21cm Hydrogen Line Radio Astronomy and The Parkes Radio Observatory

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This Essay was prepared as part of the requirements for the 2001 Astronomy Internet Masters Semester 2 “Topics in the History of Astronomy” offered by the University of Western Sydney, Australia.

ABSTRACT

Radio Astronomy is a relatively new science, less than 100 years old. Not long after the first observations of the radio sky World War II broke out. Radar research was seen as a key strategic area of the war effort. In Australia research was conducted by the Sydney based Radiophysics Division of the CSIR, which thrived and grew throughout the war. Afterwards a surplus of radio/radar scientists and equipment existed - the conditions were perfect for a boom in radio astronomy. The small autonomous teams of Radiophysics were particularly well suited to the work of early radio astronomy.

Meanwhile, the 1951 American discovery of the hydrogen line would open the way to mapping structures previously hidden by dust in the optical spectrum. 21cm hydrogen line radiation is unaffected, and the first maps of our Galaxy followed. Australia played a leading role in early hydrogen line observations.

As radio astronomy matured, it became clear that what was needed for continued leadership in hydrogen line research was large steerable accurately surfaced radio dishes, capable of focusing 21cm radiation. This was one key motivation for building the Parkes Radio Telescope.

This paper deals with coming of age of radio astronomy, the discovery of the hydrogen line, a key new tool, and the interwoven history of Australia's largest scientific instrument, built to keep the nation at the forefront of radio research. We begin with an overview of the state of radio astronomy after World War II, then quickly move to the developments that led to the discovery of the hydrogen line and early research in the field. Next we step back and look at the broad history of the Parkes facility. Finally the hydrogen line work in which Parkes is involved, and the future of such research is discussed.

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INTRODUCTION

The Parkes Observatory is operated by the Australian National Telescope Facility (ATNF), a division of the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The Parkes facility succeeded a number of smaller field stations developed and operated after World War II based on innovations in war-time radar and radio technology.

The Sydney based CSIR Radiophysics group (later the CSIRO division of Radiophysics) was, during the 1950s, the largest group in the world dedicated to radio technology research. In its infancy the study of radio astronomy was ideal for work by small innovative teams such as those which made up Radiophysics, each working independently with relatively cheap equipment. In this way that Australia established its leadership in the field early on.

At this stage a crucial discovery was made - neutral atomic hydrogen due to the phenomenon of electron 'flip transitions' - emits radio waves at 21cm (or 1420MHz), The existence of this radiation was first predicted in 1944, first observed in 1951 by American scientists, then confirmed almost immediately at Radiophysics. The hydrogen line allowed the mapping of large scale structures including our own Galaxy, the Magellanic Clouds, and far beyond.

However, technology rapidly developed and moved beyond the contributions that could be made through such "small science". Larger, more expensive instruments were needed if Australia was to remain at the forefront of Radio Astronomy.

The solution was the Parkes Radio Observatory. The centrepiece is a world class 210ft (64m) steerable radio dish. When commissioned on 1961 October 31, it was the largest in the southern hemisphere and the second largest in the world (after Jodrell Bank's Mark I). The instrument is capable of making observations from centimetre radio wavebands through to several metres (originally the surface was accurate enough only for 10cm). To achieve this, its shape deviates from a parabola by no more than a centimetre. The Parkes Telescope's relatively low cost and innovative design at the time ensured that it was well studied and acted as a prototype for other large dishes world-wide.

The instrument is well known in scientific circles for its Southern Hemisphere location and for multitude of scientific discoveries in which it has been involved. Hydrogen line research is just one area in which the telescope has enjoyed tremendous success. Other areas include Pulsar and QSO research, magnetic field polarization studies, and spectroscopic analysis of the lines of other molecules. It has been involved in numerous radio sky surveys, and continues to play a part in leading radio research.

The dish stands as an Australian icon, and a memorial to some of the most influential science to which Australia has contributed. Recently the film "The Dish", a popular fictional comedy/drama based on the role of Parkes in the first Apollo moon landing, was made (*The Internet Movie Database*) The use of Parkes in spacecraft tracking, particularly the first manned lunar mission - Apollo 11 – but also in the Voyager, Giotto and Galileo missions has maintained the dish's public profile. A visitor's centre at the site accommodates the public's interest, while allowing scientists to work with minimal interruption.

Figure 1 - The Parkes Radio Telescope

The main dish photographed from the grounds of the visitor's centre. In the background, obscured partially by the main dish is the smaller interferometer dish moved from Fleurs field station (now disused). Photograph by Javier Woodhouse 24/08/2001. Used with Permission.

Through the rest of this paper we will:

1) Outline the discovery of the hydrogen line and the development of hydrogen line research in the early years.
2) Describe the Parkes Radio Facility – how and why it was built, what work it has been involved in, why it is important scientifically and as an Australian icon, how it has been kept up to date, and what is its future.
3) Bring together the stories of hydrogen line research and the Parkes Radio Telescope.
4) Focus on the people at the heart of both these stories – their motivations, how they became involved, what roles did they play and what contributions did they make.

1. EARLY RADIO ASTRONOMY

1.1. Early Attempts and First Successes

The earliest experiments in radio astronomy failed, mostly due to a lack of knowledge of the nature of radio emissions from celestial objects. Among those that did not succeed were Thomas Edison, Oliver Lodge and Charles Nordmann. (*Robertson P. 1992: 8*). The earliest success was accidental, made in 1932 by Karl Jansky, who discovery that one type of interference he experienced with his Bell Laboratories ship to shore radio equipment was celestial in nature, varying with the rise and set of constellations (initially he suspected the sun that caused the interference, but its daily recurrence was tied to the sidereal day, and drifted away from the sun). Jansky published his findings and eventually moved on to other things. (*Robertson P. 1992: 10-14*)

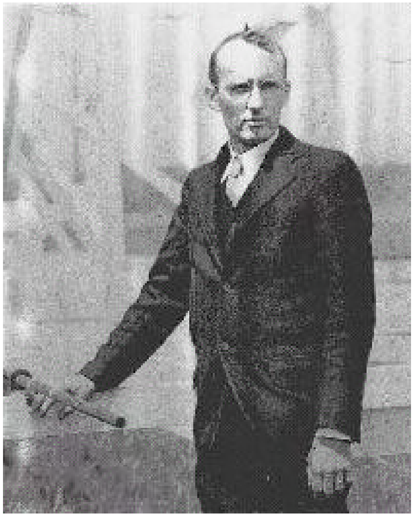


Figure 2 - Karl Jansky circa 1933

Perhaps the best known picture of Karl Jansky.

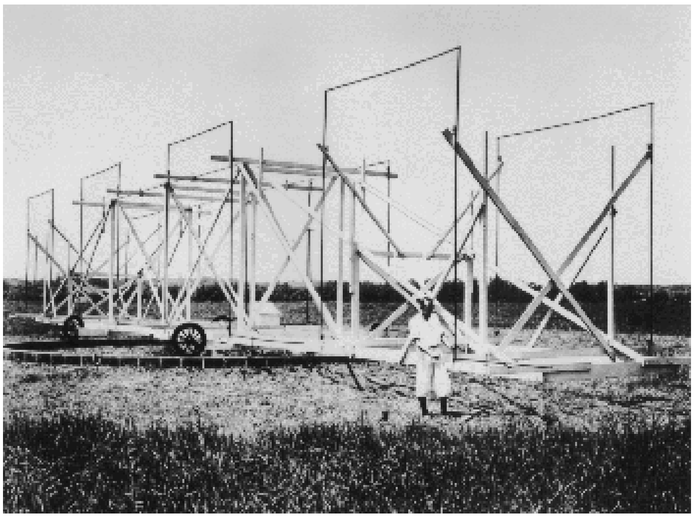


Figure 3 – Karl Jansky's Original 21MHz Antenna

Note the turntable mounting that earned it the name "Jansky's Merry-Go-Round".

Both photos taken from (*Karl Jansky and the discovery of cosmic radio waves*).

Another remarkable early pioneer, Grote Reber, took up the work at a more practical level in 1937. He built the first parabolic dish specifically designed for radio astronomy in his backyard in Wheaton Illinois, and carried out measurements between midnight and six each day (when there was the least terrestrial interference). Working observations into his schedule after full time work at the Chicago radio company, he slept between coming home from work, and midnight. His backyard radio dish was 31ft (9.5m) in size, could be pointed accurately, and cost $1300. It was constructed by Reber in 4 months while temporarily unemployed. With this instrument he constructed the first celestial radio maps of the sky, plotting radio strength vs. position. (*Robertson P. 1992: 14-16*).

Figure 4 - Grote Reber in 1937

This picture of Grote Reber is taken from the web site "Grote Reber and his Radio Telescope", reproduced from Reber G. 1988. See references for details.

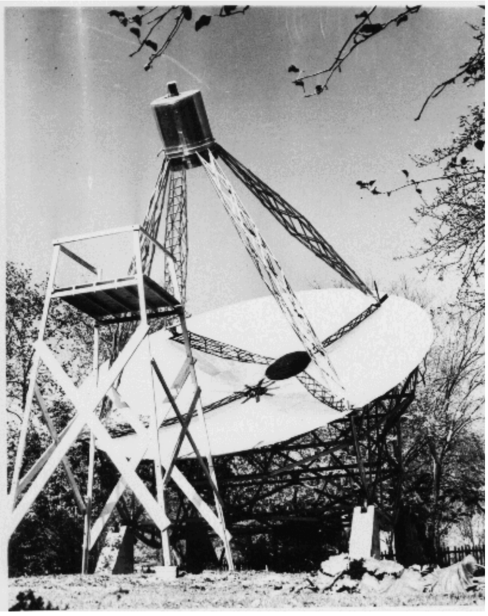


Figure 5 - Reber's Backyard Radio Telescope

Taken from the web site "Grote Reber and his Radio Telescope"

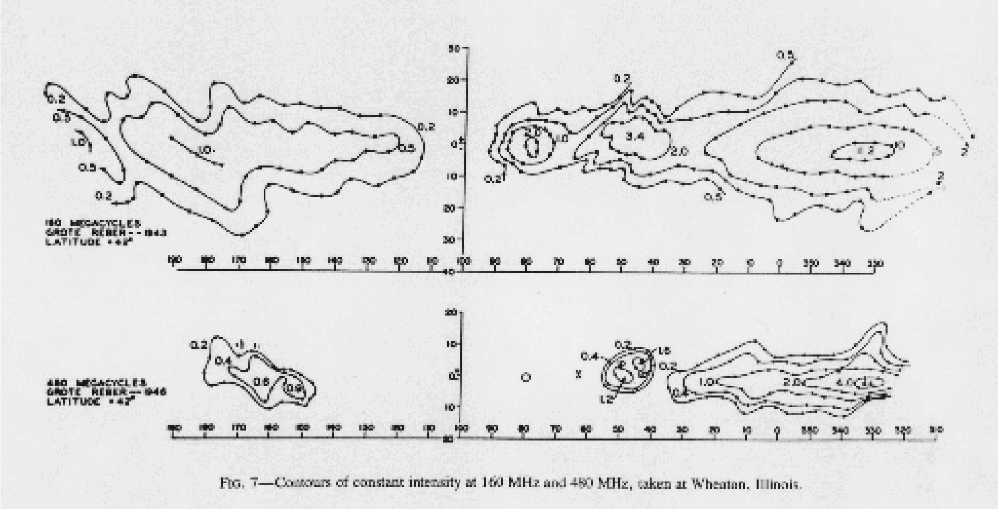


Figure 6 - Early Contour Map by Grote Reber

Taken from the web site "Grote Reber and his Radio Telescope", in turn reproduced from Reber G. 1949. See references for details.

Despite attempts at publicity for Jansky's work by Bell Labs, and the publication of both men's findings in the appropriate journals, Jansky and Reber's findings were largely ignored initially. Only the post World War II technology boom renewed interest. In particular accelerated development in radar and radio communications meant that in 1945 there was an abundance of surplus equipment and qualified staff in radio engineering world-wide.

1.2. World War II and the Radio Boom

During the Second World War, radar began to play a vital role. Used as an early warning device, it was possible to inform an intended ally of the nature and size of an immanent attack. Range and strength of transmitters, and the reliability and sensitivity of receivers also provided an advantage. A stronger signal could travel farther, and a more sensitive receiver could pick up signals farther away. The technique of bouncing signals off the stratosphere solved the problem requiring a direct line of sight between transmitter and receiver (though weather phenomenon could greatly affect this). The force with the better equipment could therefore provide the better reconnaissance, potentially giving a decisive advantage in battle.

In Australia, the Radiophysics group was formed and given responsibility for research into radar. The group grew each year as the war progressed, starting with staff and ending with 300 by the end of the war. (*Robertson P. 1992: 22-28*)

Radiophysics played a vital part in creating mobile radar stations called light weight air-warning tents, small and reliable enough to make transportation by the allied forces during the war worthwhile. These were used on the Australian coast, near Darwin, and in the Pacific. (*Robertson P. 1992: 24*). Eventually airborne radar units, which could be used for remote reconnaissance, were developed.

Radar provided another wartime advantage, which carried over into peace-time research. The ability to detect aircraft in the sky, or ships on a harbour allowed for better traffic control - today radar is employed by all but the smallest airports. On a larger scale radar proved a valuable navigational aid, ensuring that planes and ships were not lost, and conserving fuel etc.

During and immediately after the war, the big names associated with the Parkes telescope made their reputations and gained vital experience which would help them in constructing the Parkes dish. Fred White became administrator of Radiophysics, Joseph Lade Pawsey led the basic research group, having proven himself a competent experimenter under Ernst Rutherford at Cavendish and in commercial work at EMI and the BBC. Edward “Taffy” Bowen, the driving force behind the Parkes telescope, came aboard at this time. John Bolton also did his first stint with the CSIR/CSIRO. (*Robertson P. 1992: 22-28*)

1.2.1. The Men Most Responsible for the Parkes Telescope

All pictures are taken from (*Bright Sparcs*) biographical entries, except Joseph Pawsey, taken from the (*Tall Poppy Capaign*) website. See references.

Figure 7 - Frederick William George White (1905-1994)

White worked at the CSIR/CSIRO from 1942, and was chairman 1959-1970.

Figure 8 - Edward George "Taffy" Bowen (1911 - 1991)

Bowen was a driving force behind the creation of the Parkes Telescope. He worked at CSIR CSIR/CSIRO Division of Radiophysics 1944-71, and was Chief 1946-71.

Figure 9 - John Gatenby Bolton (1922-1993)

Bolton worked at the CSIR/CSIRO 1946-1955 and returned to become the director of the Parkes Telescope (later the Australian National Radio Astronomy Observatory) 1961-1971

Figure 10 - Joseph Lade Pawsey (1908 - 1962)

Pawsey worked at the CSIR/CSIRO Division of Radiophysics 1940-1962, and was Assistant Chief 1952-1962.

1.3. Post-World War Two Research

The abundance of radar and communications staff and equipment at the end of the war left a dilemma for executives of research laboratories world-wide, particularly in allied countries. Essentially equipment could be transferred and stored, or where this was deemed too costly destroyed, and staff could be redeployed into other areas. Alternately these resources could be exploited in civilian areas of radio research.

In Australia, where an early lead in radar and radio electronics had been established, rather than dismantle/cannibalise Radiophysics, that the group would instead diversify into civilian areas of research. The effort was boosted in 1945 by Australia's acquisition of 300 kg of surplus radar gear, scheduled to be bulldozed into the ocean by American carriers. (*Robertson P. 1992: 37*)

Early efforts saw the creation of a large "rainmaking" group – their aim to use radar to identify clouds that could be "seeded", thus predicting and controlling rainfall patterns. Early work looked promising, however as research continued the success rate could not be argued from a statistical standpoint. Meanwhile the radio astronomy group within Radiophysics expanded to include several field stations including Potts Hill, Dover Heights, Fleurs, Badgery's Creek, Murrybank (privately owned), Epping and Hornsby. Their work was diverse, from solar radio astronomy to early hydrogen line work and other cosmological work.

World-wide other groups were also to flourish, however Radiophysics was initially the largest. In Cambridge, home of the Cavendish laboratory, made famous by Ernst Rutherford who headed it and made inroads into nuclear physics, another radio group existed as part of the physics department. They operated a field station at Jodrell Bank. A third group existed in Manchester, also part of a university's physics department. Other small groups thrived in Holland, France and the United States. (*Robertson P. 1992: 62*)

Early successes, particularly in finding optical counterparts for radio sources began to turn the tide for radio astronomy from a fledgling field with limited potential to a serious area of astronomical research, part of a complete picture of the universe. Early hydrogen line work with small dishes led to the first maps of the Galaxy. Suddenly men with a background in astronomy were studying radioastronomy and taking it seriously – an important change from the days where most radio astronomers were electronic engineers who learnt their astronomy "on the fly". In a quest for higher resolution, and greater collecting area, a world wide race to build large receivers was about to commence - Jodrell Bank's Mark I was the first dish, Parkes the second, and a string of other radio dishes followed close behind..

2. THE 21CM HYDROGEN LINE

2.1. Nature of the Line

In 1944 Dutch astronomer Hendrik Van De Hulst, predicted the existence of a hydrogen emission line at 21.2 cm based on the physics of the hydrogen atom. (*Van De Hulst H.C. 1973 Op. Cit. Sulivan W. T. III 1982*) The electron in a neutral atomic hydrogen atom (i.e. singular hydrogen atoms as opposed to molecular hydrogen – H_2) may undergo a "spin-flip transition" where the spin property of its electron changes to be opposite to the proton in the atom, bringing the atom to a lower energy state and emitting a photon. The opposite is also possible with the absorption of a 21cm photon. That is the spin on the electron can change to be the same as the proton's and bring the atom to a higher energy state.

The transition is rare for a single hydrogen atom, on average occurring once every 11 million years, but for the vast quantities of hydrogen that exist in a Galaxies and interstellar clouds, there are enough transitions to emit a steady signal.

