aust. J. Scient. Res.* A **5**, 456–63. Mills also used the broadside array to carry out a sky survey that detected a total of 77 discrete sources (see Table 6.3 later in this chapter). He noted that the distribution of the sources could be explained on the assumption that there are two major source classes, one having a high degree of Galactic concentration and the other having a random distribution.

[7] Smith to Baade, 22 August 1951, Sullivan papers, NRAO Archives. See Smith (1951), *Nature* **168**, 555, for his report on the positions of the four sources.

[8] Baade to Smith, 3 September 1951, Sullivan papers, NRAO Archives. Smith replied on 26 September: 'The coincidence of the Virgo source with M87 is very interesting. It would be most remarkable if the "stars" are in fact extragalactic – even more remarkable than the present hypothesis of extremely common "dark stars".'

[9] Baade to Smith, 23 October 1951, Sullivan papers, NRAO Archives. Smith replied: 'We were delighted to hear of the object you have found in Cassiopeia. I am sure you need no encouragement to continue with this, but we are extremely interested.'

[10] See Baade and Minkowski (1954), *Astrophys. J.* **119**, 206–14. Baade and Minkowski originally estimated the distance to Cygnus A to be 3.3×10^7 parsec or 100 million light-years, based on the redshift of its emission lines and the then accepted value of the Hubble constant. The Hubble constant was however very poorly known and since then it has been revised downward by approximately a factor of 10 to its current accurate value. In turn, this has led to a corresponding increase in the estimated distance to extragalactic objects and so we quote the contemporary known distance to Cygnus of 1000 light-years.

[11] See note [2], p. 3.

[12] See note [10], p. 211. It is worth noting that the Baade–Minkowski paper reported the optical identifications of three radio sources: Cygnus and Cassiopeia based on the Smith positions and the third source Puppis A which had been included in the Stanley–Slee (1950) paper (see entry 21 in Table 6.1). In November 1951 Bolton sent Minkowski a more accurate position for Puppis A and noted its extended angular size. Baade and Minkowski noted the strong similarity of the Puppis and Cassiopeia nebulae 'in regard to appearance, spectrum and motions'. Puppis A thus became the seventh source to be optically identified: three supernova remnants in the Galaxy (Taurus, Cassiopeia, Puppis), three peculiar extragalactic objects (Centaurus, Virgo, Cygnus) and one normal extragalactic object (Andromeda). The seven identifications could be credited to Dover Heights 4, Cavendish 2 and Jodrell Bank 1.

[13] A story told at the time was that Minkowski challenged Baade to prove the collision theory by showing that the spectrum of visible light from the source was consistent with such an event. Baade won the bet and with it a bottle of whisky. It is not known whether Baade returned the favour when later the theory was shown to be wrong – see Robertson (1992), p. 52.

[14] See Sullivan (2009), chapter 15 for a comprehensive discussion of theories of Galactic radio emission. The very first theoretical paper in radio astronomy was published in 1937 by Fred Whipple and Jesse Greenstein, then at Harvard University. The paper theorised that radio waves were generated by thermal radiation from dust particles in the interstellar medium. However, their calculation fell short by a factor of 10,000 in explaining the strength of Jansky's signals. See Whipple and Greenstein (1937), *Proc. Nat. Acad. Sci. (USA)* **23**, 177–81.

[15] The misconception was however propagated in popular books on astronomy for many years later – see e.g. Hanbury Brown and Lovell (1962), p. 81.

[16] See Alfvén and Herlofson (1950), *Phys. Rev.* **78**, 616. Alfvén was well known for his work on applying plasma theory to a wide range of problems in astrophysics and geophysics, while the Norwegian Herlofson was an ionospheric physicist. As noted in Section 5.4, Bolton and Westfold visited Alfvén and Herlofson in Stockholm in September 1950, where no doubt the synchrotron mechanism would have been discussed in detail. In early 1948 Taffy Bowen had attempted to bring Alfvén to Sydney on a one-year fellowship with travelling expenses. The lack of theoretical expertise among the Radiophysics staff had been an ongoing concern. Alfvén agreed to the offer on condition that he could bring his wife and five children. Bowen abandoned the idea knowing that it was highly unlikely that the CSIR Executive would agree to fund the offer. Bowen to Pawsey, 8 March 1948, NAA file F1/4/PAW.

[17] Alfvén received a half-share of the 1970 Nobel Prize 'for fundamental work and discoveries in magnetohydro-dynamics with fruitful applications in different parts of plasma physics'. Ginzburg received a third-share of the 2003 Nobel Prize 'for pioneering contributions to the theory of superconductors and superfluids'.

[18] Greenstein (1994), p. 558. Greenstein and Bolton later became close colleagues at Caltech – see next chapter.

[19] Baade and Minkowski (1954), *Astrophys. J.* **119**, 215–31. This paper was published back-to-back with their paper cited in note [10] and presented an overview of the identification of radio sources. They classified the following four types of object: (i) remnants of supernovae; (ii) galactic nebulosities of a new type; (iii) peculiar extragalactic nebulae; and (iv) normal extragalactic nebulae. The evidence was reviewed for each of the known optical identifications, including the possible identifications of a further eight normal

extragalactic objects, proposed by the Cambridge and Manchester groups. Both papers ended with the acknowledgment: ‘We are greatly indebted to the members of the radio astronomy groups in Sydney, Cambridge and Manchester for their generous communication of information in advance of publication.’

[20] Bowen to A. V. Hill, 7 May 1946, NAA file A1/1/1, part 1. Hill was the Nobel Laureate in Physiology/Medicine in 1922. His other claim to fame was that his wife was the sister of the celebrated economist John Maynard Keynes.

[21] Rivett to Bowen, 20 November 1947, NAA file [E2: Outside Bodies]. In a similar vein Rivett added: ‘You will be rather amused perhaps to hear that we had a letter from Movietone News the other day, saying that they were very keen indeed to prepare films depicting our work on rain making and moon echoes. I hope these well-meaning people will not feel too deeply aggrieved at our failure to respond sympathetically.’

[22] McCready to Pawsey, 9 June 1948, NAA file C4659, Pawsey correspondence, part 8; and Bowen to M. Ovenden (University Observatories, Cambridge), 13 October 1949, NAA file A1/1/1, part 4. Ovenden made amends when he published a second article in the April 1950 issue of *Science Progress* which highlighted the research at Radiophysics. Bowen expressed his gratitude: ‘… I am writing to say how much we appreciate the description you have given of some of the work of this Laboratory. I thought you did an extremely good job of threading it in with other astronomical research and thus bringing it into clever perspective.’ Same file, 26 June 1950.

[23] The Radiophysics documentary is available at the National Film and Sound Archive in Canberra, title number 15353, director Tony Doogood. Another article featuring radio astronomy at Radiophysics appeared in *Popular Science Monthly* (Los Angeles), while Arthur Higgs at Radiophysics published a lengthy article on the subject in *The Science News* (Penguin, London, 1951).

[24] As Goss and McGee (2010, p. 189) have pointed out, there were no German or Japanese delegates invited with WWII still fresh in the memories of the organisers. Similarly, with the escalation of the Cold War there were no delegates from the USSR or Eastern European countries. Bolton had met many of the radio astronomy delegates during his 1950 European tour. During the conference Graham Smith stayed with the Boltons at their flat in Bellevue Hill. Smith and Hanbury Brown returned to England via the US where they spent a week in Pasadena discussing the optical identification program with Baade and Minkowski. Bolton to J. L. Greenstein, 11 August 1952, Greenstein papers, Caltech Archives.

[25] See Bolton (1953). Frank Kerr wrote a similar summary article on the radio astronomy program for the popular US magazine *Sky & Telescope* **12**(2) (1953) 59. He also concluded that ‘… the former term radio stars is now falling into disuse, in favour of the more general phrase, discrete sources.’ Curiously, Bolton did not take his own advice and continued using the term ‘radio star’ for several more years – see e.g. Bolton (1956).

[26] Bowen to Fred White, 4 September 1952, NAA file [E2: Outside Bodies]. Much of the success of the congress was owed to Ron Bracewell, the secretary of the local organising committee, who was meticulous in his planning of the event (see note [21] in Chapter 5). As Haynes *et al.* (1996, p. 222) have noted, Bracewell even arranged for one of the Radiophysics staff to be trained in how to make a decent cup of coffee for the international delegates.

[27] The extract of Ratcliffe’s letter was included in note [26]. White replied on 16 September 1952 [same file].

[28] See Bolton *et al.* (1954a), p. 7. The report was published with the financial support of UNESCO.

[29] While there may have been some self-selection at work, the four authors included the following numbers of their own papers in the bibliography: Bolton 11, Hanbury Brown 9, Smith 9 and Mills 6.

[30] Pawsey to Secretary CSIRO, 28 November 1951, Kellermann papers, NRAO Archives, Charlottesville, VA.

[31] Bolton to White, 10 March 1952, Bolton's personal history file, NAA file PH/BOL/005, part 1.

[32] Bowen to DuBridge, 28 September 1954, NLA file 1-2 and NAA file PH/BOL/005, part 1. It is interesting to note the grades of other senior research staff in mid-1952: Chris Christiansen (PRO I), Frank Kerr (SRO II), Bernie Mills (SRO II) and Paul Wild (SRO I). Gordon Stanley was classified as a Senior Technical Officer and Bruce Slee as a Technical Officer.

[33] See Morton (1985), Orchiston and Slee (2002) and Robertson and Bland-Hawthorn (2014).

[34] Orchiston and Slee (2002), p. 25. There are parallels between this episode and the occasion late in 1946 when Pawsey ordered Bolton and Slee back to the Lab for not sticking to their assigned task of monitoring radio emission from the Sun (see note [13] in Chapter 3).

[35] Piddington and Minnett (1951), *Aust. J. Scient. Res.* A **4**, 459–75. The Sagittarius A source is now known by its contemporary name of Sgr A.

[36] Dick McGee interview with author, 30 November 2006, Eastwood, NSW.

[37] Baade to Pawsey, 16 February 1954, NAA file A1/1/1, part 9.

[38] van de Hulst to Pawsey, 19 February 1954, NAA file A1/1/1, part 9.

[39] Oort to Baade, 22 February 1954, NAA file A1/1/1, part 9. Oort sent a copy of this letter to Pawsey, noting that he had received a copy of the contour diagram. Oort added the handwritten annotation: 'This is indeed of very great interest. As you will see below I share Baade's optimism that what you have observed may actually be the nucleus of the Galactic system.' I am grateful to Don Morton (NRC, Canada) for providing a copy of this letter.

[40] See note [36]. For a detailed discussion on the preparation of the *Nature* paper see Goss and McGee (1996).

[41] See McGee and Bolton (1954) and McGee *et al.* (1955). The detailed *AJP* paper authored by McGee, Slee and Stanley was only the second from Dover Heights without Bolton as an author. The paper did however acknowledge Bolton 'who initiated the survey and was always ready to assist in the work', and also Pawsey for 'his most helpful criticism of the manuscript'. The paper also reported 14 new discrete sources, though approximately half were later shown to be fictitious, the result of the effect known as 'confusion'.

[42] See Blaauw *et al.* (1960), *Mon. Not. R. Astron. Soc.* **121**, 123–31. In April 1960, a month after the paper was submitted to *Monthly Notices*, coauthor Colin Gum was killed in a skiing accident in Switzerland. The Leiden group collaborated closely with the Radiophysics 21 cm hydrogen group led by Frank Kerr. Early in 1953 the Radiophysics group constructed an 11 m

diameter dish at Potts Hill and began a detailed survey of the southern sky, while the Leiden group started a similar survey of the northern sky. On completion of both surveys in 1957, Kerr worked with Oort and Gart Westerhout in Leiden on splicing the two maps together to give the first complete view of the distribution of hydrogen throughout the Galaxy [see Robertson (1992), p. 84]. As we saw in Section 5.4, a sky survey by Bolton and Kevin Westfold in 1949 had produced tentative evidence for a spiral structure of the Galaxy. The combined Leiden–Sydney 21 cm map showed without doubt what had long been suspected – a spiral structure for the Milky Way similar to that observed in many other galaxies.

