**Wendt, Harry (2008)** ***The contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to international radio astronomy.*** **PhD thesis, James Cook University.**

# 11. RADIO ASTRONOMY AT MURRAYBANK

The researchers at Murraybank field station had a close relationship with those from Potts Hill, being the only other Australian site involved in investigating the Hydrogen-Line emission from the Galaxy and the Magellanic Clouds in the late 1950s and early 1960s. This section examines the Murraybank field station, its researchers and the scientific contribution which they made.

Murraybank operated from 1956 to 1961 (Orchiston and Slee, 2005a). The field station was established to test the operation of a new 48-channel H-line receiver in preparation for its potential installation in the 64-m Parkes radio telescope when it became operational in late 1961. This receiver (also known as the Murraybank Mk1 multi-channel line receiver) became one of the first operational observing systems to be installed on the Parkes telescope (Brooks and Sinclair, 1994).

## 11.1. Murraybank Researchers

In examining the development of the Murraybank field station and its scientific contribution, there are two additional members of the Radiophysics team who need to be considered and who did not work at Potts Hill; John Murray and Dick McGee.

### 11.1.1. J.D. Murray

John D. Murray joined Radiophysics in December 1947 after moving from Hobart, Tasmania. He was involved in both the 1948 and 1949 solar eclipse expeditions and was part of the Tasmanian observation team in both cases (see Orchiston et al., 2006; Wendt et al., 2008).

Initially he worked on the development of the Radiospectrograph that was installed at the Dapto field station. This was a major undertaking and the instrument was some two years in development. In 1953 he was asked by Pawsey to work on the development of a new multi-channel H-line receiver which eventually led to the establishment of the Murraybank field station. Together with McGee, Murray undertook a complete southern-sky survey at 21-cm using the newly developed receiver.

In October 1961 he moved to the Netherlands where he worked on the development of the Benelux Cross, and thus ended his involvement with Murraybank. Murray returned to Radiophysics in June 1964 and was a member of the team that discovered the Magellanic Stream (Mathewson et al., 1974) and went on to have a distinguished career with Radiophysics.

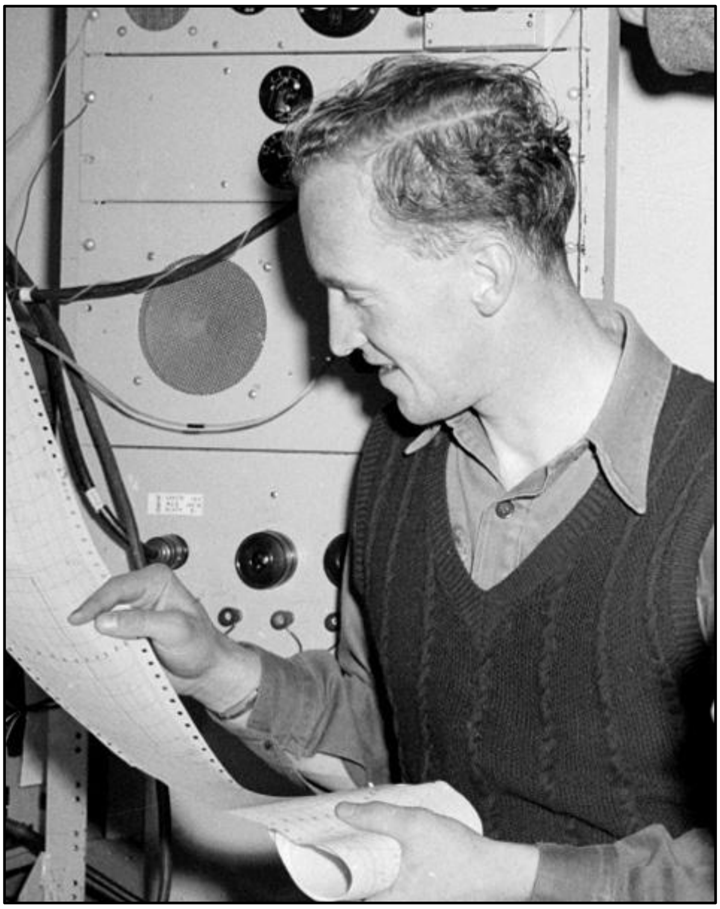

Figure 206: John Murray in 1949 (Adapted from the Mercury Newspaper, Tasmania)