In March 1951, the discovery was made by an American group in Harvard (Ewen and Purcell) of a hydrogen emission line in the radio spectrum at 21cm (1420 MHz). This discovery was quickly confirmed at both Leiden and Sydney. Both papers were published in *Nature* the same month (*Ewen H. J. and Purcell E. M. 1951; C. A. Muller and J. H. Oort 1951*)

This had profound implications for radio astronomy. At 21cm the radiation from neutral hydrogen penetrates much farther than visible light, acting as a marker for the most abundant substance in the universe (albeit only in its atomic form), allowing the mapping of large scale structures obscured in the visible spectrum by dust and gas. (*Robertson P. 1992: 70, 81; W. J. Kaufman III and R. Freedman 1998: 619-622*)

2.1.1. Hydrogen Line Pioneers

Figure 11 - Hendrik Christoffel Van De Hulst (1918-2000)

Photograph taken from (*The Bruce Medalists*) web site.

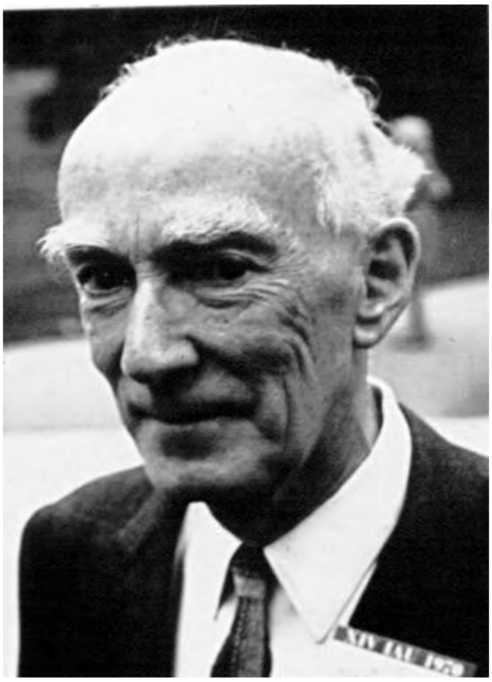


Figure 12 - Jan Hendrik Oort (1900-1992)

Photograph taken from (*The Bruce Medalists*) web site

Figure 13 - Left to right: Ed Purcell, Taffy Bowen, Doc Ewen

Photograph taken from (*The Discovery of Hydrogen Radio emission by Ewen and Purcell*) web page

2.2. Practical Implications of the 21cm Hydrogen Line

Until the discovery of the hydrogen line there was almost no interest in radio emissions of wavelength below 1 meter. Shorter wavelength observations require more precise surfaces on the receiving dish, increasing the cost of engineering and manufacture. Furthermore, if a mesh is used in place of a solid surface the mesh must be finer to reflect radio waves of shorter wavelengths.

The Jodrell Bank Mark I telescope, was initially designed outside tolerances that would allow 21cm observations. It was “far too rough for observations at 21 cm-radio waves reflected from the surface would arrive at the focus in a scrambled, incoherent fashion.” (*Robertson P. 1992: 138*). Mark I was redesigned during early construction. The 100ft (30.5m) central section was replaced with a mesh of finer weave, and made more rigid to conform to the desired shape within tolerances allowing 21cm waves to arrive at the receiver coherently. Design changes on a large structure tend to cascade. In this case the back girder and support towers had to be strengthened to support the extra weight and wind loading.

The existence of the 21cm line had been confirmed in 1951, and excavation for the Mark I began in 1952. It is therefore unsurprising that this redesign was necessary. Had the H-line been discovered later, changes required may not have been feasible, Making Mark I less useful than it turned out to be. (*Robertson P. 1992: 138-139*). The cost of Mark I escalated causing its designers and builders financial and legal problems. Their Australian counterparts were determined not to repeat the mistake with their giant radio telescope.

The Parkes telescope was designed from the start with a surface accurate enough for observations down to 10cm, ensuring that it would perform well at 21cm. The aim was to build a bigger better dish than the Mark I. When it was realized that funds were insufficient for a larger dish, Parkes’ designers focused on making a better performing instrument. (*Goddard, D., and Milne, D. 1994: 106*). A parabolic steerable dish of maximum gain (corresponding to diameter) was exactly what was needed for galactic H-line work (see Appendix 2 for more detail)

2.3. Early Hydrogen Line Work

The initial 1951 observation of the hydrogen line had taken Ewen and Purcell almost two years of work to achieve. Two groups set about to confirm the discovery, each taking about 2 months to do so. The Sydney group consisted of Chris Christiansen and Jim V. Hindman at the Potts Hill field station, who set aside solar studies to assemble the necessary equipment and confirm the Harvard result as soon as they were made aware of it by a cable sent by Frank J. Kerr. (Frank Kerr, based in Sydney at Radiophysics, was in Harvard for a year undertaking an astronomy course.) The Leiden group consisted of Jan Oort, who had been involved in refining predictions of the hydrogen line and was respected for a variety of other work, and Alexander Muller. At Purcell’s suggestion, the papers confirming the discovery of the hydrogen line appeared along with the original paper by Ewen and Purcell in the same issue of

Nature. (*Robertson P. 1992: 82-83; Ewen H. J. and Purcell E. M. 1951; C. A. Muller and J. H. Oort 1951*)

With the existence of the hydrogen line confirmed, it was a natural next step for Christiansen and Hindman to carry out observations of the sky along the plane of the Milky Way. Within 3 months of their initial confirmation of the existence of the hydrogen line, they had found evidence of a spiral structure in our Galaxy.

In 1952, the leading radio astronomy association Union Radio-Scientifique Internationale (URSI) held its 10th General Assembly at Sydney University – a sign that Australia was seen as a leader n in the field, given the geographic distance of the conference from research centres in Europe and America. The meeting was abuzz with talk of the discovery of the hydrogen line and the implications of this work. A new field of Radio Astronomy had just opened up, and already some recognised that this gave radio astronomers an edge over optical astronomers on solving certain problems such as the shape of the Galaxy. Ironically, the shape of the Galaxy had just being determined by optical astronomers through the observation of O and B star patterns, but H-line research would soon provide far more dramatic and compelling evidence.

Figure 14 - URSI Xth General Assembly

Taken from (*URSI Xth General Assembly*). Pictured are:
(left-right): John Bolton, Bruce Slee, M. Laffineur, Alec Little, Lex Muller, Ruby Payne-Scott, Lou Davies(?), Robert Hanbury-Brown, Frank Kerr, Harold Ewen, Alec Shain, Eric Hill, Jim Hindman, Steve Smerd, Jean-Louis Steinberg, John Hagen, Jack Piddington, Bernie Mills, Charles Higgins, Paul Wild, Graham Smith, Chris Christiansen

2.4. Australian Hydrogen Line Work Before Parkes

By early 1953, Frank J. Kerr had returned to Radiophysics. At Potts Hill, Kerr and Hindman constructed a 36ft (11m) parabolic antenna for H-line observation – in those early days the largest dish capable of 21cm work. Joe Pawsey had originally asked them to build a multi-channel receiver, but once they had added a few channels to the antenna they got sidetracked with hydrogen line observation (to the dismay of Pawsey, by Robinson's account).

Figure 15 - The Potts Hill Antenna

Brian Robinson working at the focus of the Potts Hill Antenna in 1953. The photo is ©CSIRO (ATNF) and has been taken from (*Image of the 36 ft. Antenna at Potts Hill – 1953*)

The Potts Hill dish was immediately put to use in a detailed H-line survey of the complete southern sky. At Leiden this work was parallelled for the northern sky by Jan Oort and Gart Westerhout. A collaboration between Frank Kerr and the Leiden group led to the first complete hydrogen line map of the sky. The spiral structure of the Galaxy was a striking feature of the mapping effort, providing clear evidence that our Galaxy resembled other "spiral nebulae", supporting "Island Universe" hypothesis that our Galaxy is just one among billions. The other striking feature of the mapping effort was the concentration of hydrogen about the galactic plane. This was so marked a feature that it became possible to determine with great accuracy the direction of the plane, and led to the revision of the accepted system of Galactic co-ordinates in 1958. Frank Kerr stated that "Many conventional astronomers had been reluctant to regard radio astronomy as a respectable branch of the subject, and this was one of the key ways in which radio astronomy came of age." (*Robertson P. 1992: 84-85*).

1953 was also the year of Brian Robinson's recruitment by Frank Kerr. At Potts Hill in 1953/1954 Robinson was able to detect H-line emissions from the

Magellanic Clouds. The Clouds are significant in that, being our Galaxy's closest neighbours, these objects, while in a separate and semi-detached system are still close enough for detailed observation. (*Kerr F. J. and Hindman J. V. 1953*). Observations showed that neutral hydrogen extended well beyond the boundaries of the system as observed in the visible wavelengths. Furthermore, observations of Doppler shift in the clouds allowed for their rate of rotation to be measured. It was determined that 20% of their masses are tied up in interstellar neutral hydrogen. The high proportion of hydrogen is considered direct evidence that the Clouds are young star systems, certainly younger than the Milky Way. (*Robertson P. 1992: 86; Goddard, D., and Milne, D. 1994: 119*).

Robinson also attempted on numerous occasions to detect galactic hydrogen in M31, but was unsuccessful. Robinson recalls the first success was at Dwingeloo with the Dutch 25m telescope (designed by Ben Hooghoudt). Sensitivity of the Potts Hill antenna also limited the ability to determine wether or not neutral hydrogen enveloped both Magellanic clouds.

The Murrybank receiver, built and tested at Murrybank and eventually moved to Parkes was used in 1960 by Frank Kerr, Jim Hindman and Dick McGee to discover a bridge of gas between the large and small Magellanic clouds. Though an improvement, resolution was still poor. It was not until the receiver's installation at Parkes that this feature was better resolved. (*Goddard, D., and Milne, D. 1994: 119*). Testing of the receiver at Murrybank was unusually promising - actually yielding the discovery of a new hydrogen cloud. (*Murray J. D. and McGee R. X. 1958*)

Throughout the rest of the 1950s efforts concentrated on obtaining a more granular picture of neutral hydrogen distributions in the Milky Way, the Magellanic clouds and other nearby galaxies. (*Gum C.S., Kerr F.J. and Westerhout J. 1960*). During this period 3-dimensional maps of the Milky Way were constructed and refined (*Kerr F. J et. Al. 1956*). Whereas the earliest surveys had focused on entire systems, later work saw these split into regions for detailed study. For example see (*Kerr F. J. 1954*) in which the Galactic Centre is studied. It is a tribute to the tenacity of the early radio astronomers that they were able to make so much progress with what they instruments they had. They laid the groundwork necessary for research with larger instruments.

3. THE PARKES RADIO TELESCOPE

3.1. The Instrument and Facility

3.1.1. Location

The Parkes telescope is located 20 km north of Parkes and 365 km west of Sydney (roughly 5 hours drive), in the in the Goobang Valley, N.S.W. (*Observatory Information*) This site was chosen for a number of reasons over other candidate sites, 30 of which were considered in 1956. Sites nearest Sydney, such as Cliffvale on the Nepean river in the blue mountains, were eliminated due to council and town opposition, and interference with existing Radiophysics projects. Plans to locate the radio telescope near Mt. Stromlo and Canberra were rejected due to increasing light pollution in the area, and a reluctance to relocate the CSIRO Radiophysics staff to Canberra. The Parkes site had many advantages including:

1) The lowest radio noise levels (confirmed by low flying aerial and ground survey using radio equipment)
2) Long running records of good weather, particularly low wind
3) Minimal planned industrial, rural and residential expansion
4) The support of local government and businesses who recognised the potential for tourism. Their support meant that the cost of major roads, power, water and sewerage would not have to come from the telescope budget.
5) An abundance of flat ground
6) The early support and cooperation of the former owner of the site (known as Kildare), Austie Helm, who sold 170 acres of the land for £16400

(*Robertson P. 1992: 160-166*)

3.1.2. A Description of the Main Instrument

The main instrument is a 210ft (64m) parabolic steerable dish, with a surface area of about 1 acre. Initial surfacing of the dish provided for a deviation of no more than ¼ of an inch (surface accuracy). This meant that at wavelengths of 10cm, the minimum for which the telescope was originally intended, 98% of reflected radiation was brought to the focus. (Later resurfacing has improved the minimum operating wavelength down to about 1cm). The surface is supported on 30 radial ribs cantilevered out from a central hub, together with 2 spiral purlins which spiral out in opposite directions meeting at right angles at each intersection, and a third set of purlins which are radial. These provide the right amount of surface tension through their geodetic structure. (*Robertson P. 1992: 177-178, 295; The CSIRO 210-Foot Radio Telescope: 7-17*)

The aerial cabin is supported by 3 legs, one of which sports a lift. Cables carry the signal from the receiver in the aerial cabin to the receiving equipment in the tower. The aerial cabin allows for the rotation of the receivers via controls at the control room. This feature has proven especially useful for studying the radio wave polarization. (*The CSIRO 210-Foot Radio Telescope: 5-9*). Over the years a menagerie of receivers has been installed in the aerial cabin. As technology has developed, receivers have improved in sensitivity, range and the number of frequencies that can be recorded simultaneously.

Figure 16 - Mesh of the Dish and the Aerial Cabin

3 distinct areas of the dish's surface appear in this photo. An inner solid section, an outer fine mesh and a courser mesh running through to the edge of the dish. Each section is figured to a given accuracy and can therefore be used to focus radiation down to a given wavelength. Through the course mesh we see the aerial tower just above the focus of the dish and can just make out the rotational receiver platform. Photograph by the Author 24/08/2001

The telescope is mounted alt-azimuth on a central tower. The dish rotates in azimuth, with bogies sitting on a circular track, and has an azimuth drive rate of 24 degrees per minute. A single pivot in altitude allows an altitude drive rate of 10 degrees per minute. Pointing accuracy is better than 1 minute of arc. (*The CSIRO 210-Foot Radio Telescope: 17*) A master equatorial drive, an engineering innovation first used in the Parkes telescope, controls pointing of the telescope, with the larger alt-azimuth device slaved to an equatorial platform. Pointing is controlled from the upper level control room in the tower. The heart of the master equatorial is an optical device, consisting of mirrors and lenses and using a narrow beam of light positioned at the intersection of the axes of rotation of the telescope. (*Robertson P. 1992: 182*)

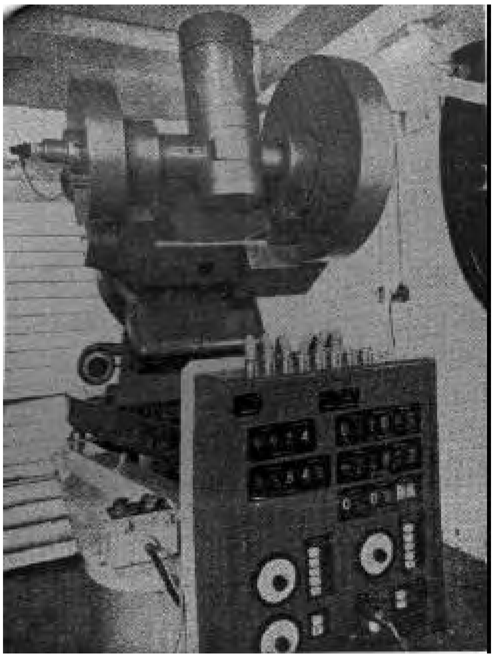


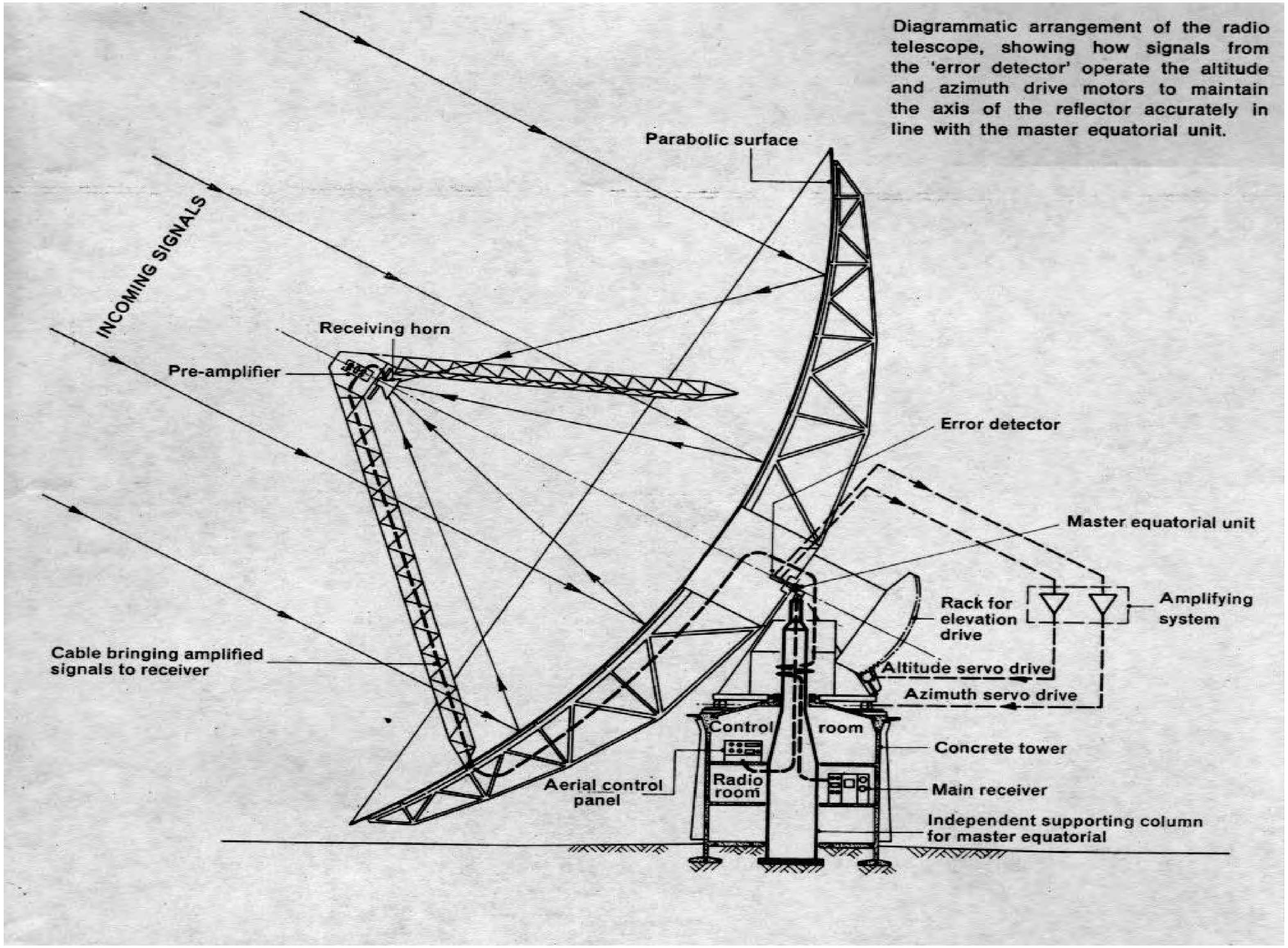
Figure 17 - The Original Parkes Master Equatorial Control

Photograph taken from (*The CSIRO 210-Foot Radio Telescope: 10*).