[43] Kellermann (2004), p. 706. At the elevation of Reber's site the curvature of the Earth becomes a major problem and leads to serious degradation of the reflected signal. As mentioned in Chapter 2, note [33], in 1954 Reber moved to Australia and settled in the small town of Bothwell near Hobart. In collaboration with physicists from the University of Tasmania, Reber took advantage of a 'hole' in the ionosphere at this latitude to study Galactic radio emission at frequencies as low as 520 kHz (wavelength 577 m). See George *et al.* (2015).

[44] See part V for an explanation of the automatic control of the receiver gain and the azimuth interferometer. Bolton (1982, p. 355) noted that the azimuth interferometer was abandoned 'when special interferometers for measurement of the sizes of the major sources were built at Jodrell Bank and Cambridge and by B. Y. Mills in Sydney' (see later in this section).

[45] Bolton (1982), p. 357. The idea for the 'tennis court' telescope appears to have come from Taffy Bowen. After visiting an airfield in Suffolk in June 1951 he wrote: 'I wonder if we have been missing out on a simple form of big aerial for radio astronomy which would be very cheap and easy to erect. It has been suggested to me by an experimental parabola being used at Martlesham for blind landing experiments. It is a simple cylindrical parabola 80 feet across and 20 feet high. The reflecting material consists of a series of horizontal wires about 8 inches apart fixed by staples to posts driven vertically in the ground. The whole thing cost a few pounds, and took a day or two to erect and gave an excellent polar diagram. For radio astronomy, it would be quite easy to erect such an aerial on a cliff site like Dover, with an aperture of say 500 feet.' Bowen to Radiophysics Lab, 10 June 1951, NAA file A1/1/1, part 6.

[46] See Mills (2006), p. 6. Mills was particularly critical of Bolton: 'He said it wouldn't work. Bolton said that in a constant temperature enclosure it would give zero output. This is of course true, but I had taken measures to overcome the problem. Apparently he convinced Bowen that it wouldn't work and Taffy didn't want anything to do with it. Pawsey however was very keen and of course he understood it all completely.' Mills interview with author, 6 July 2007, Roseville, NSW. The theory of the cross was set out in Mills and Little (1953), *Aust. J. Phys.* **6**, 272–78.

[47] Wild (1972), p. 56. For the Chris Cross see Orchiston and Mathewson (2009); for the Shain Cross see Orchiston *et al.* (2015).

[48] Stanley (1994), p. 512. Bolton took up Bowen's offer to join the Lab's cloud and rain physics group – see next chapter. For the next few months Bolton worked part-time at Dover Heights as the radio astronomy program was wound down.

[49] Slee (1955); see also Bolton and Slee (1957). Hydra A has since been shown to be a 14.8 magnitude diffuse galaxy of very small angular size. Diffraction in the interstellar or extragalactic medium is thought to cause the large intensity variations. Slee to author, 12 February 2015.

[50] Stanley and Price (1956). The deuterium line was eventually detected and the interstellar deuterium abundance was shown to be 0.002% that of hydrogen, far below the terrestrial abundance of 0.015%.

Chapter 7

Beyond Dover Heights –
An Overview of John Bolton's Career 1955–81

John Bolton had the unusual distinction of being the foundation director of not one but two major radio astronomy observatories. Although the Americans Karl Jansky and Grote Reber pioneered radio astronomy in the 1930s, the US did not build on its lead after WWII. This changed in 1955 when the California Institute of Technology (Caltech) invited Bolton and Gordon Stanley to build a new radio astronomy observatory. They chose a site at Owens Valley near the Sierra Nevada Mountains and designed an interferometer consisting of two large parabolic dishes. In 1960 Bolton returned to Australia to become the inaugural director of the Parkes telescope in central New South Wales. We will see that the remainder of Bolton's career did not deviate too far from the original program at Dover Heights. During the 1960s and 1970s he and the Parkes group carried out sky surveys that discovered and catalogued over 8000 radio sources, many of which were a new class of object known as quasars. Over his career no one did more to establish radio astronomy as a mature new science. This chapter provides an overview of Bolton's career from 1955 until his retirement in 1981.

The failure by Bolton in 1953 to get backing for a large new instrument at Dover Heights cast doubt over his future as a radio astronomer. The decision to build a full scale Mills Cross as the principal instrument for cosmic work at Radiophysics effectively made the technique of sea interferometry obsolete. Bolton's career prospects now seemed to depend on developments occurring elsewhere, beyond the doors of Radiophysics. We now trace these developments that helped to shape the future course of Bolton's career.

When Taffy Bowen joined the Radiophysics Lab in 1944 he already had an outstanding record in the development of radar. His group in England (which included Robert Hanbury Brown) created the first airborne radar by miniaturising the bulky sets, small enough to fit into the noses of aircraft. Bowen spent most of the war based at the Radiation Laboratory at the Massachusetts Institute of Technology (known as the MIT Rad Lab), where he was chief liaison officer between the US and British radar research programs. Bowen got to know a number of very influential American scientists including Lee DuBridge, the director of the MIT Rad Lab. Immediately after the war DuBridge was appointed president of the California Institute of Technology (Caltech) [1].

By about 1950 there was growing concern among American astronomers that the US was being left behind in the exciting new field of radio astronomy. Although Jansky and Reber had pioneered the field, the US failed to capitalise on its early lead. Several small groups were formed in university departments and at the Naval Research Laboratories in Washington, DC, but none of these groups rivalled the centres established in Sydney, Cambridge and Manchester. Encouraged by Jesse Greenstein, the head of Caltech's astronomy group, DuBridge decided that Caltech would take the lead in revitalising American radio astronomy. Pasadena was the home of Caltech and of the Mt Wilson–Palomar Observatories which operated the finest collection of optical telescopes in the world. DuBridge believed it was time to establish a major observatory for radio astronomy to complement America's lead in optical astronomy.

Bowen made a point of keeping in touch with his wartime contacts from the Rad Lab, including DuBridge who was impressed by the achievements of the Radiophysics group. Early in 1952 he invited Bowen to draw up a proposal to create the radio equivalent of the Mt Wilson–Palomar Observatories. Bowen proposed an observatory with a range of radio telescopes, the principal one being a large parabolic dish with a diameter in the range 200–250 ft (60–75 m). For the observatory's personnel, Bowen suggested a staff about the same size as the radio astronomy group at Radiophysics, which consisted at this time of ten research scientists plus a further thirty technical and engineering staff. Bowen's proposals were summarised in a report dispatched to DuBridge in May 1952 [2]. Implicit in the report, if the proposal did go ahead, was that Bowen would be invited to be director of the new facility with John Bolton to accompany him as his second-in-command.

Figure 7.1. Bolton with Taffy Bowen (right) at the tail of one of the RAAF aircraft used for the rainmaking trials. [courtesy: RAIA]

Until the future of the proposed new observatory was decided, Bowen persuaded Bolton to leave radio astronomy and join the Lab's cloud and rain physics group (see Figure 7.1). As discussed in Section 5.2, cloud and rain physics and the artificial stimulation of rainfall was the other main research activity at Radiophysics, with a staff and budget almost as large as the radio astronomy group. Bolton spent several months studying the properties of the silver iodide crystals used in the rainmaking trials, which led to the only research paper of his career unconnected to astronomy. He also took part in rainmaking trials in Victoria and northern Queensland. Although there were some promising early results, it was difficult to obtain firm evidence that cloud seeding had any significant effect on rainfall patterns.

By early 1954 Bowen's proposal to build a radio astronomy observatory at Caltech had been overtaken by other developments. Several of Bowen's wartime contacts encouraged him to look into the possibility of building a large radio telescope, not at Caltech, but in Australia. Bernard Lovell was already well advanced with plans for a 250 ft (75 m) dish at Jodrell Bank, so a similar Caltech instrument would be in direct competition with Lovell and probably miss out on the initial discoveries likely to be made. A large dish in the southern hemisphere would complement rather than compete with Jodrell Bank. Bowen was also encouraged to approach American philanthropic foundations to contribute funding for a giant Australian dish. In May 1954 the Carnegie Corporation in New York announced it would grant $250,000 towards an Australian dish. Shortly afterwards the Rockefeller Foundation announced it would grant the same amount on condition that the Australian government agreed to fund at least 50% of the cost of the project. Bowen's original proposal to build an American dish partly staffed by Australians had been transformed into an Australian dish partly funded by American grants.

These developments did not alter DuBridge's decision to build a major observatory for radio astronomy at Caltech. With Taffy Bowen committed to an Australian dish, DuBridge decided to invite John Bolton, assisted by Gordon Stanley, to start up radio astronomy at Caltech. In October 1954 Bolton was offered an initial two-year contract with the title of Senior Research Fellow in Physics and Astronomy [3].

7.1 High in the Sierras – The Owens Valley Radio Observatory

Bolton and his family arrived in Pasadena in January 1955. His first task was to establish an office in Caltech's Division of Physics, Mathematics and Astronomy and recruit staff to the new radio astronomy group. Caltech itself was founded in 1891 and during its early years was a vocational college, teaching a wide variety of subjects. In 1907 George Ellery Hale of the Mt Wilson Observatory was elected to the college's board of trustees. Hale decided to transform the teaching-only college into an independent university institute specialising in science and technology. He renamed the college the California Institute of Technology to reflect this change. Under the guidance of Hale's fellow trustee Robert Millikan, physics and astronomy emerged as two of the strongest areas at the new institute. Caltech also began a visiting scholars program, attracting many well-known European scientists. The most famous was Albert Einstein who made three extended visits in the early 1930s and cemented Caltech's new status as a world class research centre [4].

In the late 1940s Caltech went through a second period of expansion following the appointment of Lee DuBridge to the new position of president. DuBridge set about recruiting the best talent that he could find. The first was Robert Bacher who would be Bolton's boss at Caltech. At the end of the war Bacher had been appointed to the new US Atomic Energy Commission, the only scientist on its governing board, but he resigned to take up DuBridge's offer to become head of the Division of Physics, Mathematics and Astronomy. Another coup for DuBridge was the hiring of Jesse Greenstein, appointed to the faculty in 1948 from the University of Chicago. His brief was to build up the astrophysics group in preparation for the opening of the 200-inch Hale Telescope on Palomar Mountain, the world's largest telescope. Greenstein learnt of Jansky's cosmic noise while studying for his PhD and published the first theoretical paper attempting to explain the phenomenon [5].

When Bolton arrived at Caltech the consensus among Greenstein's astrophysics group was that the best instrument to build would be a Mills Cross. Bernie Mills had spent six months at Caltech in 1953 taking a crash course in astronomy, while the first full-scale cross was under construction at the Fleurs field station. Mills gave several talks on the work at Radiophysics, including an account of the impressive performance of the pilot model of the cross at Potts Hill. The immediate success of the full-scale cross when it came into operation in mid-1954 reinforced the view that radio astronomy at Caltech should start with its own version of the cross. Bolton disagreed with the idea. During his time at Caltech, Mills had spent several weeks visiting a group at the Department of Terrestrial Magnetism in Washington, DC. The group had also been impressed with Mills' ideas and, with funding from the Carnegie Foundation, began building a cross in Maryland shortly after his visit. The cross began a survey of the northern sky early in 1955 and so would obviously pre-empt any research program attempted by a Caltech cross [6].

Bolton's main objection, however, was a more scientific one. Within a year of coming into operation at the Fleurs field station, the Mills Cross had exploded the number of southern radio sources from the 104 sources painstakingly catalogued at Dover Heights to over 600. Similarly, the Cambridge group in its second sky survey published in 1955 – known as the 2C survey – claimed (erroneously as it turned out – see below) that the northern hemisphere sources numbered not in the hundreds, but close to two thousand. For Bolton, the priority was not to build another instrument to increase the number of known sources. Rather, the priority would be to design an instrument that could reveal the identities of this rapidly growing number of sources. Only a handful had been identified with optical objects, simply because their positions could not be measured with sufficient precision to make an identification.

The Caltech instrument would not focus on discovering new sources, but rather on revealing the identity of those already known.