### 11.1.2. R.X. McGee

Richard (Dick) X. McGee (Figure 207) joined Radiophysics in December 1950. He initially worked at the Dover Heights field station, and carried out much of the observing and data reduction for the 400 MHz transit survey using the 80-ft hole-in-the-ground telescope (McGee et al., 1955). An important finding from this survey was published in a joint paper by McGee and Bolton (1954) that appeared in *Nature*. It is this paper that is often incorrectly cited, crediting the authors with the discovery of the discrete source, Sagittarius-A, at the Galactic Centre (see Orchiston and Slee, 2002), although the paper certainly brought the source and its position to the attention of the wider scientific community.

From Dover Heights, McGee joined Murray to work on the development of the multi-channel H-line receiver and the 21-ft parabolic antenna that was installed at Murraybank. McGee was the lead author on all three papers in the series on the southern-sky H-line survey. He was also involved in the development of the digital recording and computer reduction system that was trialled at Murraybank prior to its installation at Parkes. The Murraybank survey of the Magellanic Clouds was the beginning of a long association with studies of these galaxies for McGee. He was also involved in some of the earliest measurement of molecules in our Galaxy using the Parkes 64-m telescope.

McGee had a 32 year career as a Radio Astronomer, retiring from Radiophysics in 1986.

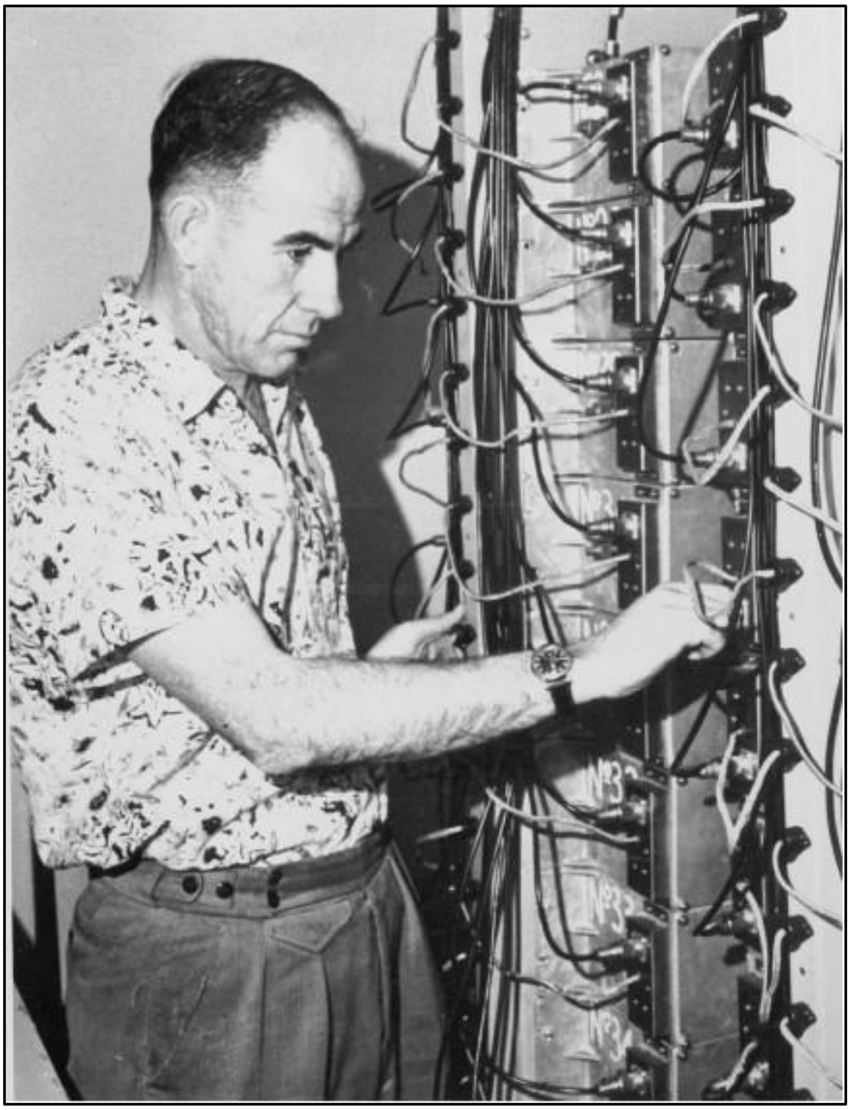

Figure 207: Dick McGee working on the 48-channel receiver at Murraybank (courtesy of Miller Goss).