The central tower is a steel-reinforced concrete structure and consists of 3 levels. The first level is used as a workshop for maintenance of equipment. The second houses receivers and radio equipment, and the last is the control room. The mass of the entire structure on its foundations is 1800 tons, 500 tons of which comprise the dish and 450 tons counterweights.

Figure 18 - The Parkes Radio Telescope Tower

The structure atop which the main dish sits houses 3 distinct levels as shown by 3 distinct rows of windows. The control room is on the top level and a workshop sits at the base level of the tower. Note the size and solid looking metallic construction of the drive mechanism and counterweights seen atop the tower. Photograph by the Author 24/08/2001



Diagrammatic arrangement of the radio telescope, showing how signals from the 'error detector' operate the altitude and azimuth drive motors to maintain the axis of the reflector accurately in line with the master equatorial unit.

Figure 19 - Simplified Diagram of the Parkes Telescope

This diagram, taken from (*The CSIRO 210-Foot Radio Telescope: 5*), is an excellent representation of the overall design and operation of the dish at a simplified level.

3.1.3. Background

The Parkes telescope arose in direct "response to these demands of sensitivity, resolving power and pointing accuracy" (*Robertson P. 1992: 68*). In the early to mid 1950s, the well established groups at Radiophysics had earned worldwide scientific respect and recognition as leaders in radio astronomy. Beginning with World War II surplus parts, yagi aerials, parabolic dishes and cross interferometers were amongst the instruments that had been designed and built at the various field stations in and around Sydney. Their research had been highly successful.

Around this time the proposals for new radio telescopes of varying designs were almost as numerous as the Radiophysics staff. Among the most memorable was a new form of interferometer proposed by John Bolton "consisting of two large parabolic dishes" (*Robertson P. 1992: 69*) – the basic concept strikingly similar to what was to be the Parkes interferometer, largely designed by Bolton at a later stage.

The choice of design for the first large telescope was a choice between a larger Mills Cross interferometer and a steerable dish. The Mills Cross had been an expensive instrument, costing roughly £5000, and therefore consuming most of the funds available in the early to mid 1950s. A direct result was that the 70ft (21m) parabolic dish planned for hydrogen work at Potts Hill was scaled down to just 36ft (11m). Bolton's two dish interferometer had no chance of funding and he temporarily left for work outside radio astronomy, then returned to radio astronomy in California where an interferometer was being built. (*Robertson P. 1992: 73*). This was another reason the dish proposal eventually came to fruition – though the choice of either instrument would cause alienation of one of the groups, (i.e. supporters of a dish and galactic observation vs. the supporters of a cross for solar observation), the Mills Cross concept was seen to have "had its turn" in funding terms.

Against this background "Taffy" Bowen, then chief of the Radiophysics group, set his sites on a large telescope in 1952 (*Robertson P. 1992: 73*). This project would be so large as to require external funding from international groups. Bowen is seen as being largely responsible for securing the funds and the official backing to proceed with what was to be the Parkes Telescope. Using wartime contacts, Bowen was able to garner interest in a large parabolic steerable telescope (see appendix 2). What followed essentially was two years of political manoeuvring during which Bowen resisted attractive offers to head a team for a U.S. based dish in preference for one he and John Bolton would operate for the CSIRO in Australia. Much of this politics focused around securing funds and around the personalities that would control the telescope.

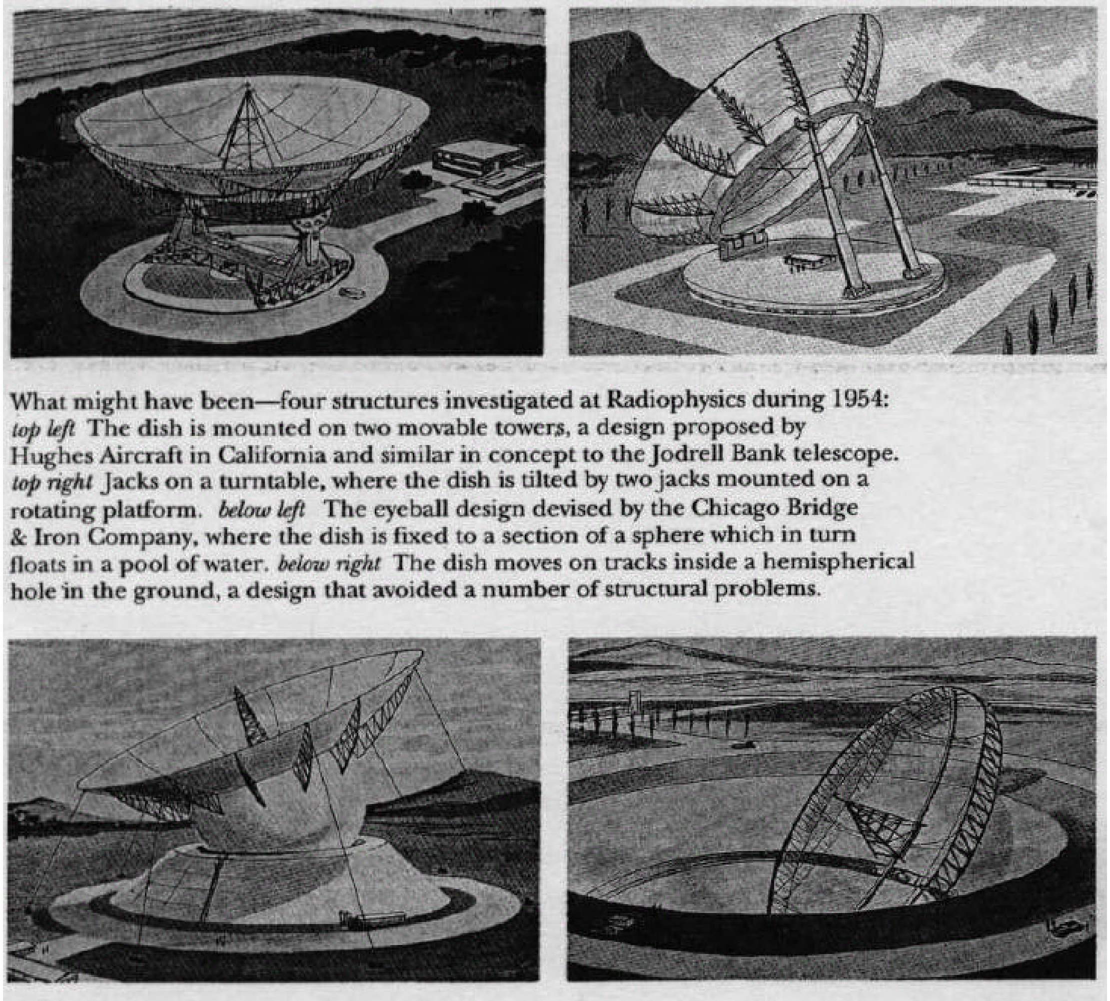
3.1.4. Conception and Funding

The Carnegie Corporation was founded by Andrew Carnegie with the goal of systematically giving away his great personal fortune for the betterment of mankind. In 1952 August, "Taffy" Bowen wrote to the president of the U.S. based Carnegie Corporation, Vannevar Bush to consider granting funds for a southern hemisphere giant large radio telescope, in addition to funds just granted to Caltech for a northern dish. In 1954 May 15, the Carnegie Corporation approved a grant of USD 250,000. This represented roughly a quarter of the total estimated cost of the telescope. (*Robertson P. 1992: 119-121*).

In 1955 April, the Menzies government was approached for funding by the CSIRO chairman, Ian Clunies Ross, and the CSIRO minister Richard Casey. Robert Menzies agreed to match funding found elsewhere dollar for dollar. Several local organizations were unsuccessfully approached for funding grants and, since a year of fund raising had only resulted in a further £20,000, Bowen was sent to the United States to contact other organisations. With the help of the foreign minister, Richard Casey, Bowen persuaded the President of the Rockefeller Foundation, Dean Rusk to officially granted the project USD 250,000 on 1995 December 17. (*Robertson P. 1992: 122-124*).

With funding secured, preliminary designs could now be considered. Design ideas were encouraged both from within Radiophysics and from without. John Bolton put forward an unusual design for a "standing paraboloid" consisting of a 200ft (70m) parabolic arc of upright 20ft (7m) poles resembling a curved fence which would then reflect signals back to a receiving pole at the focus. Bowen suggested an equally unconventional parabolic cylinder design. Bowen, largely responsible for seeking the advice of engineering firms early on, contacted the Chicago Bridge and Iron Company, which suggested an unusual eyeball design in which the dish, attached to a spherical eyeball would float in a socket. This spread the stresses on the structure more evenly. The Hughes Aircraft Company suggested enclosing the telescope in a dome to minimize wind stresses. The Fuller Research Foundation suggested a geodesic dome. More conventional designs considered included a two-pronged rotating design similar to the Mark I at Jodrell Bank.

In 1953 the Aeronautics Research Laboratories (ARL) in Melbourne, formerly part of the CSIR, and considered best suited to a design study released a report indicating that it should be feasible to construct a 250ft (76m) telescope capable of 21cm observations weighing approximately 100 tonnes and driven in alt-azimuth. In 1954, Joe Pawsey and "Taffy" Bowen put together a design committee for the telescope which produced, in 1955, a booklet detailing seven possible designs for a 250ft (76m) steerable dish "differing only in the type of mount used to support and steer the dish". (*Robertson P. 1992: 133-134*)



What might have been—four structures investigated at Radiophysics during 1954: *top left* The dish is mounted on two movable towers, a design proposed by Hughes Aircraft in California and similar in concept to the Jodrell Bank telescope. *top right* Jacks on a turntable, where the dish is tilted by two jacks mounted on a rotating platform. *below left* The eyeball design devised by the Chicago Bridge & Iron Company, where the dish is fixed to a section of a sphere which in turn floats in a pool of water. *below right* The dish moves on tracks inside a hemispherical hole in the ground, a design that avoided a number of structural problems.

Figure 20 - Early Designs for the Parkes Telescope

Early contenders for the design of the Parkes Telescope. Taken from (*Robertson P. 1992: 135*), in turn taken from a publicity booklet issued in May 1955 by the telescope's design committee.

One major driving factor for the size of the scope was a competitive drive by the Australian designers to do better than the Jodrell Bank Mark I. Initially wanting to build a dish both larger and better than the Mark I meant setting the size to be 250ft (76m) or larger. As detailed plans were considered it became clear that the budget allocated to the telescope allowed for an optimum size of 210ft, which was in fact chosen as the size of the Parkes dish. The CSIRO scientists had to content themselves with aiming for a better telescope slightly smaller than the Mark I.

3.1.5. Detailed Design and Construction

Serious work on the design of the telescope began in 1954 with the recruitment of Barnes Neville Wallis, a highly regarded engineer with an unparalleled track record, having engineered everything from dirigible and conventional aircraft to submarines, high rise buildings, and optical telescope mounts. Wallis was also a war hero, having designed the bouncing bomb of the World War II Dambusters campaign Many of Wallis' original design points for Parkes stood the test of time, including the use of a central support point for the dish (avoiding stress distribution problems with the

Jodrell Bank dish's twin support structure), and the master equatorial control system, allowing accurate pointing of the dish, which Wallis was to patent and reuse in other designs. (*Robertson P. 1992: 146-147; Sir Barnes Neville Wallis 1887..1979*)

Figure 21 - Sir Barnes Neville Wallis 1887-1979

Taken from the Web site "Sir Barnes Neville Wallis 1887..1979".

To proceed with the design, British firm Freeman Fox, whose founder Sir Ralph Freeman had designed the Sydney Harbour Bridge was contracted. Fox agreed to undertake a 6 month design study in 1955. The telescope's operating environment in relation to wind and weather was specified as was its 60 degree zenith angle limitation – both compromises made to achieve realistic costs. Freeman Fox was to take on role as principal contractor with 3 subcontractors to be chosen – one to build each of the mechanical and electrical drives, one to construct the master equatorial drive, and finally one to fabricate the heavy structural components. Initially the firms chosen were Metrovik (Manchester), Grubb Parsons (Newcastle) and Sir William Arrols and Partners (Glasgow) respectively. (*Robertson P. 1992: 148-149,154*)

The detailed design and construction phases however did not go as smoothly as hoped. Delays included drawn out contractual negotiations with Freeman Fox, and Grubb's insistence that the master equatorial would take 2 years to construct. To make matters worse Metrovik estimated a budget blow-out of roughly £200,000. This eventually led to the construction work being put out to tender in 1959, with the successful company expected to take on all mechanical, electrical and structural work. (Grubbs was still to deliver the master equatorial drive, though somewhat late and not as thoroughly tested as had been hoped.). The successful bid was £611,000 by West German firm Maschinenfabrik Augsburg Nurnberg (MAN). Freeman Fox continued in a supervisory role and retained the responsibility of overall testing of the telescope. (*Robertson P. 1992: 157, 166-167*)

Thanks to the superior efficiency of MAN and a further USD 130,000 from the Rockefeller foundation, construction was expedited, and the telescope was ready by 1961. The engineers and builders went to extremes to ensure the radio telescope was a superior instrument. Major components machined by MAN in Germany were test fitted before being shipped to Australia, the skeleton of the dish was assembled during the night when the temperature of the steel was most even (minimizing distortion and stresses on the final surface), and local labour was employed to get things working on time. (*Robertson P. 1992: 167, 174*)

The resulting telescope was one of the finest pieces of engineering in the world. Aspects of the Parkes telescope have been studied and copied in other large radio telescopes worldwide. While there was increase of the final cost, it was not of the order of magnitude experienced at Jodrell Bank with the Mark I.

3.1.6. Commissioning

The main telescope was officially opened on 1961 October 31. In addition to the Parkes radio scientists, about 500 officials were present from Sydney, Melbourne, Canberra and Parkes, including the Governor General, Lord De L'Isle, the Federal Science Minister Donald Cameron, his predecessor Richard Casey, and the Mayor of Parkes and local councilmen. Most of the Parkes community also attended.
High winds prevented the telescope being test driven - dramatic demonstration of the success of construction of the instrument planned for the event.
(*Robertson P. 1992: 2-5*)

While the commissioning was a dramatic, it took place while the telescope was still in acceptance testing. The telescope was not handed over to the CSIRO until this was successfully completed in 1962 March, and only then did the telescope become fully operational. Until then contractual obligations with Freeman Fox regarding who could operate the instrument in the acceptance test phase were in place. (*Goddard, D., and Milne, D. 1994: 17*)

3.1.7. Enhancements to and Renovations of the Telescope

Forty years is a long time for any scientific instrument to remain operational. Had the Parkes Telescope not been constantly upgraded and improved, its viability may have proved short lived. Fortunately however the site was well managed and the circumstances of its success, particularly by outside agencies, ensured the availability of funds to keep the instrument up to date in exchange for occasionally use of the instrument. This has minimized the funding required of the Commonwealth government and helped to keep the telescope viable.

The original design of the telescope called for a surface accuracy capable of focusing 10cm wavelengths. Further fine-tuning resulted in an ability to make observations at 6cm and above in the 1960s. To improve the surface further, repanelling was required. New accurately shaped perforated aluminium panels were added in two stages in 1970 and 1972 after design and wind tunnel simulations were complete. At the end of this, the newly resurfaced area extended to the tripod legs of the aerial cabin, resulting in a 37m diameter area that could be used down to 1.3cm wavelengths. A second resurfacing, with over 300 aluminium panels coated in white paint to reduce expansion due to sunlight covers the inner 17m diameter of the dish with a surface which is useable down to 4mm. This was undertaken by Don Yabsley, and has allowed Parkes to continue to compete with ever improving new radio instruments of smaller diameter where it would otherwise have been unable to. (*Robertson P. 1992: 293*)

The structure and mechanics of the dish have also required maintenance over the years. In 1969, half of the four month period between Apollo 11 and 12 was used to reinforce the tower, which was beginning to bulge under the weight of the telescope's movements, shutting down the telescope for the duration. This required the outside of the tower to be stripped back to expose the steel support columns. The opportunity was also taken to upgrade the cabling, pipes, air conditioning and to install the first computer in the control room – a PDP-9. (*Robertson P. 1992: 269-270*)

In another incident, when repairs were undertaken in the 1980s based on money provided by the ESA and NASA (for the use of the telescope during the Giotto and Voyager-Uranus encounters) it was discovered that the elevation gears on the telescope had become worn. The hard metal on the gear had been filed down with soft metal underneath exposed and deteriorating. The price of replacement gears and time to manufacture them proved prohibitive. The Parkes engineers hired a crane, and had the gears lifted and flipped so that their unworn faces were now in contact, effectively doubling the life of the gears, vital to the telescope, without costly major repairs. (*Goddard, D., and Milne, D. 1994: 131-132*)

Computerization of the telescope has also played a vital role. When first constructed the telescope was very much an analogue beast. The telescope was positioned using knobs, and recordings were made on tape in the control room and sent elsewhere for analysis. Much of this changed with the refit between the Apollo missions and the installation of the PDP-9. This was a single user machine, and programming at Parkes was undertaken in the FORTRAN programming language. As well as elementary digitization and other such tasks that were performed before, the computer could be used for on-the-fly analysis of data, and more importantly to automate control of the telescope – from tracking to automated sky searches. The PDP-9 was not however a very reliable machine and was soon replaced with a PDP-11/40. Dials and push buttons were still used, as operators were more comfortable with these. (*Goddard, D., and Milne, D. 1994: 57-59*).