Bolton drew up a proposal for an interferometer consisting of two parabolic dishes, with diameters as large as possible depending on the funds available. The large collecting area of the dishes would mean the telescope could detect very faint and distant sources, while the accurate surface of the dishes would allow operation at high frequencies producing a sharper resolution. Both dishes would be movable, mounted on two east–west and north–south rail tracks, which would allow the baseline distance between them to be varied. Overall, the telescope would lead to an improvement in the measured positions of sources by at least an order of magnitude. Bolton noted in the proposal [7]:

> ‘The main aim of the research program will be to identify several hundred radio stars with visible objects and to study the mechanism responsible for the generation of the high level radio emission. At present, almost 2000 radio stars have been detected [and] seven or eight of the identified objects appear to be grand catastrophes in nature where conditions exist for extremely efficient but little understood conversion of other forms of energy into radio frequency energy. It is likely that of the 2000 radio stars known, a large proportion are of [this] type. Recently in the study of the radio stars most workers have placed more emphasis on the search for greater and greater numbers of radio stars, rather than the more difficult task of identification. The program at the California Institute of Technology will, it is hoped, remedy this deficiency.’

Unlike the giant parabolic dishes underway in England and Australia, to be funded by a combination of government and philanthropic foundations, most of the radio astronomy centres springing up across the United States were being funded either by the US Navy or US Air Force. Although the military had no interest in radio astronomy as such, the technology of radio astronomy – the aerials, the receivers, the electronics – were very much of relevance in areas such as radar and telecommunications. Of the three arms of the military, the Navy was particularly active in promoting research through its Office of Naval Research (ONR), which funded radio astronomy startups at a number of universities such as Michigan, Illinois and, later, Berkeley. Caltech was also well and truly on its list. In July 1955 the

ONR accepted Bolton's proposal, without change, and agreed to fund both the capital and operating costs of the interferometer and one-half of Bolton's salary.

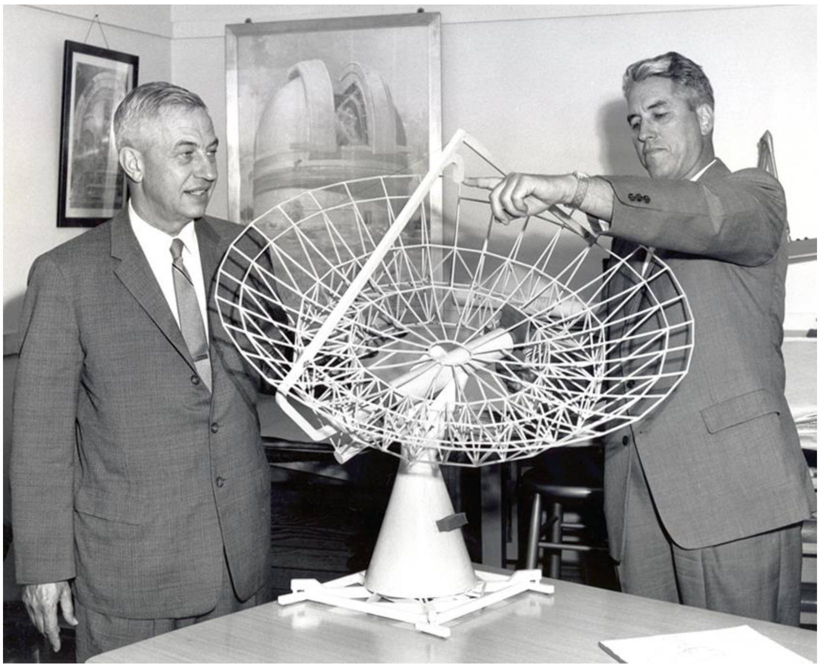


Figure 7.2. Caltech president Lee DuBridge (left) and chief engineer Bruce Rule with a model of one of the two 90 ft dishes to form the Owens Valley interferometer. [courtesy: Caltech Archives]

Shortly after his arrival at Caltech in June 1955, Gordon Stanley began a search for a suitable site for the interferometer. Stanley was under instructions from Robert Bacher that the site was not to be more distant than a two-hour drive from Pasadena, so that operating costs could be kept to a minimum. Stanley explored possible sites as far south as the Mexican border, but none proved suitable. The increasing number of towns and freeways along the coastal plain between Pasadena and San Diego were generating too much radio noise and it would only get worse. Numerous sites were investigated, including the Mojave Desert, but again all proved too noisy. Stanley decided to search further afield in the Sierra Nevada Mountains and discovered the Owens Valley, named after the explorer Richard Owens. Although 400 km due north of Pasadena, Stanley knew immediately that he had found the ideal site. It was a deep valley, sparsely populated, with large stretches of flat land covered with low

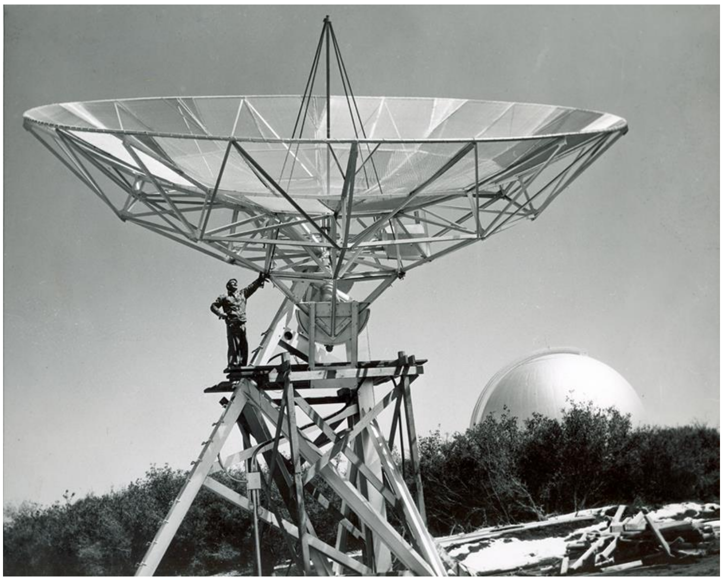


Figure 7.3. Bolton and the 32-foot radio telescope on Palomar Mountain, published in the *Los Angeles Examiner* in April 1956. The dome in the background houses the 200-inch Hale telescope. [courtesy: Caltech Archives]

Figure 7.4. At the Owens Valley site in September 1958: Bruce Rule (left), Bolton and Grote Reber. [courtesy: Jim Roberts]

semi-arid scrub and, most importantly, surrounded by high mountains that would provide a natural shield to outside sources of interference. All that remained was to persuade Bacher that the scientific advantages of the site far outweighed the additional costs of operating such a remote observatory [8].

Figure 7.5. The dedication ceremony of the Owens Valley Radio Observatory in December 1958: (above) the twin 90 ft dishes mounted on the east–west rail track. (below) Rudolph Minkowski (left), Robert Bacher, Bolton and two members of the Caltech Board of Trustees. [courtesy: (above) Jim Roberts and (below) Caltech Archives]

The detailed design of the Caltech interferometer was carried out by a team led by Bruce Rule, Caltech's chief engineer (see Figure 7.2). Rule was considered to be the dean of American telescope engineers. In the late 1940s he had overseen the completion of the 200-inch Hale telescope and since then had completed a 48-inch

Schmidt telescope also on Palomar Mountain. In parallel with the design stage, Bolton and Stanley built a 32 ft (9.7 m) dish on Palomar Mountain (Figure 7.3). Although primarily a test instrument, the dish was used to carry out a survey of the 21 cm hydrogen line and led to the first publication by the Caltech radio astronomy group [9]. The on-site assembly at Owens Valley began in July 1958, with the pre-fabricated components freighted from an engineering firm in Phoenix, Arizona (Figure 7.4). The dedication ceremony was held the following December (Figure 7.5), even though only one of the dishes had been completed. It took until late 1960 before the interferometer was fully operational, partly because a funding shortfall delayed the construction of the north–south rail track [10].

Early in 1959 the Cambridge group published the third or 3C catalogue of radio sources, superseding the 2C catalogue from 1955 which had listed almost 2000 sources. The 2C catalogue had been shown to be seriously flawed because of a problem known as ‘confusion’, which leads to an excess of faint, but fictitious, sources [11]. To minimise the problem the 3C catalogue used the same interferometer as 2C, but modified to operate at a frequency twice as high (159 MHz) and with a resolution four times better. The catalogue listed a more modest total of 471 sources, less than a quarter of the number claimed in 2C. In the meantime, Bernie Mills and the Radiophysics group had continued to expand and refine the Sydney catalogue, consisting of well over 1000 sources. The 3C catalogue agreed far better with the Sydney one than 2C, but the agreement was still far from perfect.

Owens Valley was now in a position where it could adjudicate between the Sydney and Cambridge surveys and decide which was the most complete and accurate. At a latitude well south of Cambridge, Owens Valley was well placed geographically to study the broad band of sky covered by both catalogues. Observations began at 960 MHz using the first of the two 90 ft dishes completed and by mid-1960 several hundred sources from the two catalogues had been investigated. Over 95% of the Cambridge sources were confirmed, although there were discrepancies in the measured positions for about a third. The Sydney catalogue did not fare as well. Only 75% of the compact sources could be confirmed and it was worse for the sources that Mills had labeled ‘extended’ or ‘probably extended’, with a confirmation rate just above 50%. Many of these sources were not in fact extended, but blends of two or more sources that could be resolved by the Owens Valley dish.

A group at Jodrell Bank led by Henry Palmer had been making its own observations of the 3C sources, using the 250 ft dish and a small antenna stationed at locations at distances of up to 100 km. The Jodrell interferometer with its extremely long baseline could resolve the structure of sources in far greater detail than Owens Valley, though it lacked what is known as phase stability and could not accurately measure the positions of sources. The Jodrell group reported that a handful of 3C sources had angular sizes less than 10 arcsec, unlike the typical 30 to 50 arcsec for most radio galaxies known at this time. Bolton took a particular interest in these sources which were clearly unusual. After the interferometer became fully operational, he assigned Tom Matthews to measure a more accurate position for one of them, the source 3C295. Rudolph Minkowski had recently taken a very high quality photograph of this small patch of sky using the 48-inch Schmidt telescope at Palomar. The source 3C295 appeared to coincide with a very faint wisp of a galaxy.

Minkowski decided to take a closer look with the Hale telescope. The spectrum was indeed unusual, but he was able to detect a bright emission line of oxygen. To his great surprise, the oxygen line was redshifted by 0.46, equivalent to a velocity of recession of 46% of the speed of light. This was more than double the redshift of the most distant object known in the Universe. In 1951 Milton Humason had used the Hale telescope to measure a record redshift of 0.20 for a galaxy in the constellation Hydra. However, despite considerable effort by Humason, the record had remained unbroken for the remainder of the decade [12].

The source 3C295 held the record for the most distant galaxy for 15 years, but not for the most distant object. The discovery of a new class of sources known as quasars saw the redshift record tumble frequently during the 1960s. For Bolton, the identification of 3C295 was especially pleasing for other reasons. Minkowski's observing run on the Hale telescope was his final one before retirement and proved a fitting finale to his illustrious career. Another positive outcome of 3C295 was that the identification required the combined effort of Cambridge, Jodrell Bank and Owens Valley. The identification of 3C295 was a fine example of successful international collaboration, one involving three of the four leading radio astronomy groups in the world.

7.2 Receding Horizons – The Discovery of Quasars

Taffy Bowen and John Bolton had an understanding at the time when Bolton departed Radiophysics for Caltech. If Bowen succeeded in his ambition to build a giant radio telescope in Australia, then Bolton would be his preferred choice as director of the new facility. With the announcement of the grants from the Carnegie and Rockefeller foundations in 1954–55, the Commonwealth government agreed to match these funds dollar-for-dollar which secured the future of the project. The initial design study was carried out by the renowned English engineer Barnes Wallis (Figure 7.6), while the detailed design was carried out by the London firm of Freeman Fox and Partners. In the 1920s the firm's co-founder, Sir Ralph Freeman, had designed the Sydney Harbour Bridge, Australia's best known landmark. In contrast to the early Radiophysics field stations, the site chosen for the telescope was a shallow valley near the township of Parkes in central New South Wales, well to the west of Sydney's sprawling suburbs. Part funded by the Americans, designed by the English, the telescope was very much an international project with the German firm of Maschinenfabrik Augsburg Nurnberg (MAN) selected for the construction. In December 1960 Bolton resigned from his position at Caltech and returned to Australia to oversee the construction and commissioning of the Parkes telescope [13].