### 11.2. The Establishment of Murraybank

In June 1953, Murray was summoned to the Radiophysics headquarters in the grounds of Sydney University to meet with Pawsey (Murray, 2007). Pawsey was unhappy with the progress being made on the development of the 4-channel H-line receiver at Potts Hill and asked if Murray would assist. Murray (2007) also recalled that while he was waiting to meet with Pawsey, John Bolton came storming out of Pawsey's office. This was the point where Bolton's proposal to construct a large interferometer had been rejected in favour of construction of the Mills Cross. Bolton therefore decided to leave the Radio

Astronomy Group and to work in Cloud Physics until January 1955 when he accepted the position as Professor of Physics and Astronomy at the California Institute of Technology.

Murray worked with Kerr, Hindman and Robinson at Potts Hill and after some time he concluded that it was very unlikely that the original receiver design could be improved and that it would be necessary to change to a switched system to overcome the issues with receiver drift that plagued the original design. Murray felt that it would be near impossible to get a stable bandwidth from vacuum tubes using the original design. While the filters were all on the same frequency the design worked well, but the further they were shifted apart in frequency, the more they drifted apart (Murray, 2008). After Murray reported back, Pawsey decided that it would be prudent to launch a new project. The aim of this project was to design a new type of multi-channel receiver that addressed the limitations of the original 4-channel design. This decision would ultimately lead to the establishment of a new field station called Murraybank, which was located at West Pennant Hills in the north-western suburbs of Sydney. To their credit, Kerr's team persisted and after many modifications to their receiver, managed to get it to a point where reliable observations were possible, first with a single channel, and later with all four channels.

By November 1953 three main streams of work were being undertaken within Radiophysics on radio frequency spectral-lines (Kerr, 1953a):

1. Work led by Kerr at Potts Hill on the 4-channel H-line receiver and the subsequent survey of the Magellanic Clouds and the Galaxy.

2. Work at Dover Heights to attempt to detect the red-shift in external galaxies and a search for the 327 MHz deuterium-line by Stanley and McGee (later joined by Price).

3. Work on development of a new type of multi-channel H-line receiver in the laboratory initially led by Murray.

The subsequent success of the Potts Hill H-line survey has already been discussed in Section 10.5.2.2.

The search for the deuterium-line at Dover Heights ultimately proved unsuccessful and no evidence of adsorption or emission from the Galactic Centre was found. Although the detection of high red-shifted HI in external galaxies had been proposed as an objective, no detection attempt was made after the negative deuterium-line result. The negative result was reported (Stanley and Price, 1956) only after other negative search attempts began to appear in the literature. At the I.A.U. Symposium No.4 on Radio Astronomy held at Jodrell Bank from 25-27 August 1955, G.G. Getmanzev and K.S. Stankevitch from Gorky State University, U.S.S.R, reported that they had detected a absorption line from deuterium at 327.4 MHz using a

4-metre paraboloid. The detection claim was met with some scepticism. In the discussion following the presentation Pawsey noted that Stanley and Price had been unsuccessful in 1954 using the 80-ft Dover Heights hole-in-the-ground aerial and Hey also noted they had made an unsuccessful attempt at Malvern in the U.K. (Getmanzev et al., 1957: see discussion notes). The interest in pursuing the detection of deuterium was, and still is, that deuterium was believed to have been formed soon after the Big Bang and hence its abundance provides important information on the formation of the early universe. Although the deuterium line at 327 MHz is well separated from other radio-frequency spectral lines, it is extremely weak. Most observers, like the Dover Heights team, were only able to establish an upper limit for detection. Although there have been many claims of a marginal detection, it has only been quite recently that a detection seems likely (Rodgers et al., 2005). The unsuccessful search for the deuterium-line also signalled the death knell for further research at Dover Heights, with the field station being decommissioned in 1954 (Orchiston and Slee, 2002).