In 1985, a complete new control system was put in place. The main control desk was computerized though one central panel was left in tact for sentimental reasons. At the same time the master equatorial control was upgraded to a digital unit allowing more accurate pointing of the telescope. (Birthday Dish: 25)

Figure 22 - The Original Control Room at Parkes

Photograph taken from (*The CSIRO 210-Foot Radio Telescope: 10*).

Figure 23 - The Current Parkes Control Room (2001)

Photograph taken from (*Birthday Dish: 22*)

3.1.8. Receivers and Advances in Receiver Technology

As the design and construction of the Parkes Radio Telescope was occurring, two new kinds of receiver had just been invented and were being trialled worldwide. These were the solid-state maser (Microwave Amplification by Stimulated Emission of Radiation) and the paramp (Parametric Amplifier). Both devices lowered the noise level in reception (thus increasing the sensitivity of the receiver), and were capable of being tunned to a range of frequencies. These were therefore revolutionary devices both in radio astronomy and on a commercial in radio electronics. In terms of the Parkes Telescope, they promised to further enhance the detail that could be observed with the telescope (*Robertson P. 1992: 170*)

The solid-state maser was invented at Columbia University in New York in 1956 (after an ammonia gas based maser first invented in 1954). The original masers had to be cooled to a few degrees Kelvin using liquid helium, making them cumbersome to manage. Brian Cooper gained some experience with the devices at Harvard before being recruited as the head of the receiver group at Radiophysics and was therefore in a position to keep the group up to date on developments.

Meanwhile shortly after the invention of the solid-state maser, the first paramps were built. The paramp also needed to be cooled, but only to liquid nitrogen temperatures, making it cheaper and more manageable to operate. This was the main reason that the paramp was taken up over the maser. Brian Robinson, just back from completing his doctorate in Cambridge was sent to the Netherlands to study receivers – initially both masers and paramps but was very quickly told that masers would not be appropriate for Parkes. In exchange for Robinson’s work in the Netherlands, Pawsey arranged with Jan Oort to send a duplicate paramp to Parkes, which was fitted in 1962. (*Robertson P. 1992: 171*)

In 1961, Frank Gardner and Doug Milne built the first Australian paramp, to be operated at a frequency of 20cm and the receiver group, in collaboration with Gib Bogle of the national standards lab, built a maser for operation at 21cm based on a synthetic ruby crystal doped with chromium oxide.

One of the most successful receivers built at the Murrybank field station, the 48 channel spectrometer used for Galactic Observations, was also moved to Parkes where a digital recording system was added, giving Parkes its primary neutral hydrogen receiver. (*Robertson P. 1992: 172; Goddard, D., and Milne, D. 1994: 119*).

The consequence of all this work was that what took 15 seconds to observe at Potts hill using the receivers available after World War II, with receiver noise temperatures of around 1800K, could be undertaken in 40 milliseconds at Parkes where a typical receiver had a noise of 100K. (Speeds are proportional to the square of the ratio of temperatures. Using the figures given we have a speed difference of 18 squared or 324 times). For a listing of some of the receivers used over the years see Appendix 3. See Appendix 4 for a discussion of temperature noise.

Finally, any review of receivers would be incomplete without some mention of a brand new receiver that has revitalized hydrogen line work at Parkes over the last 5 years. The new Parkes 21cm Multibeam Receiver, built entirely by the CSIRO, allows 13 beams, and therefore 13 sections of the sky to be simultaneously recorded, cutting the time required for a given survey down by a corresponding amount. A survey which would have taken decades can now be contemplated in a few years, making detailed surveys of the entire southern sky at 21cm feasible. (*Birthday Dish: 21*)

Figure 24 - The Parkes 21cm Multibeam Receiver

Built in house by the CSIRO and installed in 1997, the Multibeam Receiver has opened up a new era of detailed HI sky surveys by reducing the time taken to conduct them from decades to years. Photograph taken from the (*Parkes 21cm MULTIBEAM Project*)

3.1.9. The Parkes Interferometer

In 1963, a second 18-meter telescope was added to the Parkes site. The telescope was initially intended as a practice instrument at Parkes, but instead had been erected at Fleurs field station in 1959. It was now moved and mounted on an A-shaped track, to be used in combination with the main dish as an interferometer. It took until late 1965 to reassemble and install the telescope. (*Robertson P. 1992: 298*)

Figure 25 - The Parkes Two-Element Interferometer

The main 64m dish can be seen in the foreground and the 18m dish in the background, now stowed, disused and in need of maintenance. The picture distorts the relative sizes of the telescopes (roughly 3.5:1 in actuality). Photograph by the Author 24/08/2001

This interferometer was built in the days when unorthodox thinking was still very much a part of the Parkes mentality. John Bolton, in the words of Venkataraman Radhakrishnan "the same madman who had put a telescope on the edge of a cliff to discover some of the first sources in radio astronomy and identify them" (*Goddard, D., and Milne, D. 1994: 128*) As a result of this "seat of the pants" design, a couple of critical design elements were ignored that would limit the usefulness of the interferometer.

Firstly, there was no direct way of measuring the distance between the foci of the main and secondary dish, and secondly the cables between the telescopes were above ground, which allowed uncontrolled temperature differences to disturb the electrical signals' phase variance between the two dishes. In interferometry a critical aspect is being able to measure the phase variance and spacing between the interferometer elements. The rather unique solution employed was to observe a source at 2 frequencies a whole number ratio of wavelengths apart and slowly move the smaller dish until the subject was resolved using the visibility function of one wavelength as a reference for the other. Regardless, the phase stability problem meant the interferometer could be used to map fine structural detail in a radio source but could not be used to pinpoint the source as precisely in the sky as the larger dish could on its own. (*Goddard, D., and Milne, D. 1994: 128-129*)

Nevertheless the interferometer did produce results during its lifetime. Ron Ekers, Doug Cole and Doug Milne used it to map the structures of extended sources. They focused on sources which had already been located by the main telescope from the first Parkes catalogues. A study of the properties of interstellar space by Venkataraman Radhakrishnan and Miller Goss completed on the interferometer is "regarded as a minor classic" (*Robertson P. 1992: 302*). 21cm hydrogen line observations using the interferometer led to a team headed by Don Mathewson discovering the Magellanic Stream – a “vast filament of hydrogen trailing behind the clouds and extending in a large arc across the southern sky”. (*Robertson P. 1992: 316*).

The Parkes interferometer was revived in the late 1970s with an extension to the east-west track and the replacement of the control system. It now came to be known as TEST (the Two Element Synthesis Telescope). This allowed the telescope to be used for the mapping of the structure of spiral galaxies. (*Robertson P. 1992: 302*) The smaller dish has since been allowed to fall into disrepair with TEST having been largely superseded by long baseline interferometry in the 1980s. There has been some interest by a privately funded SETI organisation in acquiring the telescope and moving it to Queensland for SETI research. For the time being the smaller telescope sits disused at Parkes. (*MacRobert A.M. 2001*)

Perhaps the most important contribution of the Parkes interferometer has been to train several key personal in the art of interferometry on a less than ideal instrument. Many of the scientists who “cut their teeth” on the Parkes two-element system have gone on to head or co-ordinate larger interferometry projects as interferometry has become increasingly important. In the era that has followed that of the single large dish, Miller Goss had gone on to head the Very Large Array (VLA) in New Mexico and Ron Eckers the Australia Telescope (AT) (*Goddard, D., and Milne, D. 1994: 129*)

3.1.10. The Main Dish and Long Baseline Interferometers

From the outset, one of the difficulties of radio observation has been poor resolution. Increasingly large dishes have been built to improve resolution, however engineering and structural accuracy comes at an increased cost, as the diameter of the dish increases. Techniques such as rotation synthesis (using the earth’s rotation about its axis and/or rotation about the sun to simulate a larger telescope over time) and interferometry (using physically different dishes at the same time) have correspondingly become increasingly important as single large dishes reach their size limits in terms of economic viability. Interferometry went from being a new cutting edge technique to an important and integral mainstream part of the strategy for exploring the radio sky.

Overseas dishes such as the Very Large Array (VLA) in New Mexico, U.S.A were built. Longer term Australian plans to remain active in interferometry culminated in the Australia Telescope. Australia developed some expertise in long baseline interferometry when Parkes was linked by microwave in 1985 to the Tidbinbilla 64m NASA dish, 275km south of Parkes. This array was used for radio astronomy and for the tracking of the Voyager 2 spacecraft. Radio Astronomy projects included the study of “unusual galaxies, galactic radio stars, pulsars and interstellar molecular clouds...[and to]...test many of the ideas and techniques which were later incorporated into the design of the Australia Telescope“. (*Robertson P. 1992: 247*)

The original proposal for the Australia Telescope, at first named the “Australia Synthesis Telescope” was made in 1975 and called for an array to be built at Parkes. Politics and a mining operation near Parkes saw the site shifted to Narrabri in 1981 as funding was becoming available. The main dish at Parkes would still be used, but now the array would be a long baseline array, Parkes playing the role of the pivot element. (*Goddard, D., and Milne, D. 1994: 114*). The Parkes dish is still used in solitary work, but it is as part of the Australia Telescope that the future of the Parkes dish is brightest.

3.2. Overview of Other Research Programs at Parkes

This section aims to give only a brief background of non-hydrogen-line work in which the Parkes telescope played a part. See referenced works for further detail.

3.2.1. Pulsars

In 1968, Antony Hewish of the Cavendish Laboratory, Cambridge, announced the discovery of the first pulsar. The signal was first noticed in 1967 by a graduate student, Jocelyn Bell, who was studying interplanetary scintillation (radio wave scintillation due to the solar wind). The nature of the regularly repeating signals was initially unknown. All previously observed natural radio sources were continuous in nature. After eliminating the possibility that the signals were terrestrial in origin, the idea that the first pulsar may have been a signal from an intelligent alien civilization was briefly entertained. Within 3 weeks more pulsars were discovered and slowly the alien “super-civilization” hypothesis was eliminated. The Cambridge group kept the discovery secret for several months in the hope of establishing an explanations of the natural cause of the signal on their own. (*Robertson P. 1992: 305*)

Within 13 days of the Cambridge announcement, the first successful pulsar observations at Parkes were made. Techniques being developed to study sources at multiple wavelengths simultaneously using new receivers were employed. The first publication on pulsars from Parkes, by Venkataraman Radhakrishnan, Max Komesaroff and Dave Cooke was a correction to the Cambridge team’s calculation of the period of pulsar CP 1919. The more significant observation that the Vela pulsar exhibits a polarization flip each pulse soon followed.
(*Goddard, D., and Milne, D. 1994: 69; Robertson P. 1992: 309*)

This laid the groundwork for a paper in 1970 by Venkataraman Radhakrishnan and Max Komesaroff which describes the currently accepted “rotating beam, magnetic-pole” model for a pulsar, and which improved on an earlier model by Tom Gold of Cornell University. The correlation of pulsar sources and supernova remnants (eg. Vela and Crab nebulae), suggested that neutron stars were the rotating objects at the heart of the pulsars (theory eliminated white dwarves as candidates). With the explosion of SN1987a, researchers at Parkes and elsewhere looked for a pulsar in the remnant but none was found. (*Robertson P. 1992: 306,312-313; Goddard, D., and Milne, D. 1994: 69*)

The first pulsar period glitch was also observed at Parkes by Venkataraman Radhakrishnan for the Vela pulsar. The same glitch was also noticed at the Jet Propulsion Laboratories in the United States.

Parkes became heavily involved in Pulsar research. Initially the small search beam of the Parkes dish was a disadvantage, and work with the dish was relegated to following up discoveries made with such telescopes as the Molonglo Cross and Arecibo telescopes – finding accurate positions, and timing the rate of pulsation. The second Parkes-Molonglo survey, with results published in 1978, found new 155 pulsars, where 69 were previously known. (*Robertson P. 1992: 311-314; Goddard, D., and Milne, D. 1994: 70-71*)

Computerized search techniques, and later the Multibeam Receiver meant Parkes could eventually be used to hunt for pulsars directly. Nevertheless, Parkes has been used to detect numerous pulsars including the first extra-galactic PSR 0529-66 and other extra-galactic and millisecond pulsars. One survey which began in 1988 found 50 new pulsars including the second known eclipsing binary pulsar. (*Robertson P. 1992: 313; Goddard, D., and Milne, D. 1994: 72-73*)

3.2.2. Quasi-Stellar Sources

Observations of objects from the 3rd Cambridge Radio Catalogue (3C) in 1960 proved to be unusual. Henry Palmer of Jodrell bank measured the size of 3C 48 and showed it to be more compact, at 4 arcseconds, than most radio galaxies, typically 30 to 60 arcseconds in size. When the object was identified optically its spectrum was analysed by Allan Sandage, Jesse Greenstein and Guido Munch of the Hale telescope. There appeared to be a lack of hydrogen in the spectrum. Further work showed, hydrogen was present but had been red-shifted so far that it was not initially recognised.

Using lunar occultations to measure the position of another strange object in the catalogue, 3C 273 was observed from Parkes. This technique was new to accurately identifying the position of radio sources, but was well known by optical astronomers. Cyril Hazard had already used the technique at Jodrell Bank, and collaborated with John Shimmins and Brian Mackey to gather data during 2 occultations of 3C 273. The reduced data showed 3C 273 to be a double source, each of 6 by 2 arcseconds and separated by 20 arcseconds, and gave the position of the sources to an accuracy of 1 arcsecond. They coincided optically with what was thought to be a double star on a plate brought from the Hale telescope by Rudolph Minkowski. Again the spectrum did not appear to contain hydrogen, but by matching 6 spectral lines, Rudolph Minkowski's successors at the Mount Palomar observatory were able to show hydrogen was present, but at a large red-shift (of about 16%). 3C 48 had a redshift of 37%. (*Robertson P. 1992: 229-233; Goddard, D., and Milne, D. 1994: 62-63*)

These redshifts imply that these objects are incredibly distant, and therefore, to be seen at all, millions of times brighter than normal galaxies. This has profound cosmological implications, as it redefines the size of the observable universe to be orders of magnitude larger than previously realized.. While not all astronomers agree that the explanation for the redshifts observed is distance according to Hubble's Law, this is the generally accepted hypothesis.

The term Quasi-stellar radio source, later QSR or "Quasar" came from the Goddard Institute for Space Studies, New York, coined by Hong-Yee Chiu. Since the discovery that the majority of these objects are not radio emitters, the term Quasar has fallen out of favour, with QSO (Quasi Stellar Object) now preferred. (*Robertson P. 1992: 234*)

Many more QSOs have since been catalogued and Parkes has been part of this work. The objects remain poorly understood. The best theory we have for the source of their incredible power are super-massive black holes at their centres accreting matter. These monster galaxies appear only at great distances (and therefore in the distant past of the universe). This makes them difficult to study in any detail and their natures are likely to elude astronomers for some time to come.

3.2.3. Magnetic Fields and Polarization

Polarization of a radio signal is an indication that there is a magnetic field at the source. One source of radio signals is Synchrotron Emission- where electrons are accelerated in a magnetic field to a speed approaching that of the speed of light. The energy of the electrons forced to follow the magnetic lines of force is emitted as radio signal. The emissions are linearly polarized – i.e. their magnetic field vector is perpendicular to their electric field vector. (*The CSIRO 210-Foot Radio Telescope: 13*).

The Synchrotron Effect was well established and accepted theoretically by the time it was first observed. Polarized emissions distinguished it from other types of source, but by the mid 1950s few polarized sources had been observed. In 1954 polarized visible light from the Crab Nebula was observed. In 1957 researchers at the Naval Research Laboratories in Washington observed minimal polarization in the Crab Nebula at 3cm. Finally in 1962 the Naval Research Laboratory group detected 8% polarization in Cygnus A. (*Robertson P. 1992: 222-223; Goddard, D., and Milne, D. 1994: 75-76*)

On news of this the Parkes telescope was immediately brought into use to study Centaurus A. Ron Bracewell, Brian Cooper and Tom Cousins were able to detect 13% polarisation at 10 cm from one of the two compact central sources of Centaurus A. Follow-up work by Frank Gardner and John Whiteoak detected as much as 38-40% polarization. The rotating platform on which the feeds rest, at the telescope's focus, made the Parkes telescope an ideal instrument for studying polarization. The direction of the polarization of a signal is found by rotating the feed until the signal's strength is at its maximum.

Further work quickly followed with the first observations of the Faraday Effect, credited to Brian Cooper and Mark Price. This term is used to describe the rotation of the polarization of a radio signal due to its passing through a magnetic field. The amount of rotation depends both on the strength of the intervening magnetic field and the wavelength of the radiation. By observing a source at multiple wavelengths it is possible to deduce both the direction of the field at its source, and the properties of the magnetic fields through which it has passed. Therefore the magnetic fields of this and other galaxies can be mapped. (*Robertson P. 1992: 223-224; The CSIRO 210-Foot Radio Telescope: 13; Goddard, D., and Milne, D. 1994: 76-80*)

Among the triumphs of Parkes, in 1965 by Brian Cooper, Marc Price and Doug Cole made the first magnetic field map of another galaxy – Centaurus A. Closer to home, the Parkes telescope has been used for observations of the magnetic fields of Jupiter and the Sun. (*Robertson P. 1992: 225*)

3.2.4. Spacecraft Tracking and Communications

The Parkes Telescope has spent a modest percentage of its time in spacecraft tracking. What makes this area such a vital part of the story of the Parkes Telescope is that it has brought the instrument more funding and public attention than any other work.