Edwin Hubble once noted: 'The history of astronomy is a history of receding horizons' [14]. The discovery of quasars in the early 1960s with their extraordinary energy output took the astronomical world by storm. Originally known as quasi-stellar objects or quasi-stellar radio sources, the latter term was soon shortened to quasars. Although the origin and nature of these objects is not yet well understood, there is general agreement that quasars have played a central role in the creation and evolution of the Universe. Since Jansky's first observations over 80 years ago, the discovery of quasars is undoubtedly one of the finest achievements of radio astronomy. It was one in which both John Bolton and the Parkes telescope played a major part. The path to the discovery of quasars started at Caltech in late 1960 [15].

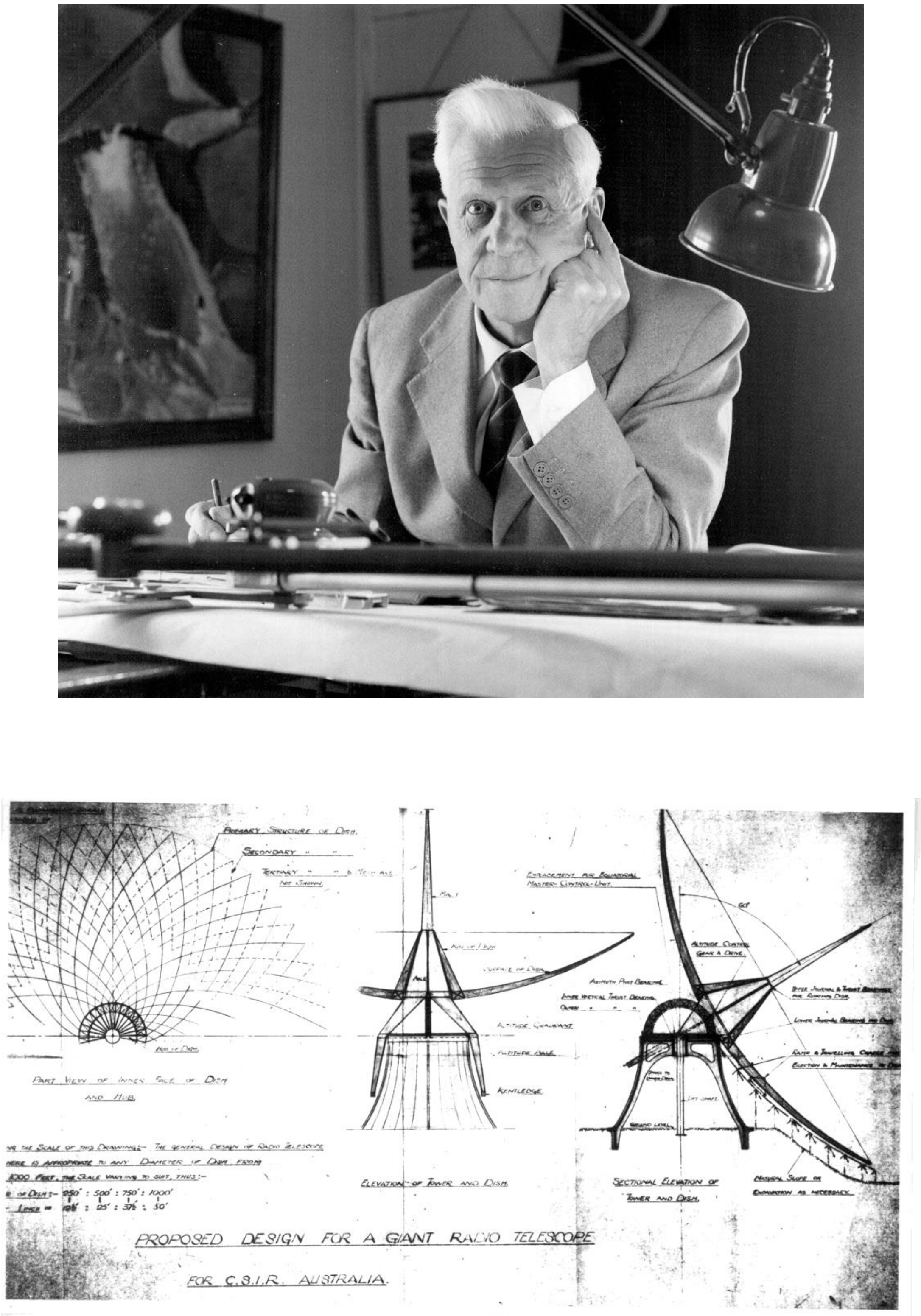


Figure 7.6. The prominent English engineer Barnes Wallis (1887–1979) carried out the initial design study of the Parkes Telescope. He introduced new ideas on how to keep a rigid shape for the parabolic surface and how to point the dish with great accuracy. [courtesy: (above) Vickers (London) and (below) RAIA]

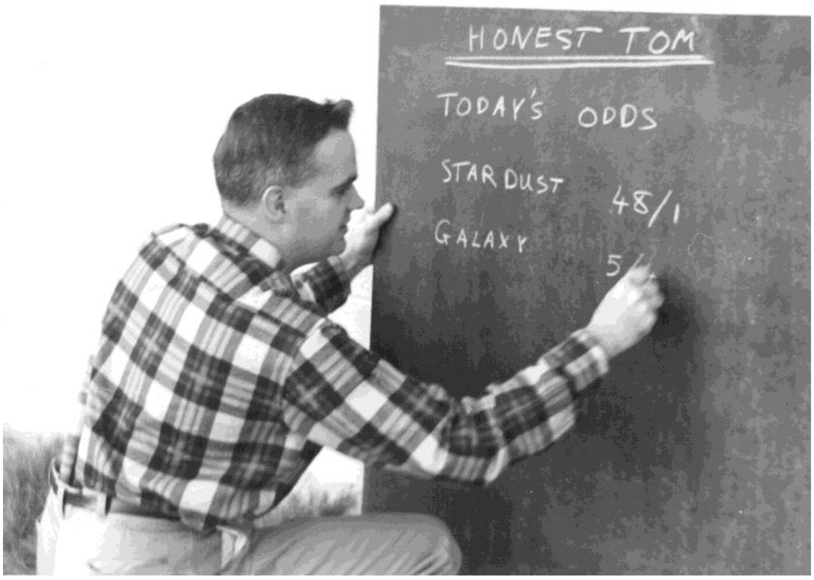


Figure 7.7. Caltech postdoc Tom Matthews jokingly speculates on the nature of the source 3C48. Matthews measured an accurate position at Owens Valley late in 1960, but for over two years the source remained a mystery. [courtesy: Jim Roberts; credit: Dan Harris].

As noted in the previous section, Henry Palmer and a group at Jodrell Bank had been observing a number of the 3C Cambridge sources with a very long baseline interferometer. They found that several sources had very small angular sizes, including the radio galaxy 3C295 with its record redshift of 0.46. The source 3C48 had an angular size less than 4 arcsec, making it an exceptionally compact source. After Tom Matthews (Figure 7.7) measured an accurate position for 3C48 at Owens Valley, Bolton found that it appeared to coincide with a sixteenth magnitude star on the Palomar plate. Further work by Jesse Greenstein, Allan Sandage and Guido Münch on the Hale telescope showed the star to have an unusual blue colour made up of a combination of strong emission and absorption lines unlike that of any star known. The most puzzling feature was that the object's spectrum apparently contained no evidence for the presence of hydrogen, the major constituent of all normal stars. Several attempts were made to fit the spectrum to known emission lines, including one by Bolton who thought that he had successfully identified a number of lines. As he reported to Pawsey in November 1960 [16]:

> 'A couple of weeks ago I wrote to Taffy and said I thought we had a star. It is not a star. Measurements on a high dispersion spectrum suggest the lines are those of Neon[V],

> Argon[III] and [IV] and that the redshift is 0.367. The absolute photographic magnitude is then –24 which is two magnitudes greater than anything known. The continuum is still going up towards the blue end and may very well be synchrotron. I think this must be the early stage of a radio galaxy, probably short lived and so very rare. The absence of the usual O[II] lines is probably due to it being very hot – the main emission probably comes only from the centre 1 kpc. The source is 3C48.'

A brief report on this highly-unusual object by Matthews, Bolton, Greenstein, Sandage and Münch (the chronological order each had joined in the observations) was made by Sandage at the Christmas 1960 meeting of the American Astronomical Society in New York. The report did not include Bolton's redshift estimate of 0.37 for 3C48. Although two magnesium and neon lines seemed to provide a good fit, their wavelengths were a few angstroms away from their correct values. These were small discrepancies but Jesse Greenstein, in particular, argued that it would cause critics to doubt an extraordinary claim that the object – after the radio galaxy 3C295 – was the second most distant object known in the Universe. Instead, the report cautiously noted [17]:

> 'Since the distance of 3C48 is unknown, there is a remote possibility that it may be a very distant galaxy of stars; but there is general agreement among the astronomers concerned that it is a relatively nearby star with most peculiar properties. It could be a supernova remnant. The radio output may be intrinsically ten million times stronger than the Sun's.'

The evidence seemed to point strongly to the discovery of the first true radio 'star' in the local Galaxy. Despite the initial interest in 3C48 the Caltech group made no further observations on the object, as Bolton recalled [18]:

> 'Looking back it is ironic that what would now be considered an excellent fit between permitted and forbidden lines in quasars stopped the clock for nearly three years. I did not pursue the matter further, for the interferometer still had to undergo tests on the newly completed north–south baseline; my personal affairs in California wound up and my family embarked on the S. S. Orcades for the journey back to Australia in mid-December for the start of the first steelwork construction at Parkes.'

While the nature of 3C48 baffled the Caltech astronomers, another strand in the quasar story had begun elsewhere. The technique of lunar occultations uses the Moon to pinpoint a precise position for a source. The technique was well known in astronomy and used to study the detailed shape and motion of the Moon against the backdrop of fixed stars. In radio astronomy the technique can be used in reverse. Because the precise position of the Moon's limb is known at any given time, a careful measurement of the times when a radio source disappears behind the Moon (immersion) and then later reappears (emersion) enables the position of the source to be calculated to great precision. The accuracy of the technique is limited essentially by uncertainties in the detailed shape of the terrain and mountains on the Moon's limb. In December 1960, shortly before the puzzling results for 3C48 had been announced, Cyril Hazard at Jodrell Bank used a lunar occultation to measure the position of 3C212 to an accuracy of 3 arcsec (Figure 7.8).

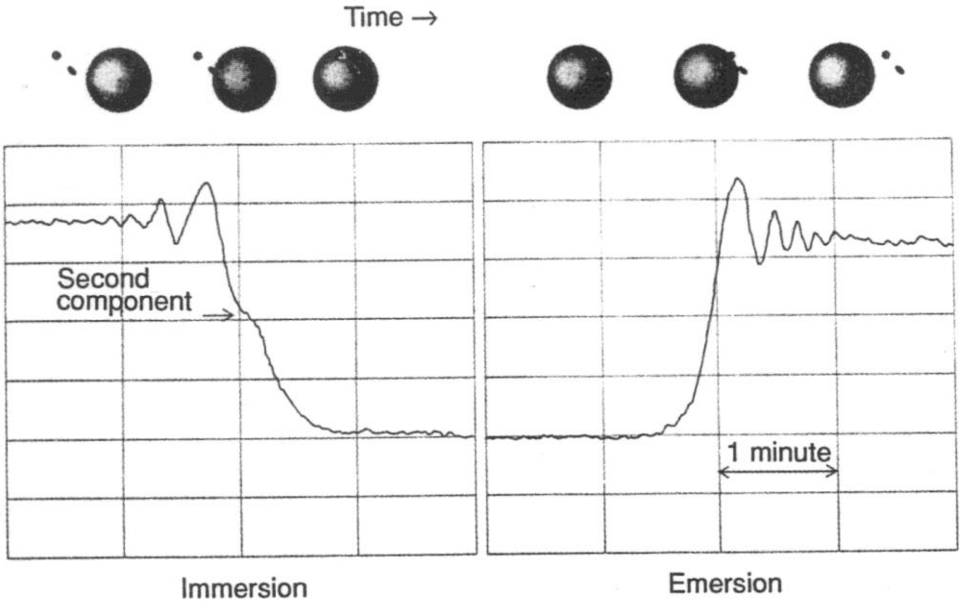
Figure 7.8. Cyril Hazard (left) and John Shimmins at Parkes carried out lunar occultation observations on the source 3C273. The precise position measured for the source led to the discovery of quasars, the most distant objects in the Universe. [courtesy: (left) AIP Emilio Segré Visual Archives, John Irwin slide collection; (right) Robert Shanks]

In 1962 a second opportunity arose for Hazard to use the technique to measure the position of another Cambridge source, 3C273. By coincidence 3C273 would undergo a series of lunar occultations at southern latitudes during 1962, an event that occurs only about once every twenty years. By then, Hazard had joined a new astronomy group at the University of Sydney to work with Robert Hanbury Brown on a new instrument for measuring the diameter of stars, known as an intensity interferometer. The first occultation observed at Parkes in May 1962 proved inconclusive. Only the emersion of 3C273 was recorded before the source passed outside the field of view, but the occultation curve did at least indicate the source to be of very small angular size. Preparations for the second occultation were made with utmost care. All roads leading to the telescope were closed, unnecessary electrical equipment on the site shut down, and rehearsals carried out over a three-day period. There was however a problem. The times of immersion and emersion were sent to Hazard by the Nautical Almanac Office in Sussex, England. However, the times were calculated for the latitude and longitude of the Fleurs field station and so the projected times for Parkes, almost 400 km to the west of Fleurs, were known only approximately. John Shimmins (Figure 7.8), who worked with Hazard on the occultations, recalled [19]:

> ‘It seemed likely that at emersion the zenith angle of the telescope would be slightly greater than 60°. The telescope will only go to 60° and then there is a solid stop. When you reach it bells ring and the brakes are applied. So, we simply removed the safety stops from operation for that observation. Just to be certain, John Bolton took a grinder and cut away some of the housing of the zenith angle bearings. This meant that we could tip the dish by almost another degree. During the occultation the rim of the dish was practically touching the ground.’

The precaution of grinding away part of the housing turned out to be unnecessary, but it illustrates the lengths Bolton would go to ensure the success of the observations.

The observation of the occultation carried out by Hazard, Shimmins and Brian Mackey on 5 August 1962 went according to plan (see Figure 7.9). An analysis of these records, combined with the results of a third partial occultation (immersion only) in October, revealed that 3C273 is not a simple point source, but a double with each component about 6 by 2 arcsec in area with a separation of about 20 arcsec between the two centres. In the meantime, the precise immersion and emersion times had been sent to the Nautical Almanac Office which then supplied Hazard with the relevant data on the shape and motion of the Moon’s limb. After a detailed analysis, Hazard calculated the position of the double object 3C273 to an accuracy of 1 arcsec – at the time the most accurate position determined for a radio source.



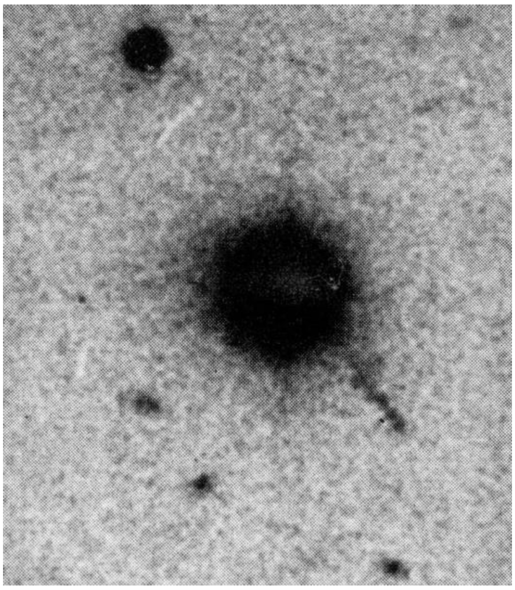


Figure 7.9. Lunar occultation of the quasar 3C273 recorded at Parkes on 5 August 1962. (above) From left to right: the signal from the two-component source is blacked out, with the curve showing where the second component starts to disappear. Because of their orientation with respect to the Moon's limb, both components emerge at the same time. The wavy curve is caused by diffraction of the signal around the Moon's limb. (below) Palomar photograph of 3C273 showing the unusual jet extending at lower right. Note the similarity between this object and the galaxy NGC 4486, identified with the Virgo A source by the Dover Heights group in 1949 (see Figure 4.11). [courtesy: RAIA]

By coincidence, Rudolph Minkowski happened to be visiting the Radiophysics Lab at this time, following his retirement from Mt Wilson–Palomar. Minkowski brought a number of sky plates, including one for the region of sky containing 3C273. The radio position calculated by Hazard coincided exactly with a double source on the plate, the compact core of one radio component matching with what appeared to be a blue star, the other with a peculiar jet extending out from the star in one direction.

Next came the turn of Maarten Schmidt, a Dutch astronomer who had joined the Caltech astrophysics group in 1959. In December 1962 Schmidt measured the optical spectrum of 3C273 and found six strong emission lines. Four of these lines formed a simple harmonic series with a separation and strength similar to the type of series which characterises hydrogen and certain highly ionised atoms. However, an extensive search of the tables of spectroscopic data failed to identify the atom responsible. After six weeks puzzling over the lines, Schmidt finally found the solution. Rather than belonging to an unusually rare atom, four of the emission lines in the spectrum belonged to hydrogen, but with an entirely unexpected redshift of 0.16. The redshift measured by Schmidt corresponded to a distance of about 3 billion light-years. And yet, in view of the brightness measured for the object – thirteenth magnitude – this had a startling implication: the comparatively small and compact source 3C273 was radiating at least 100 times more energy than the most luminous galaxy then known.

Schmidt’s success in identifying the spectrum of 3C273 prompted Jesse Greenstein (Figure 7.10) to return to the spectrum of 3C48, which had remained a mystery since Sandage had announced the peculiar features of this star-like object at the New York meeting in December 1960. To his surprise Greenstein was able to recognise a number of lines in the spectrum belonging to magnesium, oxygen and neon, but redshifted by an extraordinary 0.37. Bolton had been right all along. The source 3C48 was at a distance of 7 billion light-years, over twice the distance of 3C273, and with a recession velocity close to one-third the speed of light. The English astronomer Fred Hoyle wrote to his close friend Bolton from Cambridge [20]:

Figure 7.10. Jesse Greenstein, head of the Caltech astrophysics group at the time of the discovery of quasars. Initially Greenstein believed quasars to be ultra-dense radio 'stars' closeby in the local Galaxy. [courtesy: AIP Emilio Segré Visual Archives]

> 'Just a note to inform you that the Caltech chaps have changed their story about the sources of very small angular diameter. According to a letter from Willy [Fowler], Maarten Schmidt and Jessie are giving $\Delta\lambda/\lambda = 0.37$ for 3C48. My memory isn't what it was, so I may be wrong in thinking this is very close to what you said a long time ago. If it really is your identification (was it Na VI?) you might want to watch the situation!'

As mentioned above, it was assumed that 3C48 and 3C273, along with several other 'quasi-stellar' objects under suspicion, were compact radio stars in the local Galaxy. Greenstein had already sent a theoretical paper to the *Astrophysical Journal* arguing that these objects were nearby, ultra-dense stars formed from the collapsed cores of supernovas, with emission spectra arising from intense radioactive decay of material on the object's surface. The redshifts measured for 3C273 and 3C48 led Greenstein to quickly withdraw his paper from publication. Rather than nearby stars within the Galaxy, these were among the most distant objects in the Universe.

A letter by Hazard, Mackey and Shimmins on 'Investigations of the radio source 3C273 by the method of lunar occultations' was published in *Nature* in March 1963, accompanied by three others. One by Maarten Schmidt reported the redshift of 3C273, noting that the object is ‘about 100 times brighter optically than the most luminous galaxies which have been identified with radio sources thus far’ (see Figure 7.11). The second paper by J. Beverly Oke at Mt Wilson–Palomar reported the energy characteristics of the 3C273 optical spectrum, while the third by Greenstein and Matthews gave the results for 3C48, concluding with the understatement that ‘so large a redshift, second only to that of the intense radio source 3C295, will have important implications in cosmological speculation.’ [21]

Figure 7.11. Maarten Schmidt and Bolton at the Parkes Observatory in March 1963. The same month, Schmidt published the redshift of 3C273 in *Nature*. [courtesy: Bolton family]

The publication of the first papers on 3C273 and 3C48 in March 1963 triggered one of the most intensive hunts ever witnessed in astronomy [22]. Shortly afterwards Schmidt and Matthews announced that 3C47 is a quasar with a redshift of 0.43. Next came 3C147 with a redshift of 0.55, exceeding the value of 0.46 for the radio galaxy 3C295 found by Matthews, Bolton and Minkowski late in 1960. In April 1964 Hazard and Brian Mackey in collaboration with Bill Nicholson at the Nautical Almanac Office announced the discovery of a further three quasars detected by the lunar occultation technique at Parkes [23]. By the end of 1964 a total of 40 quasars had been reported, leading some astronomers to predict that these extraordinary objects make up a substantial fraction of the hundreds of radio sources already catalogued, but unidentified. Several of these quasars were found to have redshifts approaching 2.0, corresponding to distances of approximately 10 billion light-years. In less than two years the discovery and study of quasars had led to a doubling of the distance scale of the Universe. The distance record was broken regularly during the 1960s, with several record-breaking quasars detected at Parkes. At one stage in 1966, the four most distant quasars were all Parkes sources. As we see in the next section, the most distant of the four, PKS 0237–23 with a redshift of 2.22, was identified by Bolton in collaboration with astronomers at the Palomar and Lick Observatories.

7.3 An Australian Icon – The Parkes Radio Telescope

The inauguration of the Parkes telescope in October 1961 marked an important stage in the development of science in Australia (see Figure 7.12). 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 a different level the Parkes telescope also had a major impact in shaping the way astronomy developed in Australia. In contrast to the 1940s and 1950s, when small Radiophysics teams 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 fulltime specialist group of technicians would look after the maintenance and routine operation of the telescope and radio astronomers would now have to compete with their peers for observing time on the new instrument. In this respect the completion of the Parkes telescope marked the arrival of 'big science' in Australia and the arrival of radio astronomy as a mature scientific discipline. In some respects too, it marked the end of the most innovative and interesting period.

In this section we will give a brief overview of John Bolton's research from 1961 up to his early retirement in 1981, caused by ill-health. Bolton's research program remained essentially unchanged from the Dover Heights years: to survey the southern skies; to detect hundreds of new sources; to identify as many as possible with optical objects; and to classify the objects into well-defined types. As the inaugural director

Figure 7.12. An Australian icon – the Parkes dish shortly before its inauguration in October 1961. On horseback is ‘Austie’ Helm who sold part of his farm to CSIRO to provide a site for the telescope. The site was named the Australian National Radio Astronomy Observatory (ANRAO), with Bolton as its inaugural director. [courtesy: Bolton papers, National Library of Australia]

of the Parkes telescope much of Bolton’s time was taken up with routine administrative duties and other projects unrelated to his research. As one notable example, over the period 1969–72 Bolton directed the involvement of Parkes in the Apollo program of manned Moon landings. At this time NASA did not have a large dish in the southern hemisphere, so it arranged with CSIRO to contract the Parkes dish to be a part-time tracking station. Parkes received the television signals of the Apollo 11 moonwalk in July 1969, an event of unique historical importance [24]. Parkes also played an important role in rescuing the ill-fated Apollo 13 mission and was part of each of the remaining missions up to the final Apollo 17 in December 1972. Bolton devoted approximately half his time to the Apollo program during this period.

The First Parkes Survey at 408 MHz (1962 – 66)

The first survey of radio sources began late in 1962 at a frequency of 408 MHz (wavelength 75 cm). The strategy was to divide the sky accessible at Parkes (from declination +20° north down to the south celestial pole –90°) into four zones and then to make a preliminary scan of each zone. Even with a rapid telescope drive rate, over twenty full nights of observation were required to cover each zone. Once this preliminary ‘finding’ survey had been made at 408 MHz, all of the sources were then examined in more detail at the higher frequencies of 1420 and 2700 MHz. These more detailed observations of each zone took a further forty nights to complete. The survey of the first zone from declination –20° to –60° by Bolton, Frank Gardner and Brian Mackey was published in April 1964 and listed almost 300 sources [25].