NASA has used Parkes to do its tracking at various times, particularly before their own 64 meter dish network was completed. Parkes' size and position in the southern hemisphere meant that spacecraft communications could continue when the earth blocked the path between northern hemisphere receivers and the spacecraft. In return for use of the Parkes telescope for tracking missions, NASA paid for the time, and provided funding for upgrades and maintenance (*Robertson P. 1992: 267,269*)

The most famous tracking assignment for which Parkes was employed was the Apollo 11 mission in 1969 – the first manned lunar landing. The first ever moon walk was delayed several times but when it was finally time to transmit, Parkes was carrying the signal and so achieved international acclaim as the receiver for the first live broadcasts from the moon. To add to the drama the dish was forced to operate at wind speeds beyond its safety limits. Recently a fictionalized account of the story was told in the movie "The Dish" (*Robertson P. 1992: 269-272; The Internet Movie Database*).

The first NASA-Parkes collaboration was Parkes' involvement in tracking Mariner IV which sent back pictures of the surface of Mars. Unfortunately NASA publications made no mention of Parkes causing some ill will. Apollo 11 and subsequent Apollo mission collaborations were more successful (even where the mission wasn't i.e. for the ill-fated Apollo 13, Parkes provided outstanding support). With Apollo everyone was aware the stakes were high – human lives were at risk (*Robertson P. 1992: 267-272*)

In 1986 Parkes tracked the Voyager 2 spacecraft's encounter with Uranus. The distance of the spacecraft from earth made Parkes the best candidate for receiving the faint signals. Later in the year the European Space Agency's (ESA) Giotto spacecraft was also tracked from Parkes during its encounter with Halley's comet. This situation left NASA and the ESA competing for equipment space in the Parkes control room. The ESA had priority by virtue of first request. Both missions were successful, despite the virtual destruction of Giotto. In 1989, when Voyager 2 encountered Neptune, once again Parkes was used as a prime relay station. (*Robertson P. 1992: 274-276*).

Parkes' most recent tracking work has been support of the Galileo spacecraft in 1997. The main antenna on this probe, sent to the Jovian system, failed to open, leaving it with only a makeshift low bit rate, low powered backup antenna. Parkes was one of the most heavily used instruments in salvaging the mission, and spent 10 hours a day for a year tracking the probe. As a result an estimated 70% of the scientific goals of the mission have been completed – an amazing feat with a crippled probe. In order to allow a new Galileo receiver to quickly be exchanged with other receivers at Parkes, NASA funded a new aerial cabin with room for 4 receivers, instead of the 1 the original cabin could hold. (*Birthday Dish: 27*)

3.2.5. Education and Popularisation of Astronomy

In the earliest days of the Parkes Telescope, tours were conducted every Sunday afternoon. This came about as a result of requests by numerous public groups, local and international who wished to see the telescope. The public was led through the control room and facilities of the Parkes dish, and the telescope was driven in demonstration. This would mean that work was interrupted for the afternoon, but the scientists at Parkes accepted and understood the importance of public relations (*Robertson P. 1992: 300-301*)

As the tour grew more popular and it became clear that tours every Sunday afternoon were too disruptive – work halted and delicate or important equipment and data needed to be locked away, It was decide to replace the Sunday afternoon sessions with open weekends once every 3 months. Unfortunately, this exacerbated the problem, as up to 6000 people would attend the open weekends. One of these open weekends became a legend at Parkes: Heavy rain meant that the crowd of visitors tracked mud through the control room. As the mud dried it became dust which interfered with the operation of the more sensitive equipment in the control room for many weeks. The new PDP-9 was due for installation and depended heavily on a dust free environment. Parkes staff reluctantly cancelled the open days in 1964. (*Robertson P. 1992: 300-301*)

To compensate for this a public visitor's centre was planned. Government funding was initially refused, but in 1968 the first visitor's centre was opened. (*Robertson P. 1992: 301*)

In 2001, a new visitor's centre twice the size of the old was opened. It contains a wide variety of displays on the research conducted at Parkes, a drivable scale model of the main dish, a gift shop and two auditoriums where documentaries on Parkes and the solar system are shown. (Entry to the centre is free though the shows are not). It caters for roughly 100,000 visitors per year.

Figure 26 - The Parkes Observatory Visitor's Centre

The Parkes Visitor's Centre as it stands in 2001. In the background on the right is a partial view the Parkes main dish, giving an indication of just how close the visitor's centre is to the main instrument. Photograph by the Author 24/08/2001

In addition to the visitor's centre, Parkes supports work experience programs for school students, and special events such as a screening of the film "The Dish" help keep up public relations. The Parkes astronomers, technicians and administrators are keen to continue the reputation of the facility as a friendly fun place to learn about science, while giving researchers the time and space they need to keep Parkes as successful as ever. (*Parkes Visitors Centre*)

3.2.6. Other Spectroscopic Lines – Interstellar Molecules

The 21cm hydrogen line was the first spectroscopic radio frequency line discovered. However as time has gone by, other lines corresponding to molecules have been found in astronomical radio sources, while others which have been identified in the laboratory have not.

The earliest searches targeted deuterium. They failed. Searches for Hydroxide (OH) were more successful. Hydroxide radiates at four frequencies, two of which had been measured in 1958 by scientists at Columbia University New York. Each of these is at around 18cm (1665 and 1667 MHz) with relative strengths of 5:9. In 1963, Sandy Weinreb at the MIT Lincoln Laboratory was able to detect interstellar OH by its absorption lines, present in source Cassiopeia A at precisely the correct relative strengths. Parkes did some follow up work on Sagittarius A and confirmed the discovery just ahead of other groups at Cambridge, Berkeley and Harvard. Due to Sagittarius A's strength the Parkes astronomers were also able to detect the other 2 hydroxide lines as absorption at 1612 and 1720 MHz ahead of physicists detecting them in the laboratory - a first in radio astronomy. (*Robertson P. 1992: 320-321; Goddard, D., and Milne, D. 1994: 10; Robinson B. J. and McGee R. X. 1967*)

Other molecules quickly followed. Amongst these are ammonia (NH_4), formaldehyde (HCHO), carbon monoxide (CO), cyanogen (CN) and hydrogen cyanide (HCN). At Parkes the following were discovered: thioformaldehyde (HCHS), methyl formate ($HCOOCH_3$) and vinyl cyanide (CH_2CHCN) and methylamine (CH_3NH_2). Hundreds of molecules have now been discovered. Since many of these have lines that are at short wavelengths, one effect of this has been to put pressure on radio astronomers to construct dishes with greater and greater surface accuracies capable of focusing these frequencies. The discovery of interstellar organic molecules has also led to a great deal of speculation about the possibility of the existence of extraterrestrial life (though no amino acids or proteins have been found to date). Relationships between the existence of different molecules in different dust and gas clouds are also providing clues to the processes that take place in interstellar space. (*Robertson P. 1992: 322-329*).

3.2.7. The Search for Extra-Terrestrial Life

The first search for extraterrestrial life using the Parkes Telescope took place in 1966 and was conducted by Ken Kellerman. His target, PKS 1934-63, turned out to be a radio galaxy. Early in the history of the Parkes Telescope, SETI searches were not a favoured use of the telescopes time. The next search, in 1992, by David Blair studied 176 objects at a frequency of HI times Pi.

In 1995, the first serious SETI search took place over 6 months. Project Phoenix, a privately funded search which is the spin-off of a programme that lost funding at NASA, and which aims to conduct 10 years worth of SETI searches on world class instruments, kicked off at Parkes. Its aim is to study solar systems which are considered to be likely candidates for life. Project Phoenix moved on to other telescopes, and it wasn't until 1998 that the Southern SERENDIP (Search for Emissions From Nearby Developed Intelligent Populations) began. SERENDIP, run by the University of Western Sydney, relies on analysing data from other projects. Another project likely to do something similar using Parkes Multibeam data is SETI@Home, famous for using idle CPU time on volunteers' computers world wide via the internet to simulate a supercomputer for data analysis. (*Birthday Dish: 23-24; How to look at Southern SERENDIP data; SETI@Home*)

3.2.8. Confirming General Relativity

In July 2001, using the Parkes Radio Telescope, U.S. and Australian scientists computed the orbit of millisecond Pulsar J0437-4715 and its white dwarf companion with extreme precision by measuring signals to an accuracy of 100 nanoseconds. This feat required some 50,000 gigabytes of data to be processed. General Relativity predicts a slow-down of this pulsar's timing due to gravitational distortion resulting from the proximity of the white dwarf. This effect was successfully measured at Parkes and is the first such confirmation of General Relativity. This research is still in its infancy. Scientists now have plans to attempt to measure ripples in space time shortly after the big bang through the precise observation of pulsars.
(*Birthday Dish: 22*)

4. 21CM HYDROGEN LINE WORK AT PARKES

4.1. Key Differences Between the Field Stations and Parkes

It is worthwhile taking the time to note some of the operational differences between work at the early field stations and the Parkes Radio Telescope, in order to gain an appreciation for why the instrument changed the way radio astronomy was conducted.

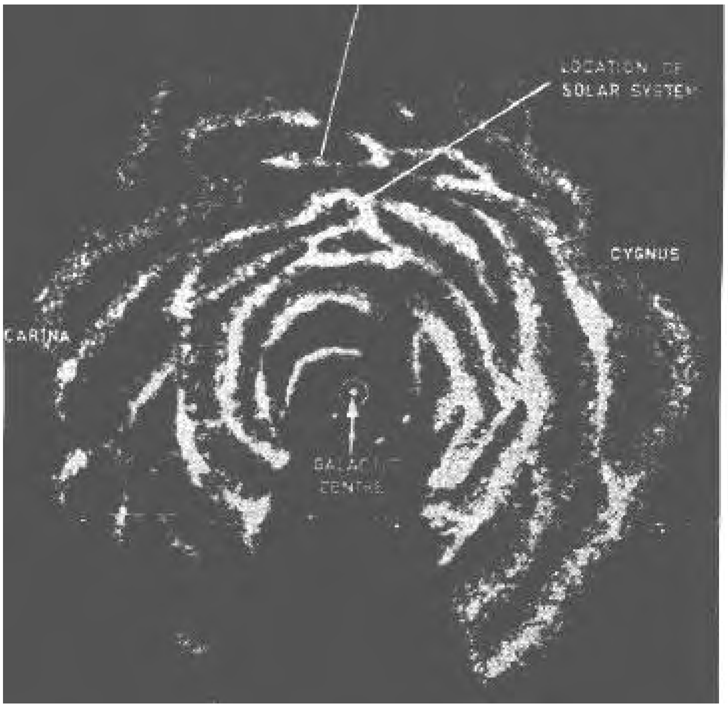
Firstly, one instrument now existed where many independently operated instruments had beforehand. Time on the telescope had to be planned and allocated as with any large instrument, and the "small science" approach where the key was innovation had to be replaced by a more planned approach to the work being undertaken. Conflicts would also arise in the management of the telescope. As Joe Pawsey's role in the CSIRO diminished, many perceived that he was "pushed aside", by John Bolton who wanted to run the dish. Regardless of the politics there was unquestionably more competition for the use of such a key resource. Personal interactions inevitably became more important.

There were also important technical differences at Parkes. The Parkes Telescope had been built as large as it had so that its beam width could be made small, allowing for finer detail to be studied for a given target. The Potts Hill aerial had had a beam width of 1 degree, requiring scans to be made 30 arc minutes apart for maximum data to be gathered. The Parkes Telescope has a beam width of 16 arc minutes, giving it the ability to resolve much greater detail. The trade-off for this detail however was that 14 points would need to be sampled to cover the same area as covered by 1 point at Potts Hill. This extended the time required for a given survey and made computerized techniques more important to the telescope when computers were introduced. A counter-effect of sorts came in the new receiver technology employed at Parkes. As discussed, in comparison to their post World War II counterparts, reduced noise in the new receivers also reduced the time required to obtain data.

4.2. Early Work

4.2.1. *The Milky Way*

When the Parkes telescope was handed over to the CSIRO, Frank Kerr, by then recognised as the chief specialist in H-line work at the CSIRO, undertook a new survey of the Milky Way using the new instrument. With the resolution offered at Parkes he was able to refine the detail of, and clarify problems in the Leiden-Sydney map. Kerr was also able to refine the detail of his work on the Galactic Centre. He found that the movements of hydrogen there were more complicated than first thought and involved "violent streaming processes in and around the galactic core". (*Robertson P. 1992: 315; Goddard, D., and Milne, D. 1994: 118; Kerr F. J. 1961*)



The distribution of neutral hydrogen in our Galaxy, as determined from 21-centimetre H-line observations, confirms that it is a spiral nebula.

Figure 27 - Hydrogen Map of the Milky Way

Note the prominence of the spiral structure vindicating early expectations of spectacular evidence of the shape of our Galaxy. Note also the area behind the centre of the Galaxy from the point of view of our system requires later efforts to map. It is known as the Zone of Avoidance (ZOA). Photograph taken from (*The CSIRO 210-Foot Radio Telescope: 12*).

The late 1960s and early 1970s saw increasingly detailed maps of the Milky Way constructed. Two Parkes surveys published in 1969, together with northern hemisphere data gave the first picture of not only the distribution but also motion of hydrogen in the Galaxy. (*Birthday Dish: 23*). As data was studied, its limitations would become apparent and a more detailed survey would seek to replace or augment the data as required. Increasing computerization and constantly improving receiver technology facilitated this process, constrained by observing time on the Parkes Telescope. A classic example of this process can be found in (*Kerr F. J., Harten R. H. et. al. 1976*), which describes the reduction of observations made 5 years prior with plans for refined observations to fill in the gaps, and intermediate results presented.

4.2.2. The Magellanic Clouds

The Magellanic Clouds were also natural targets for early hydrogen line work at Parkes. At the distance of the Clouds, the Parkes Telescope was capable of resolving features as small as 200 parsecs. (*Goddard, D., and Milne, D. 1994: 119*) Observations of the Small Magellanic Cloud by Jim Hindman and his collaborators have proven the neutral hydrogen in the disk to be an evenly distributed slightly flattened rotating system, edge on to our line of sight. An unexpected discovery was made observing the Doppler shifts of the cloud – there are 2 distinct masses of gas and stars moving apart at around 50km/s – there are therefore in fact 3 Magellanic Clouds, the smallest of which has been dubbed the Mini Magellanic Cloud.

At the same time the Large Magellanic Cloud came under the scrutiny of Dick McGee and Janice Milton. The distribution of neutral hydrogen in this cloud is not uniform but rather consists of complexes of “clumps” of gas – each of these are a stellar nursery, harbouring new stars while others still coalesce. The biggest surprise this time was discovery of evidence of a simple “primitive but discernable” spiral structure in this galaxy, previously thought to be an irregular. (*Robertson P. 1992: 315-316*)

The McGee and Milton observations were published in 1966, followed by Hindman’s in 1967 and they have become the “standard reference works for the Magellanic Clouds”. (*Goddard, D., and Milne, D. 1994: 120*)

In the late 1960s there was a lull in the work undertaken on the Magellanic Clouds. However new research by Don Mathewson in 1973 led to the discovery of a filament of hydrogen extending from the Magellanic Clouds across a large arc of the southern sky. Known as the “Magellanic Stream”, Mathewson originally proposed that this was the result of a collision between the Magellanic Clouds roughly 400 million years ago. Another theory held that the stream was the result of the clouds travelling through the intergalactic hydrogen surrounding the Milky Way and that this was a kind of “intergalactic wake”. Our current understanding is that the stream is likely to be the result of a combination of both theories. (*Robertson P. 1992: 316; Caught Red-Handed: Our Galaxy Is Destroying Its Neighbours*)

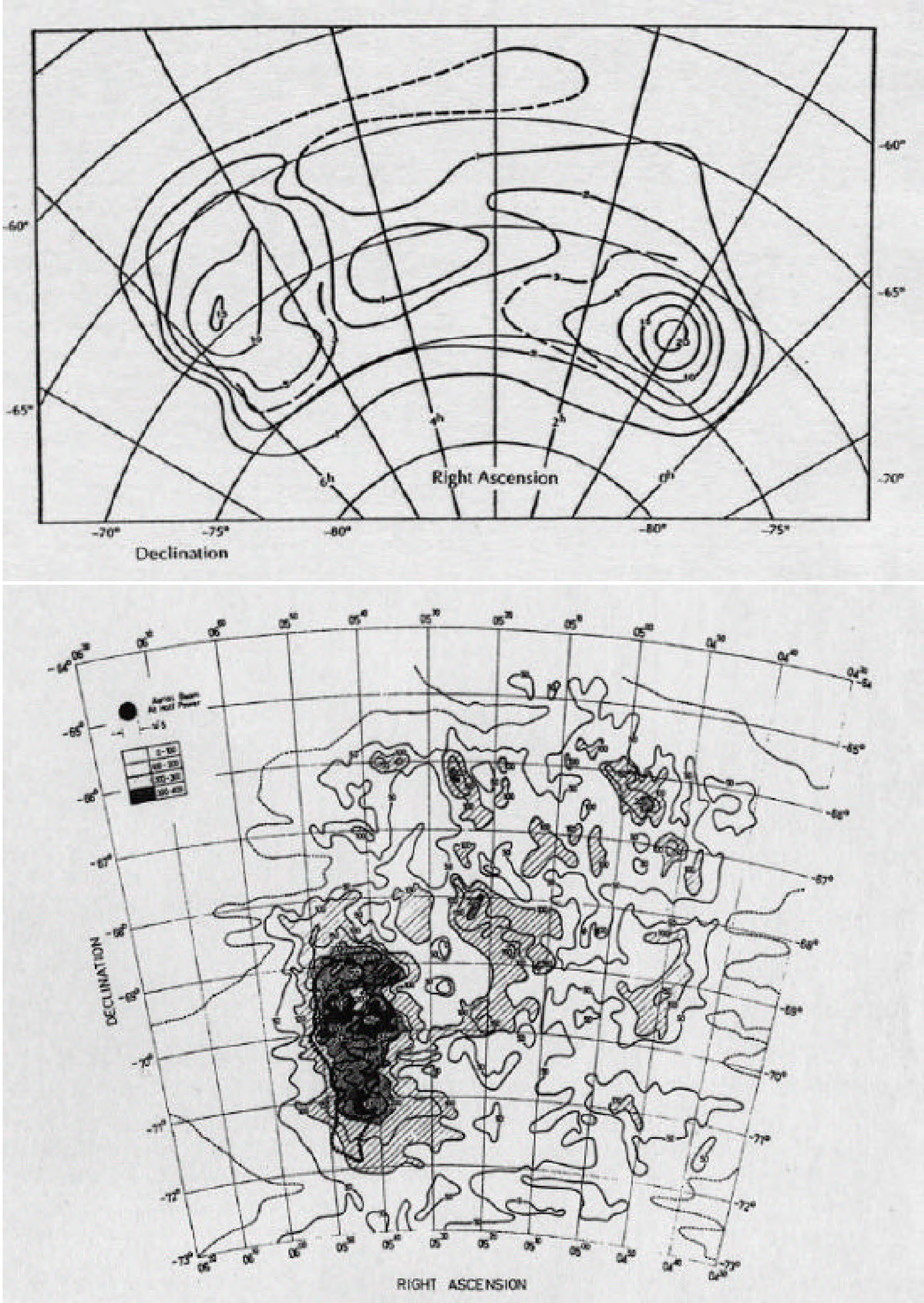


Figure 28 - Improvement in Sensitivity and Mapping Detail at Parkes

These images show the dramatic improvement the Parkes Telescope made in the detail observed in the Magellanic Clouds. The top contour map in HI of the Clouds is from work done by Hindman at Murrybank in 1953. The bottom, of the Large Magellanic cloud was made by McGee and Milton using the Parkes dish in 1964. Notice the detail in curvature, and the key indicating densities. Taken from (*Goddard, D., and Milne, D. 1994: 120-121*)