A feature of this first survey paper was how each source was named. Until then new sources were usually named after the observatory to first detect them; for example, 3C48 referred to the 48th source listed in the third Cambridge catalogue. The Parkes sources were now listed in the form PKS 0106+01 with the numerals specifying its approximate position: the first two digits give the hour of right ascension and the next two digits give the minutes, followed by the (±) degrees of declination. In 1973 a designation similar to this was adopted by the International Astronomical Union to standardise the names of sources from all observatories. This was the second occasion where Bolton had a significant influence on the nomenclature of radio sources. As we saw in Chapter 4, early in 1948 he introduced the convention of naming radio sources after the constellation in which they are found, followed by the letters A, B, …, to indicate the strongest, second strongest, etc. source in that particular constellation.

The catalogues for the other three zones were completed and published during 1965–66 to give a grand total of 2133 sources for the first Parkes survey. The complete catalogue recorded the position of each source, its flux density (ie. emission intensity), its degree of polarisation, its angular diameter, and whether or not the source had been included in the earlier survey carried out with the Mills Cross at the Fleurs field station (see Section 6.4). Another parameter listed was the spectral index, describing how the flux density of the source varies with frequency and which could be determined from separate observations at 408, 1420 and 2700 MHz. The value of this index provided a strong clue to the nature of the source. For example, if the source was compact with a flat spectrum it could be provisionally identified as a quasar, independently of whether it had been identified with an optical object.

In December 1964 Bolton made the first of several extended visits to California to begin the task of optically identifying the sources in the new Parkes catalogue. He used the Palomar Sky Survey, the comprehensive collection of 2000 photographic plates he had learnt to use previously during his time at Caltech. The survey covered all of the northern sky and the southern sky down to a declination of –33°, overlapping with approximately half the Parkes catalogue. Bolton and Allan Sandage carried out a number of observing runs on the 200-inch Hale telescope to confirm or rule out some of the optical identifications. Of those confirmed, about 90% were galaxies (down to magnitude –18) and about 10% were quasars. Over the next 18 months Bolton would author or co-author 16 papers, the most productive period of his career. All but three of the papers reported the optical identifications of extragalactic objects in the Parkes catalogue [26].

With such a large sample it was now possible to recognise four distinct classes of extragalactic radio sources. First are the 'normal' galaxies that emit radio power on a scale similar to our local Galaxy. Second are galaxies of high intrinsic luminosity where the radio source is smaller than the optical galaxy and is probably associated with the galactic nucleus. Next are the radio galaxies such as Cygnus A which represent only about 0.1% of all galaxies and which radiate at levels up to a million times that of normal galaxies. They are almost exclusively elliptical galaxies of very high intrinsic luminosity. Fourth are quasars which are characterised by a marked excess of ultraviolet radiation and which are the most luminous objects known in the Universe.

In August 1966 Bolton made a second extended visit to California, on this occasion collaborating with Tom Kinman at the Lick Observatory near San Francisco. Bolton and Kinman published a series of papers identifying 43 of the Parkes sources as quasars, with the identifications based on photographic, photoelectric and spectroscopic measurements taken at three telescopes: the 48-inch Palomar Schmidt (Bolton), the 120-inch Lick (Kinman) and the 200-inch Hale (Sandage). One of the quasars 0237–23 created particular interest with a highly unusual spectrum. Detailed studies of the spectrum by Kinman and Halton Arp led to the identification of emission lines with a redshift of 2.22, breaking the previous redshift record. PKS 0237–23 was not only the most distant object known in the Universe, but its apparent magnitude showed this quasar to be at least five times more luminous than any other object [27].

The Second Parkes Survey at 2700 MHz (1967 – 79)

As we have seen, the main project at Parkes during the period 1962–66 was a sky survey at 408 MHz leading to the first Parkes catalogue of 2133 sources. On completion of the survey Bolton embarked on an even more ambitious project. The observations at 1420 and 2700 MHz had revealed that about 10% of sources had the flat or inverted spectra characteristic of quasars. Bolton predicted that a high-frequency survey at 2.7 GHz would reveal a source population with a much higher proportion of quasars. However, such a survey would be difficult to carry out primarily because the telescope beamwidth is much narrower at the high frequency, and thus it would take much longer to survey a given area of sky. The 408 MHz survey took almost four years to complete. As it turned out, the 2.7 GHz survey would take 12 years to complete and preoccupy Bolton for most of the 1970s.

Although the optical identification program during the 408 MHz survey had been largely a solo project, Bolton began to involve other Parkes staff in the 2.7 GHz survey. In a series of four papers during 1971–73 Bolton, Bruce Peterson, John Shimmins and Jasper Wall confirmed the identifications of a further 129 southern quasars [28]. The increasing number of quasars meant a statistical analysis could be made of their properties. There appeared to be three main classes of quasars:

- The first are those mainly found in low frequency surveys such as the 3C and 4C Cambridge catalogues. The flux density falls away quite steeply at higher frequencies, similar to most radio galaxies. The majority of these objects have emission-line spectra and so their redshifts can be determined

- The second class are the flat spectrum sources where there is no overall decrease in flux density at higher frequencies. About half the quasars in the 2.7 GHz survey were of this type. They are also characterised by large variations in flux density over time. The variations at 2.7 GHz are typically 30% in a year and variations in optical brightness are even greater. A small fraction of these objects show no emission lines and so their redshifts cannot be measured

- The third class are very stable quasars that show no variation in flux density by more than about 1%, even over a timescale of ten years. Optically these objects have very strong emission lines. They are excellent sources for calibrating the performance of telescopes such as Parkes.

The fourteenth and final part of the Parkes 2.7 GHz survey, covering the zone –4° to –15°, was published in April 1979, twelve years after the project started. Bolton was an author on all but two of the parts. In his autobiographical memoir for the Royal Society, Bolton estimated that close to fifty PhD students, postdocs and Radiophysics staff had made significant contributions to the catalogue. The number of sources reported in the 14 parts totalled over 8000, ranging from declination +25° down to the south celestial pole. Aside from the catalogue papers, the great majority of Bolton's papers during the 1970s reported either the optical identification of sources or the redshifts of quasars in a particular zone. As Bolton had predicted, the 2.7 GHz survey showed dramatically how the overall appearance of the radio sky varies according to frequency. In the 408 MHz survey, most of the strong sources detected were shown to be giant elliptical galaxies, relatively closeby, while in the 2.7 GHz survey a much higher proportion of the strong sources were quasars. Similarly, quasars accounted for approximately 10% of sources in the 408 MHz survey, but rose to approximately one half in the 2.7 GHz survey.

In a paper in *Monthly Notices* in 1978 Don Morton, Ann Savage and Bolton showed that the quasar PKS 0438–43 had the highest radio luminosity of any known source. The source was identified on a UK Schmidt plate and its spectrum measured on the newly-completed Anglo-Australian Telescope at Siding Spring in New South Wales. A plot of the flux density versus frequency showed that 0438–43 is a classic flat spectrum quasar. The flux density rises from 80 to 160 MHz and then barely changes until 10 GHz where it starts to fall away. A redshift of 2.9 was measured for 0438–43 and, with the distance to the source known, the absolute luminosity of the source could be calculated. PKS 0438–43 was shown to be almost one hundred times more luminous than the Cygnus A source, which in comparison is relatively closeby. Perhaps it is fitting that Bolton's career as an astronomer began with the famous Cygnus A source and drew to a close with the discovery of an object with even more extraordinary physical properties. The paper concluded with two sentences that would have been better suited to a popular astronomy magazine, rather than a conservative research journal: 'The total radio luminosity of 0438–43 has the same power as the optical output from ten trillion Suns. Alternatively, the output of radio energy is equivalent to that of seven Type I supernovae per day!' [29]

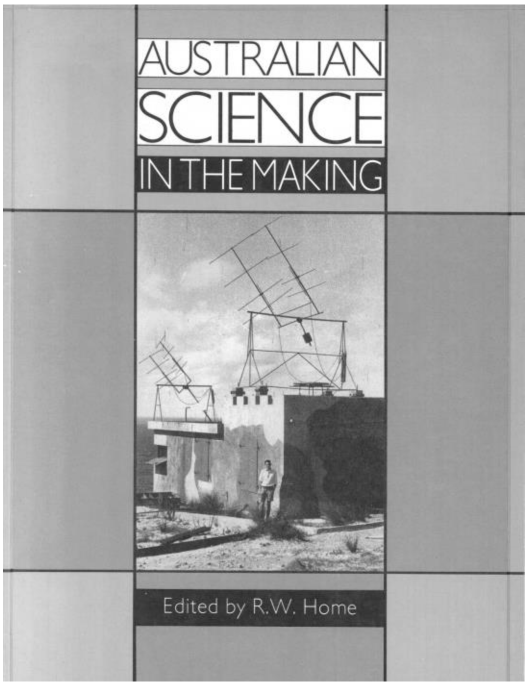


Figure 7.13. One of the official events to mark Australia's Bicentenary in 1988 was the publication of the book *Australian Science in the Making*, edited by the eminent historian of science Rod Home. Gordon Stanley's photo of John Bolton and the Dover Heights blockhouse in May 1947 featured on the cover (see Figure 3.3). [courtesy: Cambridge University Press]

In 1979 Bolton suffered a severe heart attack and went on extended sick leave. His health continued to deteriorate and in 1981 he was forced to take early retirement, aged 58. Apart from his time at Caltech (1955–60), Bolton spent his entire career (1946–81) on the staff of the Radiophysics Lab (later renamed the Australia Telescope National Facility).

Bolton's contributions to the foundation and development of radio astronomy were recognised in a number of different ways (see e.g. Figures 7.13 and 7.14). He received the highest awards from both the American and British astronomical communities:

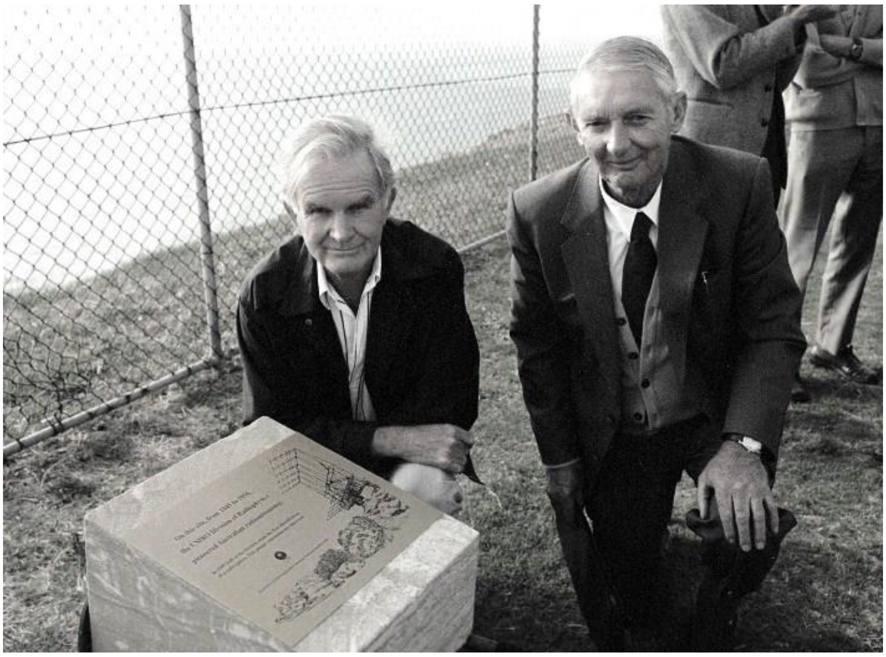


Figure 7.14. With Bruce Slee at the unveiling of a plaque in November 1989 at Rodney Reserve, the site of the Dover Heights field station. The plaque celebrated the birth of extragalactic radio astronomy forty years earlier. The field station was converted into a rugby field with the plaque close to the halfway line. [courtesy: RAIA]

- In 1967 he was invited by the US National Radio Astronomy Observatory to present the inaugural Karl Jansky Memorial Lecture; in 1968 he presented the Henry Norris Russell Lecture to the American Astronomical Society; in 1977 he received the Gold Medal of the Royal Astronomical Society; and in 1988 he was awarded the Bruce Medal by the Astronomical Society of the Pacific

- Bolton was elected a Foreign Member of the American Academy of Arts and Sciences; an Honorary Fellow of the Indian Academy of Sciences; and a Foreign Associate of the US National Academy of Sciences

- In 1969 he was elected a Fellow of the Australian Academy of Science and in 1973 a Fellow of the Royal Society of London (the award he valued most)

- Bolton also served two terms as a Vice-President of the International Astronomical Union (1973–79).