4.2.3. Parkes Hydrogen Line Scientists

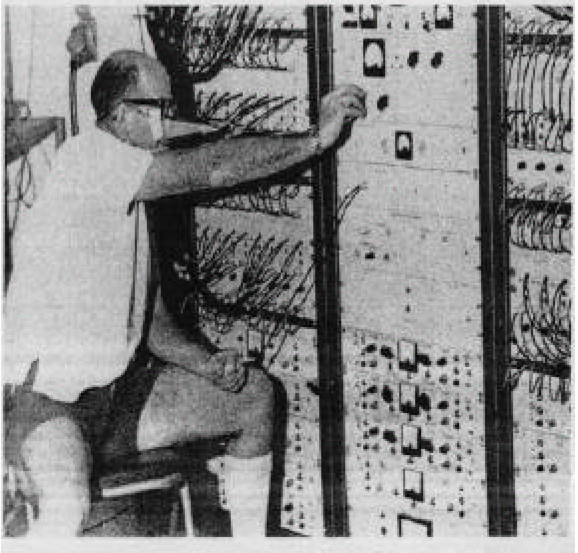


Figure 29 - Richard X. McGee

Richard McGee wearing a silly nose for the day at Parkes on a bet. Photograph taken from (*Goddard, D., and Milne, D. 1994: 52*)

Figure 30 - Brian Robinson at the Console

Robinson seated, seen talking to John Bolton at the right. Photograph taken from (*Goddard, D., and Milne, D. 1994: 39*)

4.2.4. Other Galaxies and Intergalactic Hydrogen

The availability of the Parkes telescope also allowed radio astronomers in the southern hemisphere to finally tackle problems requiring greater sensitivity than their previous instruments allowed. This included studying the hydrogen lines of more remote galaxies, and studying hydrogen line absorption in the intergalactic medium.

Observing Galaxies in neutral hydrogen has allowed astronomers to determine the amount of material in each left for further star formation. This gives an indication of the maturity of the galaxy. Much of the early work in this area was conducted by Brian Robinson and concentrated on the Virgo cluster. The led to the current picture of spiral galaxies being active in star formation and containing between 2% and 10% hydrogen depending on their “maturity”, and elliptical galaxies containing only slight traces (as low as 0.1%) of free hydrogen with the rest having gone into star formation. (*Robertson P. 1992: 316*)

The first detected intergalactic absorption was measured by Koehler and Robinson, They found intergalactic HI in absorption in the spectra of Virgo A and 3C 273 (*Koehler J. A. and Robinson B. J. 1966*). The amount of interstellar hydrogen is of significance because it dictates whether or not further galaxy formation is likely. They showed, and it has been confirmed, that intergalactic hydrogen is very sparse and that further galaxy formation is impossible based on current evidence. These studies and others have led scientists to account for roughly 20% of the mass required to form the universe we observe, based on modelling of gravitational forces. The rest of the mass is referred to as dark matter and as yet unobserved, has led to many theories regarding what it comprises.

4.3. Recent Work – 21 cm Surveys and Mapping

The new Parkes 21cm Multibeam Receiver has led to somewhat of a revival of HI research at Parkes since its installation in 1997. This receiver has been used to detect objects that do not emit at all in the visible spectrum. In 1998 it was used to confirm that the Milky Way is ripping apart the Magellanic cloud system. The receiver has also been used in the search for young pulsars. The receiver however was designed specifically for hydrogen survey work and is capable of being used to detect 100 times more hydrogen than previous surveys. What follows is a brief description of some of the surveys undertaken recently at Parkes with this instrument.

The HIPASS (HI Parkes All-Sky Survey) survey has just been completed and took roughly 3500 hours of observing time. It was a breadth-type survey which covered the entire southern sky. An extension also covered parts of the northern sky. Aims included gathering information on the "distribution of galaxies, the power spectrum, the HI mass function, the dynamics of groups and superclusters, the frequency of dwarf galaxies, the space density of giant low-surface-brightness galaxies". (*The HI Parkes All-Sky Survey*) Numerous papers have already been published on results of the survey already available, which are a long way from being fully analysed.


HIPASS scans completed as of 8 Sep 2001:

Note: the short coloured marks are only about 1/6th as long as the actual 8 deg scan. The declination of the scan centre (ie, the dec in the sched file name) is crossed by the yellow marks.

Figure 31 - Status of the HIPASS survey as at 2001 September 8

Percent done (southern hipass) = 100.00
Percent done (northern extension) = 96.45
This is taken from the project's web site, specifically:
http://www.parkes.atnf.csiro.au/people/multi/scanlog/hp_zoa_progress.html
See the site for a more up to date representation of progress.

The Deep Survey aims to cover smaller sections of the sky than HIPASS but at greater sensitivity and with greater detail. This survey has been split into sub-surveys based on the section of sky observed. Completed parts of the survey include the HIPASS Intermediate Deep Field (IDF) and DEEP-I (P298) surveys, carried out on a 4^{o} by 8^{o} section of sky centred on $13^{h}40^{m}00^{s}$ $-30^{o}00'00''$ near M83 in the Centaurus A group; and DEEP-II (P308), an 8^{o} by 8^{o} section of sky near the centre of the Sculptor group. The overall survey is still in progress.

The Zone of Avoidance (ZOA) Survey sought to gather data on nearby galaxies optically obscured by material in the plane of our galaxy (the Zone of Avoidance). This data will help astronomers to better understand gravitational interactions within the local group of galaxies and beyond. The 1500 hour observing project is complete and follow-up work has been undertaken on the Australia Telescope Compact Array (ATCA).

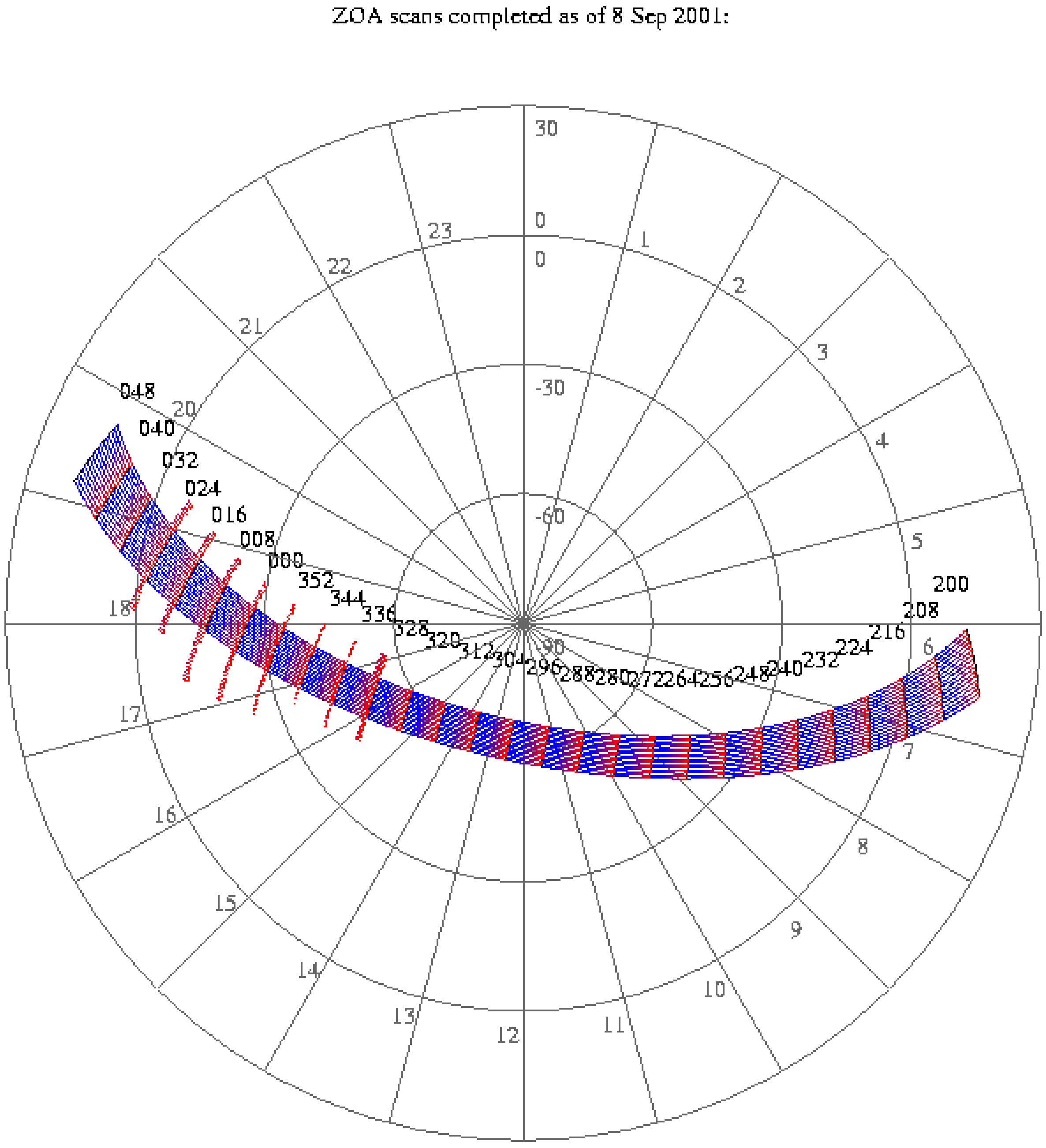

ZOA scans completed as of 8 Sep 2001:

Figure 32 - Status of the ZOA survey as at 2001 September 8

Percent done (zoa) = 64.96
This is taken from the project’s web site, specifically:
http://www.parkes.atnf.csiro.au/people/multi/scanlog/hp_zoa_progress.html
See the site for a more up to date representation of progress.

More detailed information on these surveys is beyond the scope of this paper, but for those interested it should be noted that many recent research papers based on these surveys can be found at the (*Parkes 21cm MULTIBEAM Project*)

4.4. A Note on the Future

The future of hydrogen line research is increasingly part of a whole picture of the universe being developed by radio and optical astronomers, “new” astronomy at wavelengths opened up by space instruments, and theoretical modelling. The last few years have seen a revival of hydrogen research at Parkes with the 21cm Multibeam Receiver. There are undoubtedly still some surprises left in the field, and as we dig deeper with new instruments they will come to light. 60 years ago we only had optical astronomy to investigate the universe with. Today we’ve added the radio, Gamma and X-Ray spectrums to our toolkit.

In a sense the “golden age” of radio astronomy is gone – a few individuals with some relatively inexpensive equipment can no longer further this branch of science. Those who have lived through this period and had an interest in the field have been very fortunate. It took until the end of the last century for optical astronomy to reach the point where the amateur’s contributions were limited – almost 300 years passed between the conception of the optical telescope and this point in history. By contrast, less than a human lifetime has passed between the time of the first radio observations, and the point where “big science” is required to contribute to the field. The main contribution to the speed of this resolution has been the timing of the availability of the right technology. In the last 40 years receivers have improved dramatically, and computers have come into play allowing for more accurate control and recording of data, and faster, less error prone analysis.

Now it seems that even the age of the single large radio telescope is coming to an end. The future lies in techniques that synthesize large telescopes – rotation synthesis and most importantly long baseline interferometry. Single large dishes become exponentially more expensive with their size, where the relationship is more linear with an array of dishes. Many of the obvious answers and surprises have already been seen in hydrogen line work. More profound answers coming from highly specialized and detailed work that may cut across disciplines await us. We will of course have to surmount the usual problems – the same ones that faced the Parkes Telescope – who will make the decisions, who will do the work, and who will fund it.

5. CONCLUSION

The twin intertwined histories of 21cm hydrogen line research and the Parkes Radio Telescope are a prime example of the timing of technological development dictating the development of a science. We’ve followed radio astronomy from an embryonic “small science” – innovative and relatively inexpensive scientific endeavours by individuals and small teams made for a wealth of early discovery. In the boom in radio astronomy that followed World War II, Australian scientists shared in these discoveries. The instruments and the research matured together, necessitating larger investments in time and money to progress the field. The Parkes Telescope was a necessary next step – one that was kept Australia up to date with the technology of the day. The Parkes dish has become a part of the Australia Telescope, and spectroscopic analysis at radio wavelengths has extended to a wide variety of molecules. Hydrogen line surveys now use sophisticated computerization and the Parkes 21cm Multibeam Receiver capable of tracking 13 patches of sky at once.

Both the stories told in this paper are interesting in their own right, and are of course part of the larger story of radio astronomy as a whole. By focusing on one area of research I hope to have dramatically shown how the technology, the instrumentation and the men and women of the day came together to move forward in their knowledge of the universe.

From Jansky and Reber, to Van De Hulst and Oort, White and Pawsey, Bowen and Bolton, Kerr and McGee, Robinson and Hindman, to the up and coming hydrogen line radio astronomers of today, all these men and women share a commitment, dedication and tenacity that can be traced to the beginning of their field. Armed with the right instruments they have solved some of the grand mysteries of the universe, and their enquiry has not by any means ended yet.

A lot has happened in just under 60 years. One of the few certainties regarding the future of radio astronomy, in Australia and world wide, and of the instruments we build to pursue the science is this: If we collectively do not abandon our studies, what we learn about our universe and of our own capabilities will continue to surprise, thrill and inspire us all as human beings.

6. ACKNOWLEDGEMENTS

In gathering information for this work a number of people have been very helpful, and I am indebted to them for their generosity, time and effort.

I would like to thank the staff of the N.S.W State and Mitchell libraries for helping me get access to much of the material I had on Parkes – particularly in the form of the two books “Beyond Southern Skies” and “Parkes: 30 Years of Radio Astronomy”.

For his support as the lecturer of History of Astronomy at U.W.S., his efforts in discussing this paper with me despite incredible time pressure, for his helping with contacts that proved invaluable such as Dr Brian Robinson and Dr Richard X. McGee, and for providing me with copies of material I was unable to obtain in time on my own, I thank Dr. Wayne Orchiston.

For discussing his work with me, answering numerous questions, allowing the inclusion of an email interview as an appendix to this work, and for his general advice, encouragement and help in researching Parkes and H-line astronomy I thank Dr Brian Cooper.

For commentary which proved invaluable to getting a feel for the motivations of key players during the early years of Australian H-line research, and for his responses to my queries I thank Dr Richard. X. McGee.

For accompanying me to visit the Parkes Radio Telescope, and for the contribution of figure 1, I thank Javier Woodhouse.

I would also like to thank Alex Hons for his continued support throughout the AIM program.

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>
> The HI Parkes All-Sky Survey (HIPASS)
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>
> An HI survey in the Zone of Avoidance
> http://www.atnf.csiro.au/research/multibeam/lstavele/milky_abstract.html
>
> HIPASS/ZOA Survey Status
> http://www.parkes.atnf.csiro.au/people/multi/scanlog/hp_zoa_progress.html

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Tall Poppy Capaign
Cavalcade of Scientists
Joseph Pawsey
http://www.tallpoppies.net.au/pawsey.html

8. APPENDICIES

8.1. Appendix 1: Timeline of Events: The Parkes Radio Telescope and Hydrogen Line Research

Year/Date	Event
1932	Karl Jansky. Earliest confirmed detection of extraterrestrial radio noise.
1937	Grote Reber builds his first parabolic radio dish specifically for radio astronomy, and soon begins first map of the radio sky in his off hours.
1939	Beginning of World War II.
1939	The CSIR Division of Radiophysics is created.
1940	Edward “Taffy” Bowen joins Radiophysics.
1942	Fred White joins Radiophysics.
1944	21cm hydrogen line (including wavelength) predicted by Van De Hulst.
1945	End of World War II. The CSIR Radiophysics division has a staff of around 300. Post-war research including radio astronomy pursuits begin.
1946	John Bolton joins Radiophysics.
1949	The CSIR ceases secret and military work and its name is changed to the CSIRO (Commonwealth Scientific and Industrial Research Organisation).
1951	21 hydrogen line first observed by Ewen and Parcel of Harvard.
1952	Joe Pawsey becomes Assistant Chief at the CSIRO department of Radiophysics.
1952	First Proposal for a giant radio telescope.
1952	Union Radio-Scientifique Internationale (URSI) holds its 10th General Assembly. There is much discussion of the recent discovery of the hydrogen line.
1953	At Potts Hill Frank J. Kerr and Jim V. Hindman constract a

	36ft (11m) parabolic antenna for 21cm hydrogen line observation. This instrument is used in a multitude of groundbreaking observations. Mapping of the Milky Way begins.
1953	Brian Robinson recruited at Potts Hill Field station. Observes extra-galactic H-line emissions from the Magellanic Clouds.
1954 May 15	The Carnegie Corporation grant USD 250,000 for a giant radio telescope in Australia.
1954	The Rockefeller Foundation grants another USD 250,000. With the Austrlian Government matching each contribution dollar for dollar, funding is assured and detailed planning for the new giant radio telescope commences. Telescope design committee formed.
1954	Frank Kerr does a detailed study of the Galactic Centre at 21cm.
1954	Pamphlet outlining competing designs produced by the giant telescope design committee.
1955	Barnes Wallis is recruited for initial design of the radio telescope. Freeman Fox is awarded the contract for construction. 7
1955	John Bolton leaves CSIRO Radiophysics.
1958	Leiden-Sydney map of the entire sky at 21cm completed.
1959	Design of the giant radio telescope is completed. Delays by subcontracts lead to construction work going to tender and won by Maschinenfabrik Augsburg Nurnberg (MAN).
1959	Fred White becomes chairman of the Department of Radiophysics.
1960	"Murrybank" receiver tested with intention to install it at Parkes. Frank Kerr, Jim Hindman and Dick McGee to discover a bridge of gas between the large and small Magellanic clouds.
1961	John Bolton returns to the CSIRO to become the Director of the Parkes Radio Telescope.
1961 October 31	Parkes Telescope officially commissioned.
1961-1962	Paramp and Maser technology mature and are trialed at Parkes. Both devices are much more sensitive and less noisy

	than previous receivers by orders of magnitude. Paramps soon win out as they need to be cooled less than Masers.
1962 March	Parkes Telescope acceptance tests completed. The telescope is handed over to the CSIRO for research programs to commence.
1962	Joe Pawsey leaves the CSIRO.
1962	Parkes involved in tracking Mariner II.
1962	Pioneering work on polarization and magnet field undertaken by Parkes. First high levels of polarization are detected confirming the presence of Synchrotron radiation. Brian Cooper and Mark Price observe the Faraday Effect
1962	Parkes involved in pioneering Quasar work. Radio source 3C 237 is located via the lunar occultation method and its visible counterpart is identified.
1963	18m dish moved from Fleurs to Parkes.
1964	Regular Parkes open days cancelled due to overwhelming demand.
1965	Brian Cooper, Marc Price and Doug Cole make the first magnetic field map of another galaxy – Centaurus A.
1965	Two element interferometer assembly and construction completed. The Parkes Interferometer is born.
1966	Koehler and Robinson find intergalactic HI in absorption in the spectra of Virgo A and 3C 273. Galaxies now seriously targeted by hydrogen-line radio astronomers.
1967	First pulsar discovered. Initially the discovery was kept secret by astronomers at Cambridge while they tried to understand the source of the signals.
1967	Dick McGee and Janice Milton publish the “standard reference works for the Magellanic Clouds” based on Parkes observations.
1968	First pulsar work undertaken at Parkes.
1968	First Parkes visitor’s centre opened.
1969 July 21	Parkes used to relay 1st manned moon mission landing by Apollo 11.

1969	The Parkes Telescope is shut down and upgraded between the Apollo 11 and 12 missions. The tower is reinforced after bulging is detected, the cabling and pipes in the tower is replaced, the control room is upgraded, airconditioning is fitted. The PDP-9 is insalled.
1969	Results of 2 Parkes H-line surveys published. Together with Northern Hemisphere data they provide the first complete data on hydrogen gas motion as well as distribution.
1970	Venkataraman Radhakrishnan and Max Komesaroff propose the widely accepted "rotating beam, magnetic-pole" model for a pulsar, a refinement of work by Tom Gold of Cornell University.
1970	Fred White steps down as chairman at the CSIRO Department of Radiophysics.
1971	Parkes Telescope panels upgraded with more accurate panels.
1971	John Bolton leaves the CSIRO.
1971	Parkes used to discover the spectral line of HCHS (thioformaldehyde).
1972	Second Parkes Telescope panelling upgrade. The telescope is now capable of 1.3cm observations.
1973	Don Mathewson discovers the Magellanic stream using the Parkes telescope.
1975	The "Australia Synthesis Telescope" later to be renamed the Australian Telescope is first proposed.
1978	Parkes-Mongolo survey is published 155 new pulsars found where only 55 were previously known.
1980	Two Element Synthesis Telescope (TEST) revamp completed and modified interferometer first used.
1982	First extra-galactic pulsar discovered at Parkes.
1985	New control system for the main dish is installed at Parkes.
1986	Voyager Uranus flyby. Giotto intercepts Halley's comet. Parkes plays a major role in each mission.
1987	Supernova 1987a explodes. Despite attempts by Parkes and world-wide, no pulsar is found at the core of the explosion.

1989	Voyager Neptune flyby. Parkes again plays a major role in tracking.
1989	The Parkes Radio Telescope becomes a part of the Australia Telescope. Management is given to the Australian Telescope National Facility (ATNF)
1995	Parkes involved in tracking Galileo. A new aerial focus cabin is installed capable of holding 4 receivers instead of one.
1995	Parkes used in SETI search Project Phoenix.
1997	The 21cm Multibeam Receiver is installed at Parkes HIPASS (HI Parkes All-Sky Survey) commences. Deep and ZOA (Zone of Avoidance) surverys also planned.
1998	Southern SERENDIP SETI search commences using data gathered by other projects instead of seeking to gain access to telescope observing time.
2000	The movie "The Dish" premiers.
2001	New Parkes visitor's centre opened.
2001 July	Pulsar observations give first observations of an effect predicted by General Relativity.
2001	HIPASS (HI Parkes All-Sky Survey) completed

8.2. Appendix 2: A Proposal for a Giant Radio Telescope

This excerpt is taken from Goddard, D., and Milne, D. 1994, pages 115-116. It has been reproduced in full because it clearly and concisely serves to demonstrate the design features of the Parkes telescope which were consider to be of greatest importance, and the prominence of design features aimed at observing the 21cm hydrogen line (which was at the time the only spectroscopic line known in the radio waveband.). The proposal is interesting for a second reason - “Taffy” Bowen, the man who had most influence on the project, is the author. Note that half of the paper below is devoted to the explanation of the use of such a dish in hydrogen line studies.

(Reprinted from *A Proposal for a Giant Radio Telescope*, CSIRO, Division of Radiophysics, Sydney, 1955, pp. 24-26)

ASTRONOMICAL CONSIDERATIONS

Before discussing in detail the type of astronomical information which might be obtained from observations with a large radio telescope, we should distinguish between two properties of such an aerial, high resolving power and high gain, since these find application in different problems .

Resolving power is the ability to distinguish between adjacent objects which have only a small angular separation . The gain of an aerial, on the other hand, determines the amount of radio-frequency energy which it can collect . Resolving power depends on the linear extent of an aerial, whereas gain is a function of the surface area .

High gain is necessary for detecting objects of small angular size when the received intensity is low. Very often, however, the energy received from a region of the sky may be quite large, but its distribution over the sky complex. High resolving power is then required to reveal the fine structure of the space distribution.

High resolution (but not high gain) has recently been obtained by special aerials developed by the Radiophysics Laboratory, such as the Christiansen multiple-beam interferometer at Potts Hill (wavelength 21 centimetres) and the Mills 'cross' at St . Marys (3-5 metres) . These aerials have the large linear extent required to produce high resolution but are relatively small in area, so that their gain is low . For work at one particular wavelength, in cases where the received intensities are relatively high, these aerials are very satisfactory, but their use is limited .

At 21 centimetres, this type of aerial is sensitive enough only for work on the Sun, and little can be done with the very important cosmic radiation in this wavelength range . At the longer wavelengths, a cross aerial is superior to a parabola for cosmic noise studies on a single frequency, but the inflexibility of such a system is a very serious limitation . There is great need here for an aerial which can operate over a wide range of wavelengths for simultaneous observations at several separate frequencies or for spectroscopic work over a wide range.
At the shortest wavelengths there is no alternative to a parabola for cosmic work,

and it is in this range that the greatest need for such an aerial arises . For this reason, it is essential that the proposed giant radio telescope should be built with sufficient accuracy for work at short wavelengths .

Twenty-One-Centimetre Hydrogen Line

The most important uses of a large radio telescope will be in studies of the 21-centimetre hydrogen line, where no other method is available for obtaining high resolution because the radiation is always of low intensity .

This line, which is produced by the hydrogen in interstellar space, was first detected only in 1951, but it has already made very important contributions to galactic astronomy. It is of great importance astronomically, because by far the greater part of interstellar matter was previously undetectable by any known means. This recent development offers a striking example of the complementary role of radio studies in astronomy .

Because this is line radiation, frequency displacements due to the Doppler effect can be measured, providing information on the velocities of the sources of radiation. In addition, it shares the property, common to all types of cosmic radiofrequency radiation, of being able to penetrate large distances of space. Studies of the line can, therefore, reveal both the distribution and motions of a gas throughout a galaxy . It is believed that our galaxy contains a spiral structure of the form seen in external galaxies, with the Sun near one edge . Optical studies cannot unravel much of this structure, because light waves are strongly absorbed by the widespread clouds of interstellar dust. The centre of the galaxy is believed to be in the direction of the brightest part of the Milky Way .. . but all the visible stars are within a small fraction of the presumed distance to the centre .

Knowledge of the large-scale structure of our own galaxy and also of the Magellanic Clouds has already been greatly extended by hydrogen-line studies, and it seems likely that the spiral structure of each of these systems could be plotted out in detail, given sufficient resolution . Use of a larger aerial would also bring other galaxies within reach of this powerful method. The gas in our galaxy is to a large extent concentrated into clouds . With present aerials only a small number of these clouds can be seen individually, but increased resolution would permit large numbers of hydrogen clouds to be studied. This would lead to important results on the cloud structure of the interstellar gas, with applications to the evolution of stars from clouds of gas. Observations of individual gas clouds throughout a complete revolution of the Earth around the Sun should also yield a precise value for the Earth's orbital velocity, and hence for the Earth's distance from the Sun, an important astronomical constant .

The red shift which is observed in the light from distant galaxies is usually interpreted as due to a rapid movement away from the observer. This has led to the theories of the expanding universe . It is possible, however, that some hitherto unsuspected physical principle is involved . Important evidence would be obtained if red shifts at radio wavelengths could be measured and compared with the optical values . This can be done only if the 21-centimetre line from a substantial number of galaxies can be detected at sufficient strength for precise frequency measurement, for which a high-gain aerial is essential . A recently-discovered effect, in which the 21-centimetre radiation from discrete sources ('radio stars') is absorbed by the interstellar hydrogen in front of them, provides the first possibility of measuring the temperature of this gas. The absorption effect is proportional to the gain of the receiving aerial, and precise temperature measurements require a high gain .

It is estimated that considerable advances could be made towards solution of all the above problems with an aerial whose beam width at 21 centimetres is of the order of 0.1 to 0.2 degree . This corresponds to an aperture of 200 to 350 feet.

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8.3. Appendix 3: Improvement of Receiver Technology at Parkes

The following table showing some of the receivers used at Parkes is taken from Goddard, D., and Milne, D. 1994, pages 48 – 49. The table was originally titled “Parkes receiver development 1961-1991”. For those without a background in radio electronics the table may make sense if the following definitions are kept in mind. The details of the differences between the types of receiver lie outside the scope of the paper.

	Receiver	**First Installed**	**Personnel**
1	Mk 1 21cm H line multi channel	Oct 1961	J.V .Hindman, R.X .McGee, J.D .Murray
2	10-cm crystal mixer	Feb 1962	T. Cousins
3	75/21-cm	Mar 1962	B .Mackey, R.D. Ryan, F .Tonking
4	20-cm cooled (77 K) paramp	Apr 1962	F.F .Gardner, D.K .Milne
5	220-cm (136-MHz) cascade triode	early 1962	Mackey
6	Various mixers (polarisation studies)	May 1962	Tonking
7	H-line extragalactic Rx, up-converter paramp	late 1962	B .J . Robinson, K. van Damme
8	11-cm paramp	Dec 1962	B.F.C .Cooper, L .Gruner, C. Howarth, Cousins
9	18-cm mixer	Nov 1963	G J .Bolton, Gardner, Robinson, van Damme
10	6-cm tunnel diode	Oct 1963	Cooper, Gardner, Tonking
11	9-m mixer	Early 1964	Bolton, Gardner, McGee, Robinson
12	H-line, narrowband (10-kHz filters added to Mk I H-line Rx)	Jul 1964 filters	C. J.Ohlston, M.W. Sinclair, G.H . Trent, Hindman, McGee
13	150-MHz solid-state receiver	Feb 1965	R.A. Batchelor
14	H-line paramp	Oct 1965	Hindman, Robinson, Sinclair,

			Trent
15	Interferometer (75/21-cm continuously variable baseline)	Oct 1965	R .Clarke, D.G .Cole, R.D. Ekers, A. J . Shimmins, G.Wells, Batchelor, Bolton, Cooper, Howarth, Milne
16	600-MHz Ferranti paramp	Nov 1965	P .Crosthwaite, A .Falson, Cooper
17	11-m broadband correlation	Apr 1967	J.W .Brooks, J.V.Wall, Batchelor, Cooper, Howarth
18	18-m room temp paramp + Mk II line receiver	Sep 1967	Batchelor, Brooks, Howarth, McGee, Milne, Sinclair,Trent
19	Greenbank 6-cm cooled paramp	Apr 1968	Batchelor, Brooks, Cooper, Gardner, Milne
20	Installation HI-line interferometer	Aug 1969	W.M. Goss, D .Morris, V. Radhakrishnan, U. Schwarz, Brooks, Cooper, Murray
21	9-m paramp (room temp)	Sep 1969	Gardner, Sinclair
22	Cryogenic 6-cm	Dec 1970	D.C. Dunn, Brooks, Cooper Sinclair, Trent
23	Installation 3.4-cm	May 1971	P.W .Butler, D. J. Cooke, A. R. Kerr, L. M. Newton, Batchelor, Cooper, McGee
24	1 .3-cm mixer (NRL)	Aug 1971	K. Johnston, Batchelor
25	1 .3-cm mixer (room temp)	Mar 1972	M.G .McCulloch, Batchelor, Brooks
26	Digital correlator	Apr 1972	J.G. Ables, A.J. Hunt, G.G. Moorey, Brooks, Cooper
27	9-m paramp (room temp)	Oct 1972	Sinclair
28	18-m dual-channel receiver (room temp)	Feb 1973	N. Fourikis, Cooper, Howarth, Sinclair
29	Acousto-optic spectrograph (AOS), film output medium	Jul 1973	T.W. Cole
30	5-cm paramp (room temp)	Oct 1974	Batchelor, Cooke, McCulloch

31	AOS (prototype)	May 1975	Batchelor, Cole
32	1-8/1-65/1-3-cm cooled mixer	May 1975	M. Balister, S. Knowles Batchelor, McCulloch
33	7-mm cooled mixer (20 K)	Jun 1976	Balister, Batchelor, McCulloch
34	7/3-mm cooled mixer	Jan 1977	Batchelor, McCulloch
35	2-cm cooled paramp (20 K)	Feb 1977	G .J. Gay, B.M.Thomas, Howarth, Sinclair
36	AOS programmed to PDP9	Mar-Jun 1978	A. Bos, L. Simons, Batchelor, Cole, Milne, Robinson
37	TEST	Mar 1980	J.R. Fisher, R.N. Manchester, P.T. Rayner, Ables, Butler
38	21-cm FET amplifier	Nov 1980	K .J .Wellington
39	K-band (1 -3-cm) maser	Jul 1981	C.R. Moore, B. Wilcockson Brooks, McGee, Milne, Murray, Sinclair
40	843-MHz FET (MOST)	Oct 1983	Milne, Wellington
41	X-band cooled FETs	Nov 1983	R. J. Bolton, H.R .Kanoniuk, Sinclair, Wellington
42	ESA 3-cm test Rx	Nov 1983	R .J. Bolton, Kanoniuk, Sinclair, et al.
43	Q-band maser	Jun 1985	Gay, McCulloch, Moore
44	Multi-frequency (AT prototype, 3/6/13/20-cm)	Oct 1986	R.J .Bolton, R.G. Gough, P.H. Seckold, Moorey, Sinclair

8.4. Appendix 4: An Email Interview with Brian Robinson

1) What were the most important early surveys done before/after Parkes was commissioned? How were the parameters of the surveys chosen?

** The main galactic plane HI survey before Parkes was from the cooperative Leiden/Sydney observations. At Potts Hill Frank Kerr and Jim Hindman observed the southern galactic plane - from Sydney you can see 90% of the plane, with the galactic centre passing overhead. From Dwingeloo in the north of The Netherlands (where Ben Hooghoudt built the 25 metre dish) the galactic centre just comes above the horizon. The difference in latitude between Sydney and Dwingeloo is 87 degrees!
The parameters of the survey were set by:
a. The beamwidth of the telescope(s): For the 36 foot dish at Potts Hill the beam at 21 cm was 1.0 degree. For maximum information, scans need to be made 30 minutes-of-arc apart.
b. The bandwidth of the observing channel(s). At Potts Hill this was set at 40 kHz - which represented a spread in radial velocity of 8.4 km/s. For observations where the frequency was scanned, the number of frequency changes was determined by the width of the 21 cm emission profile. The initial 1951 observations by Christiansen & Hindman had shown, for example, that near galactic longitude 210 degrees galactic rotation had broadened the emission profile over more than 300 kHz. That was more than 8 frequency channels. So observe 16 to get some baseline to the emission profile.
c. The sensitivity required or desired. Fifty years ago, 1420 MHz receivers (from World War II technology) at were very noisy. Averaging the receiver output over 15 seconds reduced the r.m.s. noise level to 2.4K. The maximum 21 cm emission gave an antenna temperature of under 100K.