After his retirement Bolton moved from Parkes to the small town of Buderim on Queensland's Sunshine Coast. He died of pneumonia on 6 July 1993, aged 71. He is survived by his wife Letty and two sons Brian and Peter.

Notes to Chapter 7

[1] Bowen (1987), chapter 12.

[2] 'A Large Radio Telescope for Radio Astronomy', Bowen to DuBridge, 22 May 1952, NAA file A1/3/11, part 1.

[3] See NAA file PH/BOL/005 for the relevant correspondence.

[4] See Goodstein (1991) for a history of Caltech.

[5] See note [14] in Chapter 6. Caltech had a number of current or future Nobel Laureates on its staff. The physics laureates included Carl Anderson (1936) for his discovery of the positron; Richard Feynman (1965) for his contribution to the development of quantum electrodynamics (QED); Murray Gell-Mann (1969) for his development of the quark theory of particle physics; and Willy Fowler (1983) for his studies of the nuclear reactions that lead to the formation of the natural elements.

[6] Bernie Mills interview with author, 6 July 2007, Roseville, NSW. Bowen and DuBridge had agreed in 1953 for a member of the Sydney group to spend six months at Caltech to share information between the optical and radio astronomers. Bowen could not decide whether to recommend Bolton or Mills, both of whom he ranked very highly: 'Their characteristics are so similar that it is hard to distinguish them.' Bolton's departure to rainmaking cleared the way for Mills. Bowen to DuBridge, 26 November 1952, DuBridge papers, Caltech Archives.

[7] John G. Bolton, 'A Proposal for a Radio Astronomy Facility at the California Institute of Technology', 12 pp., July 1955. I am grateful to David Munns (City University of New York) for providing a copy of the proposal.

[8] Gordon Stanley, unpublished memoir, Stanley papers. I am grateful to his daughter Teresa Stanley for providing a copy of the memoir.

[9] Bolton *et al.* (1958), *Publn Astron. Soc. Pacific* **70**, 544–55.

[10] See Cohen (1994) for the origins of the Owens Valley Radio Observatory.

[11] If two relatively weak sources are in the primary beam of an interferometer, their fringes can 'beat' together to form what appears to be a third source, but one which is in fact fictitious. The problem of confusion had been discussed in detail in the Dover Heights survey on discrete sources with large angular widths [see Bolton *et al.* (1954b) and Section 6.4]. It appears that this paper was not read by the Cambridge group.

[12] The record redshift was reported by Minkowski (1960), *Astrophys. J.* **132**, 908–10, and by Bolton at the London URSI meeting in September 1960. Bolton recalled: 'Shortly after the result was known Milt Humason came into my office. He said "I want congratulate you. You have succeeded in doing what I spent the last ten years of my life trying – and failed".' See Bolton (1990), p. 382.

[13] In February 1958 Bolton had been appointed to the tenured position of Professor of Radio Astronomy and Director of the Owens Valley Radio Observatory. See Robertson (1992), part 2, for a detailed account of the funding, design and construction of the Parkes telescope.

[14] Quoted in Robertson (1956), *Scient. Am.* **195** (3), 81.

[15] For two recent and detailed accounts of the discovery of quasars see Hazard *et al.* (2014) and Kellermann (2014).

[16] Bolton to Pawsey, 16 November 1960, NAA file F1/4/BOL/2.

[17] The report on 3C48 by Matthews *et al.* to the AAS meeting in New York was briefly summarised by an anonymous reporter in *Sky & Telescope* **21** (1961) 148.

[18] Bolton (1990), p. 382.

[19] Shimmins interview with author, 7 March 1984, Albert Park, Victoria.

[20] Hoyle to Bolton, 19 February 1963, NAA file C4633.

[21] For the four letters cited see *Nature* **197** (1963) 1037–41.

[22] See e.g. Waleska (2007).

[23] See Hazard *et al.* (1964), *Nature* **202**, 227–28.

[24] See Sarkissian (2001). The TV signals of the moonwalk received at Parkes were relayed to NASA in Houston, and then broadcast globally to a record audience of over 600 million people. The involvement of Parkes in the Apollo 11 moonwalk was the subject of a popular Australian film *The Dish*, released in October 2000. The lead role of Cliff Buxton (aka John Bolton) was played by the New Zealand actor Sam Neill.

[25] See Bolton *et al.* (1964), *Aust. J. Phys.* **17**, 340–72.

[26] For the first of the identification papers see Bolton *et al.* (1965), *Aust. J. Phys.* **18**, 627–33. Identifications were suggested for 55 extragalactic sources, eight of which were quasars.

[27] See Arp *et al.* (1967), *Astrophys. J.* **147**, 840–45. PKS 0237–23 was included in the *Guinness Book of Records* under the heading ‘Remotest Object’. The entry was accompanied by a photo of its discoverer, Dr John G. Bolton. Two years later, the entry had to be updated when PKS 0237–23 was overtaken by the Cambridge source 4C25.5 with a redshift of 2.38.

[28] For the first of the four papers see Shimmins *et al.* (1971), *Astrophys. Lett.* **8**, 139–43. Bolton recruited Wall from the University of Toronto, while Peterson was a postdoc at the Mt Stromlo Observatory near Canberra.

[29] Morton *et al.* (1978), *Mon. Not. R. Astron. Soc.* **185**, 735–40. Two of the data points on the 0438–43 spectrum were measurements at 80 and 160 MHz made by Bruce Slee using a solar radio telescope in northern New South Wales. Bruce and John had remained good friends, but this was the first professional exchange between the two since their Dover Heights days.

Chapter 8

Concluding Remarks

In this final chapter I will attempt to draw together the main points and conclusions of John Bolton's career during the Dover Heights years 1946–54. In a series of bullet points I will summarise Bolton's personal achievements, the significance of the research by the Dover Heights group, and the contribution of the Radiophysics Lab to the development of radio astronomy. Next, I will suggest a few topics related to this thesis which might prove fruitful areas to investigate by future researchers. Although much has already been written about the Radiophysics Lab and its staff over the period 1945–60, the field has by no means been fully covered. This is an indication of both the breadth and depth of the contribution made by the Radiophysics Lab to the early development of radio astronomy. Finally, I will make a few remarks about Bolton's later years, showing that the Dover Heights period was the first stage of what turned out to be a remarkable career in astronomy – both radio and optical.

As we saw in Chapter 2, in terms of his background and training, Bolton was well qualified to be a pioneer of radio astronomy. He did not begin formal education until grade 6 in primary school and he was largely self-taught and independent in his thinking. He showed his academic talent at secondary school and in his final year won two scholarships to study at Trinity College, Cambridge. He majored in mathematics and physics in his Bachelor of Science degree which provided a solid theoretical foundation for his career ahead. Bolton enlisted in the Royal Navy in 1942 and spent two years developing airborne radar equipment and then a further two years as a radio officer onboard an aircraft carrier. He became an expert in getting radio and electronic equipment to operate correctly, often in difficult physical conditions and often under the urgency of wartime deadlines. In retrospect we can see that his four years in the navy were an excellent preparation for a career in radio astronomy.

In 1946 Bolton joined the Radiophysics Laboratory in Sydney, part of the Council for Scientific and Industrial Research (the forerunner of CSIRO). The Radiophysics Lab had been formed in 1940 to carry out secret wartime research on radar for the Australian armed forces. By the end of WWII the Lab had a large and highly-skilled staff and was the best-equipped laboratory of its kind in Australia. The Lab investigated a wide range of possible peacetime applications of radar. Radio astronomy turned out to be the unexpected success story and, by 1950, half the resources of the Lab were devoted toits pursuit. If the Radiophysics Lab had been a government research organisation with a rigid research program, it seems unlikely that radio astronomy would have emerged to become one of the great success stories of Australian science.

The discovery of radio waves from space was made in 1932 by the physicist Karl Jansky, who worked for the Bell Telephone Laboratories in New Jersey. Jansky was given the task of identifying the sources of interference to a new trans-Atlantic radio communication service. In a fine example of serendipity in science, Jansky found that there was a steady component in the interference that appeared to have no terrestrial origin. Jansky’s discovery was followed up by the radio engineer Grote Reber, who built his own radio telescope at his home near Chicago. Reber produced sky maps of the radio emission which seemed to suggest that the emission was produced by ionised clouds of matter in interstellar space. At the end of WWII, the time was ripe for other enterprising radio engineers and physicists to enter the field.

- A major conclusion of this thesis is that it was Bolton and colleagues who took the next major step forward in ‘cosmic’ radio astronomy

When Bolton joined the Radiophysics Lab in September 1946 he was stationed at a cliff-top field station at Dover Heights, a short distance south of the entrance to Sydney Harbour. During the war a number of investigators had independently discovered radio emission from the Sun. The Radiophysics Lab began its own program of solar observations in October 1945 and Bolton was assigned to the team recording and analysing the emission. He speculated that, in addition to the Sun, other astronomical objects might also be the source of radio emission. With colleague Bruce Slee, he tried to detect emission from various objects such as the Moon and the planets, but the attempt failed.

Several months later Bolton decided to investigate a report by an English group that there was unusually strong and variable radio emission coming from a small region in the constellation of Cygnus. With colleague Gordon Stanley, Bolton used a technique known as sea interferometry which uses one or more Yagi aerials. The cliff-top aerial points out to sea where it picks up the direct radio signal from above the horizon and the signal reflected from the sea surface to create an interference pattern. In June 1947 Bolton and Stanley succeeded in detecting emission from the Cygnus constellation and, from the distinctive interference pattern, they were able to conclude that the emission came from a very compact point-like source. By the end of 1947 Bolton, Stanley and Slee had found a further five of these point-like sources:

- The Dover Heights group provided strong evidence for a new class of astronomical objects previously unknown to astronomers

- The existence of these point-like sources indicated that the radio emission studied by Jansky and Reber could be partly resolved into individual discrete sources

- The prevailing view that the mechanism for radio emission – ionised clouds of matter in interstellar space – seemed most unlikely to explain the intense emission from these discrete sources.

As we saw in Chapter 4, the celestial positions of the first radio sources were known only approximately and so it was not possible to positively identify them with particular visible objects located in crowded star fields. Bolton decided to find a better observing site than Dover Heights. He needed a site where the cliffs were much higher (and thus would give better resolution) and where he could observe the sources rise above the horizon in the east and then set below the horizon in the west (and thus give better estimates of sources of error such as atmospheric refraction). A suitable site could not be found on the eastern seaboard of Australia, so Bolton chose the north island of New Zealand where there were very high cliffs on both the east and west coasts near Auckland. Gordon Stanley built a sea interferometer on a mobile trailer which was shipped to New Zealand in June 1948.

Bolton and Stanley returned to Sydney after three months of observations. It took Bolton several months to analyse the data and by the end of the year he had derived relatively accurate positions for the four strongest sources, named after the constellations in which they were found – Cygnus A, Taurus A, Centaurus A and Virgo A. The Cygnus position was still not accurate enough to make a positive identification, but each of the other three coincided with unusual optical objects. Taurus coincided with the Galactic object known as the Crab Nebula, a supernova remnant which had been studied intensely by astronomers. The other two, Centaurus and Virgo, coincided with what appeared to be peculiar extragalactic objects. Bolton, Stanley and Slee published their first three identifications in a short note to *Nature*:

- The apparent identifications with extragalactic objects challenged the view that the discrete sources, or 'radio stars', were nearby objects in the local Galaxy

- The first optical identifications established a bridge between traditional optical astronomy and the fledgling new radio astronomy

- The first optical identifications marked the birth of extragalactic radio astronomy, arguably the most influential branch of astronomy during the second half of the twentieth century.