In summary, a minimum observation was a point at at least every degree in the sky observed for 15 secs at each of, say, 16 frequency settings.

Then allow for the data being recorded on chart recorders - to be read off later and processed by teams of Sydney University undergraduates (who thereby earned some money from CSIRO to help with their studies).

2) What were the biggest surprises to come out of hydrogen line spectroscopy?

** The surprises were many. The hydrogen layer turned out to be very thin, and very flat - "like a gramophone record" - (inside R = 10 kiloparsecs). There was a systematic distortion of the HI out of the plane beyond R = 10 kpc.

The percentage of the Galaxy's mass in HI was a few percent - much less than the 25 percent we had observed in the LMC and SMC in 1953.

The multiple peaks in the profiles in some directions strongly suggested that we were seeing spiral arms. I am looking at a much-published map by Kerr and Westerhout from 1960 showing "Spiral Structure of the Galaxy".

The 21cm observations of Doppler shifts showed that the centre of the

Galaxy was near Sgr A. During the surveys we had used a system of galactic coordinates (latitude & longitude) that was clearly shown to be wrong. The International Astronomical Union then set up a sub-Commission to define the correct coordinate system for the Galaxy (which we use to this day).

Something that emerged more slowly was that the galactic rotation speed did not fall off in a Keplerian manner beyond R=10 kpc. The great mass of the stars is seen to be inside R = 10 kpc, so it was expected that the bulk of the MASS of the Galaxy would be inside R = 10 kpc. However the galactic rotation speed in the outer parts remained fairly constant, instead of falling off towards a (1/R squared) Keplerian curve. What was providing the mass outside R = 10 kpc? Certainly not stars. (In 2001 we still don't know for sure!)

3) In your opinion what were the most important skills, experiences, and knowledge gained at Potts Hill? Which of these was important when you went to Parkes?

** That's a multi-pronged question! My answers will probably only cover part of it.

Firstly, re hardware: We needed much better receiver sensitivity. We needed a multi-channel spectrometer. We needed a much easier way of recording the data for later processing in Sydney.

About receivers: Joe Pawsey organised with Jan Oort that I spend 1958 to 1961 in The Netherlands on a joint project involving CSIRO Radiophysics, Philips Research Laboratories, The Kamerlingh Onnes Physics Lab and the Netherlands Foundation for Radio Astronomy. In 1958-59 we worked on the development of MASERS for 1420 MHz. Gib Bogle and Frank Gardner did some parallel work in Sydney. In 1959 I then advised that masers would be unsuitable for use at Parkes, and started work in Holland on Parametric Amplifiers. The history of this is all in my review in Annual Review of Astrononmy & Astrophysics Vol. 2 (1964) pp. 401 - 432. At Potts Hill in 1953 we had a receiver noise temperature of 1800K. At Parkes in 1961 we had reduced that to 100K. That speeds up the observations by (18 squared) = 324 times. So what took 15 secs to measure at Potts Hill could be done at Parkes in 40 milliseconds!

Multi-channel spectrometer: This was proposed by Joe Pawsey in 1953. The 48-channel spectrometer was built by John Murray, and tried out at "Murraybank" by John Murray and Dick McGee. I am reading a report in 1960 which said: "In a recently completed survey with a 2 degree aerial beam, 74,000 profiles were recorded in 130 days: with currently used sweeping receivers the same survey would require more than twelve years of observation ..."

Automatic Data Processing: That same 1960 report went on to say: "However, the collection of so many profiles has required automation of data processing. This is now achieved with additional equipment which converts the observed information into digital form and records it on punched paper tape. In this form it is suitable for rapid analysis by one of the modern automatic computers." The "modern automatic computer" was, I think, the CDC 3200 at CSIRO Chippendale. It was operated by the CSIRO

Division of Computing Research.

4) Which discoveries in other areas of radio astrnomy have most influenced the direction of hydrogen line research? For example did the polarization work done at Parkes, and the mapping of magnetic fields for the Galaxy and beyond compliment hydrogen line studies?

** I don't think that the polarization work at Parkes had much impact on 21 cm line studies. Nor did the mapping of the magnetic field. Except perhaps that the magnetic field work didn't show magnetic fields along spiral arms! The observed magnetic field turned out to show sudden reversals of direction. So 21 cm observers were left with the question: "What produces the "arms", what produces spiral structure?"

5) We are always hearing about how radio astronomy compliments traditional optical astronomy. Did any of the hydrogen line radio astronomy you were involvled with influence or shape optical research? In your opinion are the barriers between these different techniques breaking down or does the level of specialization required today demand that each scientist focus on either radio or optical work?

** To answer the last bit first: TODAY if we want to understand an ASTROPHYSICAL problem we NEED to know about all wavelengths - radio, millimetre, infra-red, optical, ultraviolet, x-ray and gamma-ray. As an example, look at the recent work on gamma-ray bursters; we are just beginning to understand the bursters - which are over in seconds - because we've found radio and optical features that last a bit longer and can be pinpointed and mapped.

For the first part of your question: Back in the 1950s, the answer about barriers depended very much on WHERE you were. In Australia there was excellent cooperation between optical and radio astronomers - Joe Pawsey at Radiophysics, and Bart Bok at Mt Stromlo. (I could expand on that!) Similarly, in The Netherlands there was total cooperation between radio and optical. The same went for France. It was VERY different in the U.S. and Canada, and also in England (where I saw the conflict first hand in Cambridge).

Re "influence or shape optical research" -- because radio astronomers could see through the dust (see the subtitle of the HI 50 Conference in Canada starting 20 Oct 2001) the optical astronomers could not see what was showing up in radio observations. That pushed the traditional observatories to develop hardware to observe in the infrared and far-infrared. That eventually led to the great infrared surveys.

Another influence was that Radio Astronomy had revealed new sorts of astronomical objects, often not seen on optical photographs. So various groups were led to try observing at wavelengths blocked by the Earth's atmosphere. I have mentioned the infrared. But the race was on to observe in the UV, at x-rays and finally at gamma rays. Some observations were made from balloons, others from rockets, and finally from satellites.

Today the most important space observatories are the Hubble Space Telescope, the CHANDRA x-ray observatory and a number of gamma-ray satellites. Complemented by large radio arrays and by the new optical telescopes (e.g. Hawaii and Chile). The NEW ASTRONOMY.

6) Without the resolution of a steerable dish, how did H-line work proceed before Parkes? What were the frustrations and limitations of the work? Were H-line researchers optimistic that a large dish wo uld be built? If Parkes had not been the second large dish built (after Jodrell Bank's Mark I) how long before Australian researchers would start looking overseas.

** There are a number of things I could say about this:

The improvement from the 36 foot dish at Potts Hill to the 210 foot dish at Parkes was twofold: Firstly, the beamwidth went from one degree to 16 minutes of arc; that enabled us to see more detail in the structure of the HI gas clouds; but for the large scale structure of the galaxy it was not so good -- it meant that there we now 14 points to observe in each square degree, which didn't help much when if we were looking for the large scale structure. That work dragged on for years. Frank Kerr was appointed to a Chair at the University of Maryland, and he plus students would make regular trips down south.

This question of dish diameter was very much to the fore later on (in the 1980s) when I had to choose the optimum size for a telescope to look at the large-scale galactic structure in the spectral line of Carbon Monoxide at a wavelength of 2.6 mm; the 4 metre mm-wave telescope at Epping was my choice; but a smaller one might have been just as good! See later (Q.10)

The larger 210 foot dish was great for the work on detailed regions - such as the galactic centre. It also made it possible to make use of ABSORPTION at 21cm -- because the continuum temperature of small radio sources went up as the ratio of the telescope AREAS, a ratio of 34 times. ABSORPTION gave information that we couldn't get by measuring EMISSION profiles.

** Another important point is related to the end of your question about <<would Australian researchers would start looking overseas?>>. That was not really an important question at the time. Taffy Bowen was keen to build a dish to bring him to parity with Sir Bernard Lovell. I have sent you the quotation from Sir Edward Appleton's opening address to URSI in Sydney in August 1952:

\>

\> "It seems to me now the radio-astronomer's turn for substantial subventions

\> for building bigger and better radiotelescopes and for organising total

\> ecplise studies of coronal emissions in the radio spectrum . I am happy

\> to report, in this connection, that my old Department of Scientific and

\> Industrial Research has decided to join the Nuffield Foundation in sharing

\> the cost (336,000 Pounds) of the construction of a large steerable

\> radiotelescope for radio-astronomical studies in Manchester University

\> under the direction of Professor A.C.B. Lovell. Professor Lovell already

\> has a radiotelescope with a diameter of 220 feet but it is fixed. The

>new instrument will have a paraboloid aerial with a diameter of 250 feet and
> the diameter of the platform on which the telescope will rotate will be
310 feet.   Elevating racks from two British battleships, which are now being
> broken up,m will be incorporated in the new design .   ... I will only
add to these few remarks ... that those of us who follow this subject, either
> as workers or interested onlookers, would much like to see, in due course,
> a similar instrument at the disposal of your radio astronomers here in the
> Southern Hemisphere."
>

Because the engineer building the Jodrell Bank 250-foot dish decided to WELD the steel plates on the surface - which distorted it - the dish was never much good for work at 21cm wavelength. But Bernard Lovell was not pushing for 21cm work. Lovell's main interest was RADAR ASTRONOMY, and he wanted the dish to be good at 400 Mc/s!! Which it was.

After URSI 1952, Taffy Bowen wanted to build a large southern steerable dish, and Harry Minnett spent the 1950s years at Freeman Fox & Co in London designing what was to become the Parkes 210 foot dish. [Freeman had been the designer of the Sydney Harbour Bridge!]
Taffy always specified that The Dish should work to 10cm wavelength - that was to make sure that it would work very well at 21 cm wavelength.

Taffy also wanted John Bolton to run The Dish. That meant that Joe Pawsey was being pushed aside as Head of the Radio Astronomy Group. Many people were loyal to Joe Pawsey, and didn't want to see this happen.   Another factor was that there were interesting alternatives to going the route of building a large dish. Bernie Mills wanted to build a larger Mills Cross; Once The Dish was on track, Bernie decided to leave Radiophysics: he got funding from Sydney University to build the Molonglo Observatory Synthesis Telescope; Alec Little went with him as did Arthur Watkinson.   Chris Christiansen was very loyal to Joe Pawsey, and resigned from CSIRO to become Professor of Electrical Engineering at Sydney University; Chris also kept control of the Fleurs field station and the "Chris Cross". Ron Bracewell had left some years before for Stanford University (on the momentum of the book Pawsey and he had written about 1954).   The point here is that support for The Dish was not unaminous. A related controversy was that there was three-way competition for non-Parkes funds between Bernie Mills, Chris Christiansen and Paul Wild.   Paul Wild won the jackpot, and built the solar observatory at Culgoora.
** A related point here is that to look at the fine-scale structure of the HI it would have been better to build an interferometer with two smaller dishes - as John Bolton had been doing at Owens Valley. Another alternative would have been to build an HI synthesis telescope. The word "synthesis" made Taffy Bowen throw up.   So any planning for a synthesis telescope was kept on ice until well after Taffy Bowen retired -- it was not until 1982 that Bob Frater and I sold the idea of the ATNF to Malcolm Fraser as a Bicentennial Project. Fraser liked it, as did the Bicentennial Committee - ATNF would commemorate the great science done by the first generation of Australian radio astronomers AND also give the next generation a world-class instrument to continue that work.

My answers to Question (6) bring out that in the world of funding the scientific arguments can sometimes be pushed aside by personality questions or the alternative ambitions of key figures. Fortunately, in the difficult period 1958 to 1961 I was (a) Not a key figure and (b) I had my head down in The Netherlands developing low-noise receivers that would enable The Dish to make a big step forward -- in fact, many big steps forward = quasars, Hydroxyl lines, pulsars, the Apollo missions, the water line at 22 GHz, many organic molecules right across the spectrum, ...

7) How did computerization at Parkes affect the work? Was the PDP-11 used for H-line mapping or to assist with the research? How did more modern computers fit into the scheme? What software and hardware has been crucial to the development of the program?

** Hardware: It was a PDP-9. When we first purchased the PDP-9 in 1968, it had 8K of memory. In those days memory was very expensive! With just 8K (18-bit words), the PDP-9 did a few things: It drove the telescope; It made the Doppler corrections for Earth's rotation and orbital motions; It collected and stored the data on magnetic tape. There was absolutely no way that it could also process the data. After some time I managed, with difficulty, to scrape together enough funds to buy another 8K of memory! But data processing continued to be carried out in Sydney (on the CDC 3600 by then).
** Software: Initially we had an internal problem. One staff member (resident in Sydney) took total control of the software, and announced that no one could use the PDP 11 until he had completed writing his "Radio Astronomy Program" - a program that would do "everything"! Fortunately for The Dish, that plan for a "Radio Astronomy Program" bit the dust when pulsars were discovered - for a basic assumption of "the program" was that data would be sampled only every 2 seconds or so; it was quite unable to countenance sampling at millisecond intervals! A second fortunate event was that Dick Manchester joined us in 1968 from the University of Newcastle. We based him at Parkes, and he got stuck into the software. Dick would be able to tell you more, but we ended up with separate programs for different observations - e.g. a program for radio source scanning, another for spectral line work using the 48-channel spectrometer, another program for pulsars, ...
** Later came the digital correlator, which we decided should have 1024 channels. That was driven by the spectral line work - especially the OH-line observations which needed all four Stokes Parameters to define the polarization - giving 256 channels for each spectrum. (See below for more on molecular lines.)

8) How important was the Parkes interferometer in early work? I understand that there were problems with the system in terms of resolution. Was any attempt made to fix it? What were the key factors that went into the decision to discontinue its maintenance?

** The interferometer between the 210-foot dish and the 60 foot dish on its rail tracks was not designed for spectral line work. It was intended to provide a quick means of estimating the size of continuum radio sources. John Bolton had built a very good interferometer at Owens Valley. But the Parkes interferometer was just awful. One major problem was the coaxial cable connecting to the 60-foot dish - the cable was above ground and subject to large temperature variations in the western Sun; thus the system had very marginal phase stability, which meant that observing time had to be much less than the time in which the phase varied. Spectral line work requires narrow bandwidths, and that leads to long integration times. Some observations were made of OH lines. But I can't recall any H-line observations - though it would have been possible to observe 21-cm absorption spectra.

9) As the instruments have become more complex, the role of the operator and astronomer has diverged. In what ways do you think this deskilling of the astronomer has affected the work itself? In contrast, in what ways has transfering the burden of operations helped?

** One possible danger I see is that astronomers will be looking for things that we already know about, or in directions where objects are known, or at wavelengths where the observatory has its operating receivers. The early pattern of observer/telescope-builder/receiver-builder combined in the one person or in a small team certainly left the way open to try something new or different or mad!

When I directed the research of the Parkes radio astronomers (1963 to 1982) and also controlled funding for the receiver construction group, I tried in the later years to encourage the old Radiophysics Laboratory "suck-it-and-see" attitude. When time on The Dish was allocated each three months, I reserved a small fraction of the time for "wildcat experiments" - but I was disappointed by the feeble response.

10) To what extent did the discovery of the lines of other molecules shift emphasis away from hydrogen line work? Did this take significant man power away from the hydrogen work or did it serve to compliment the hydrogen surveys?

** The answer to that depends on the person. Frank Kerr kept straight down the H-line track - the new molecular lines did not distract him. I had been doing H-line work on spiral galaxies - observing NGC 55, 300, 1313, 3019, 5236, 6744, 6822 and 7793 plus IC 1613. There was a limit to what could be done at 21 cm with the Parkes beam - and synthesis was the next obvious step. But the discovery of the 18 cm OH lines in 1963 sent me off in a new direction with the Parkes dish. Another H-line observer was Dick McGee; he joined me in the OH work -- see Annual Review of Astronomy & Astrophysics Vol. 5 (1967) pp 183-212. Dick also made a lot of observations of hydrogen recombination lines.

The discoveries I was making using OH (e.g. regions of star formation) lead on to observations of the 22 GHz water vapour line. These lines often showed maser emission - which linked back to my work on maser amplifiers in The Netherlands in 1958! Some of the maser emission pinpointed regions of star formation, while others were linked to late stages of stellar evolution. Later we observed a wide range of organic molecules. Methyl alcohol also showed maser emission. By the end of the 1970s radio astronomers had discovered 71 new molecules, and for many there were several lines observed. We also had a list of over 150 "unidentified lines". Some of the molecules we indentified are not found on Earth - they are too unstable to survive at atmospheric densities.

That was so very exciting for me. When I started in radio astronomy in 1952-53, ONE spectral line had just been discovered - we called it "The Line". No one in 1952 would have imagined that we would later have hundreds of lines! And that most of them would be produced by organic molecules - like methyl formate or methyl cyanoacetylene or ethyl alcohol or ...

One final point. By the 1980s, the old 21 cm surveys of the Galaxy were complemented by surveys in the Carbon Dioxide line at a frequency of 115 GHz - a wavelength of 2.6 mm. The CO was found in even denser, even dustier regions. So I funded the construction of the 4 metre diameter dish at Epping. Because there was no radiocommunication interference at 115 GHz, we did not have to go outside the city. Building the 115ghz receiver was tough, but Bob Batchelor and Malcolm Sinclair did it. For the CO spectrometer we used something quite new - a laser beam diffracted by a wave propagating through a crystal; the beam was then focussed on an array of photodiodes by a long-focus lens (which now sits on the bookshelf behind me. It was a far easier and cheaper way of making a really wide-band spectrometer (to cope with the large Doppler shifts at that high frequency) and easily providing 1024 channels.