By 1950 the Dover Heights group was one of a number of Radiophysics groups involved in radio astronomy at field stations in and around Sydney. Approximately half the radio astronomy resources were devoted to radio studies of the Sun and the other half to studies of 'cosmic' radiation. Collectively, the Radiophysics radio astronomy group under the leadership of Joe Pawsey (Bolton's boss) was the largest in the world. The two main rivals to Radiophysics were the group at the University of Cambridge led by Martin Ryle and the group at the University of Manchester led by Bernard Lovell. Both these groups were however relatively small and during the postwar austerity in England could not match the resources available at Radiophysics. As described in Chapter 5, Bolton spent most of 1950 touring the major astronomical observatories and the emerging radio astronomy centres in England, Europe and North America. He lectured extensively on the research at Dover Heights and helped to publicise the work at Radiophysics:

- By 1950 the Radiophysics Lab was the largest and best resourced centre for radio astronomy in the world, the first occasion where Australia became a leader in a major branch of the physical sciences

- After his tour of centres in Europe and North America, Bolton was undoubtedly one of the best connected and most knowledgeable of the growing band of scientists referring to themselves as ‘radio astronomers’.

The second half of the Dover Heights period, covering the years 1951–54, was a time of consolidation that built on the successes of the late 1940s. A succession of larger Yagi arrays and improvements to receivers and electronics led to a significant improvement in the sensitivity and resolution of the sea interferometers. Similarly, it was a period of increasing competition from other groups, both from within the Radiophysics Lab and from a number of groups emerging overseas.

In Chapter 6 we returned to the source Cygnus A which, as discussed in Chapters 3 and 4, was the primary focus of the Dover Heights group during 1947–49. Unlike the Taurus, Centaurus and Virgo sources, the attempts to identify Cygnus with an optical object turned out to be frustrating failures. However, increasingly-accurate positions for the source made by Bernard Mills at Radiophysics and by Graham Smith at Cambridge finally led astronomers at the Mt Wilson–Palomar Observatory to identify the source with a distant object – one that appeared to be two galaxies in collision. The identification, more than any other event, convinced astronomers of the importance of this new branch of astronomy:

- As the third brightest object in the radio sky, the identification of Cygnus A with a very distant object demonstrated the power of radio astronomy to probe much deeper into the Universe than optical astronomy.

Until the early 1950s the Dover Heights research program was based almost exclusively on the technique of sea interferometry. In 1952 the group branched out by building a large parabolic dish in the sandy surface of the field station. The transit telescope was used to map radio emission along a band of sky containing the plane of the Milky Way and led to the discovery of the exact position of the Galactic nucleus. The discovery helped prompt the International Astronomical Union in 1958 to define a new set of Galactic coordinates based on the new position:

- The discovery of the Galactic nucleus was another striking example of radio astronomy being able to make a discovery beyond the reach of traditional astronomy

The discovery of the Galactic nucleus was the swansong of the Dover Heights field station. Without the prospect of funding for a major new instrument, operations were wound back until the eventual closure of the field station at the end of 1954.

Suggestions for Further Research

As discussed in the Literature Review (Section 1.1), the origins and early development of radio astronomy in Australia has been possibly the most intensively-studied chapter in the history of Australian science. The first to write about the history of Australian radio astronomy were the early practitioners, the radio astronomers themselves. Personal recollections have been given by, among others, Bolton (1982), Bowen (1988), Mills (2006), Pawsey (1961), Slee (2005) and Wild (1972), all prominent members of the Radiophysics Lab. Sullivan (1988) was the first professional historian of science to research the early history, his study forming a chapter in a book celebrating the bicentenary of Australian science. The books by Robertson (1992) on the history of the Parkes radio telescope and by Haynes *et al.* (1996) on the history of Australian astronomy both devote lengthy sections to the early years of radio astronomy.

More recently, the early radio observations at a number of Radiophysics field stations have been the focus of two PhD theses. Stewart (2010) has examined the solar radio astronomy carried out at the Penrith and Dapto field stations, while Wendt (2009) has examined the contributions of the Potts Hill and Murraybank field stations to international radio astronomy. In addition to these substantial studies, over the past ten years or so there has been a significant number of journal articles by Orchiston, Slee and others on various aspects of early Australian radio astronomy.

In view of this growing body of work, the question can be asked: Is there much of significance or of particular interest to attract further scholarly studies in the field? In my opinion the answer is yes. As noted above, the Radiophysics Lab was the largest of the early radio astronomy groups with enough resources to span most areas of solar and cosmic studies. Some of these areas have not been studied in any detail and could make interesting additions to the existing body of work.

This thesis has concentrated on the contributions John Bolton made to the early development of radio astronomy. It would be of considerable interest to see similar studies of other prominent members of the Radiophysics group. As noted in Chapter 7, after the closure of Dover Heights and Bolton's temporary departure from radio astronomy, Bernard Mills became the leading figure in cosmic studies at Radiophysics. His invention of the cross-type instrument led to the construction of a pilot model at Potts Hill and then in 1954 a full-scale version at the Fleurs field station. The Mills Cross dominated cosmic studies at Radiophysics for the rest of the decade. In its first full year of operation it detected and catalogued over 600 sources, dwarfing the number of 104 sources listed in the final Dover Heights sky survey carried out with a 12-Yagi array.

As it turned out, the Mills catalogue was in serious disagreement with the second Cambridge sky survey (known as the 2C survey) published by Martin Ryle and his group in 1955. The Cambridge group claimed almost 2000 sources, but in the area of sky common to both Cambridge and Sydney there was very poor agreement between the two surveys. Both surveys became caught up in the controversy that raged in the 1950s between two rival cosmologies – the big bang cosmology developed by George Gamow and colleagues in the US and the steady state cosmology developed by Fred Hoyle and colleagues in England. Ryle claimed that the 2C survey provided compelling evidence in favour of the big bang, while Mills maintained that his survey did not provide strong evidence in favour of either cosmology. A detailed study of role played by Mills and the Radiophysics Lab in the controversy would be of considerable interest.

Of course future historical studies of Australian radio astronomy need not be confined to the Radiophysics Lab or to the period 1945–60. It would be interesting to see a detailed study of the events beginning in 1960 when the Radiophysics group underwent a major transformation. Until then the personnel of the group had been relatively stable since 1945, but several developments led to deep divisions within the group. One development was the nearing completion of the Parkes telescope and Bolton's return to Australia from Caltech to be its inaugural director. All non-solar research would now be concentrated on this single instrument and the tradition of developing novel instruments such as the Mills Cross would cease. The group essentially divided into two camps, with opposing views on the future of Radiophysics. One camp supported Taffy Bowen, Bolton and the big dish, while the other camp remained loyal to Joe Pawsey and the view that innovation of new aerials and techniques was the way of the future. Another development was the decision in 1960 by the School of Physics at the University of Sydney to set up its own radio astronomy group, in direct competition to Radiophysics. Mills, Christiansen and several other Radiophysics staff were recruited to the new university group, leading to a bitter rivalry that lasted until the end of the 1960s. A study of these events would probably be as much sociological as historical, but nevertheless of interest in how it shaped the future development of radio astronomy in Australia.

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Chapter 7 provides a brief overview of Bolton's career after the closure of the Dover Heights field station in 1954. Bolton had the unusual distinction of being the inaugural director of two major observatories for radio astronomy, beginning with the Owens Valley Radio Observatory built by Caltech (director 1955–60) and then followed by the Parkes Observatory built by CSIRO (director 1961–71). It could be argued, in fact, that Bolton had the unique distinction of being the founder of not two, but three major radio astronomy centres. It would be pretentious to refer to the Dover Heights field station as an observatory and to describe Bolton as its director. The Dover group never exceeded five people, but Bolton was its clear leader and the one who set the research agenda. Although Joe Pawsey was his boss, Bolton resented attempts by Pawsey to influence the research agenda and, in fact, there were at least two occasions when Bolton openly challenged Pawsey's authority. The first was late in 1946 when Bolton and Bruce Slee set aside their solar observations in an unauthorised attempt to detect other cosmic sources of radiation. A second occasion was when the Dover group constructed the hole-in-the-ground telescope in secret, suspecting that Pawsey would not support the idea and veto the project. There is little doubt that Bolton was chiefly responsible for making the Dover group the world leader in cosmic radio astronomy in the immediate postwar years.

Chapter 7 briefly summarises Bolton’s later contributions to astronomy – both radio and optical – over the period 1955–81. There is however another legacy to his career which has not been mentioned. In the 1940s and 1950s the Radiophysics radio astronomers played no formal role in the supervision of university graduate students. Bolton’s first contact with graduate students was at Caltech where, in addition to the demands of building Owens Valley, he became the supervisor of eight PhD students. When Bolton returned to Australia in 1960, the astronomy group at the Australian National University, under the leadership of Bart Bok, had introduced a graduate program where students could be co-supervised by CSIRO radio astronomers. Over the years Bolton supervised a succession of ANU students. Most were impressed by his hands-on approach to research, including his insistence that students needed to be self-reliant, to understand their instruments and to be able to fix problems as they arose.

With the rapid expansion of radio astronomy in the 1960s, this ‘second generation’ of radio astronomers trained by Bolton went on to have successful careers of their own. A significant number became directors of observatories or heads of radio astronomy groups in universities. I will mention just two. Robert Wilson began his PhD at Caltech under Bolton and after graduating joined the Bell Telephone Labs in New Jersey, the same place where Karl Jansky made his momentous discovery in 1932. In 1965 Wilson and fellow radio astronomer Arno Penzias detected the cosmic microwave background radiation, a serendipitous discovery just as Jansky’s had been. The discovery ranks as one of the most important in astronomy during the twentieth century and led to the award of the Nobel Prize for Physics to Penzias and Wilson in 1978. Wilson was later appointed head of Bell’s radio physics research group. Ron Ekers was Bolton’s first Australian PhD student at Parkes and went on to make major contributions to the Parkes sky surveys. He was the inaugural director of the Very Large Array (1980–87) in New Mexico and then the inaugural director of the Australia Telescope National Facility (1988–2003), the successor to the Radiophysics

Lab. In 2003 he became the first Australian to be elected president of the International Astronomical Union.

As we also saw in Chapter 7, Bolton's research program in later years remained essentially unchanged from the Dover Heights years: to survey the southern skies; to detect hundreds of new sources; to identify as many as possible with optical objects; to measure their redshifts; and to classify the objects into well-defined types. Bolton published relatively little research during his time at Caltech (1955–60) as he focussed on the planning and construction of the Owens Valley Radio Observatory. However, one triumph in 1960 was the discovery of the radio galaxy 3C295, with a redshift more than double the most distant object known in the Universe. Bolton's role in the discovery of quasars was also examined in some detail, beginning with the observations on the source 3C48 at Caltech and concluding with the lunar occultation observations on 3C273 at Parkes.

Bolton's main research program in the 1960s was the Parkes sky survey at 408 MHz which took four years to complete and catalogued over 2000 sources. He made a number of extended visits to the Mt Wilson–Palomar and Lick observatories to carry out the optical identifications. Bolton's time was now divided equally between radio and optical astronomy. In 1967 the Parkes team began a more ambitious sky survey at 2.7 GHz, one that catalogued over 8000 sources and took 12 years to complete. Bolton's program of optical identifications received a boost with the construction in the mid 1970s of the Anglo-Australian Telescope and the UK Schmidt Telescope at Siding Spring in NSW, thus ending his reliance on the large telescopes on the US west coast. Bolton's career was a fine example of how the distinction between radio and optical astronomy (and indeed other bands of the electromagnetic spectrum) had become increasingly irrelevant.

Although Bolton took early retirement in 1981 because of poor health, he had enjoyed a remarkably productive career in astronomy since joining the Radiophysics Lab thirty-five years earlier. It is fair to say that no one had contributed more to the development of radio astronomy – in particular extragalactic radio astronomy – than John Gatenby Bolton.

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List of Tables and Figures

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Sources of Tables and Images

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Other Sources

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Appendix: Dover Heights Bibliography

[A] Papers by Dover Heights group in chronological order 1947–57

Authors: Bolton 19; Stanley 10; Slee 9; Westfold 5; McGee 2

Journals: *Nature* 7; *Aust. J. Scient. Res.* 6; *Aust. J. Phys.* 6; Other 4.

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[B] Most cited papers by the Dover Heights group

Citations include both astrophysical and historical articles. Total number of citations was 426 in May 2015. Source: SAO/NASA Astrophysics Data System (ADS) operated by the Smithsonian Astrophysical Observatory.

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The Dover Heights group 1946 – 54

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