As an interesting aside, in an outline of the potential for spectral-line investigations, Kerr raised the possibility of not only searching for the deuterium line at 327 MHz, but also the 3He line near 9,000 MHz (Christiansen, 1952). Goss (2008) has noted that this appears to be one of the earliest references to the potential for the 3He line being considered (e.g. compared to Goldwire and Goss, 1967; Townes, 1957).

The development of a new multi-channel H-line receiver was a major undertaking and, after some initial experimentation, a broad plan was drawn up by Murray in early 1954 outlining the steps necessary to complete the receiver design. In May 1954 in a letter to Oort, Pawsey noted:

> "We are working on the development of a multi-channel receiver (e.g. 30-channel) but, although I am happy about the objective, our equipment is not yet satisfactory." (Pawsey, 1954a).

By June 1954 more progress had been made on the power supplies and the first stage local oscillator, but many components including the channel filters remained on the drawing board and the question still remained as to when an operational receiver could be produced. The work on the receiver was being conducted in the Radiophysics laboratory workshops. Murray had to compete for resources with many other projects and with the other Radiophysics groups such as Air Navigation and Cloud Physics. While attempts were made to explore the possibility of outside groups such as A.W.A. constructing some of the components, no outside interest could be generated (Murray, 2008).

At the June meeting of the Hydrogen-Line Planning Committee the need for a "...Following Aerial..." for future H-line work was discussed. The Potts Hill 36-ft aerial (being a transit instrument) imposed limitations on examining fine structure and access to some parts of the southern sky. The idea of constructing a new paraboloid of approximately 25-ft diameter and re-using a mount from Dover Heights was suggested and Hindman was tasked with looking at the feasibility of upgrading of the Dover Heights mount. It was at this stage that the question of a new site for H-line work was first raised:

> "The question of a new site more free from interference than the present Potts Hill position was deferred until more evidence on the sources of interference and the future expansion of the same become available in this regard. It was noted that the Water Board is intending building a welding shop on the old Balt camp site at Potts Hill. (Note: This has since been confirmed with the engineer on the site and steel for the construction of buildings has commenced to arrive)." (Kerr, 1954c).

With the likelihood of increased levels of electrical interference at Potts Hill, it was subsequently agreed that a new site would be necessary. The selection of the site was somewhat simplified when John Murray's father, who had an orchard called Rosebank at West Pennant Hills, offered to allow Radiophysics to setup a new field station on his property. This field station would become known as Murraybank i.e. the concatenation and abbreviation of Murray's orchard and Rosebank. Murray (2008) has also noted that there were a lot of other "bank" stations around at this time e.g. Jodrell Bank and Green Bank, so the name was entirely appropriate.

The Murraybank field station was in the corner of an approximately 2.5 hectare block of land that also contained the orchard, the Murray's home on the top of the hill and an old weatherboard cottage in which John Murray lived for some time.

Meanwhile, the design of the multi-channel receiver continued to be a very complex undertaking. In a letter to Pawsey in August 1954, McCready noted:

> "I had to give John Murray extra T.O. [Technical Officer] assistance in the 1420 Mc/s Multi-channel Receiver. This was due entirely to the large amount of detail in it. It was a bit of a struggle to get him the right type of assistance but eventually got him a Diplomat-elect from the Rain Physics Group (Keith Weir)." (McCready, 1954).

Later, McGee joined Murray on the project following the unsuccessful search for the deuterium-line at Dover Heights. In a letter to Pawsey in September 1955 McGee noted:

> "We hope to be moving into Murraybank at the beginning of next week and initial tests will be under way about the time of your return." (McGee, 1955).

Although McGee's letter indicated that tests of the equipment at Murraybank would be commencing soon, this proved extremely optimistic. On Pawsey's return from the U.K. he undertook a review of progress. The review identified nine major tasks that remained to be completed on the receiver. Pawsey assigned these tasks between Murray, McGee and also Warburton who had now been appointed to assist. McGee had earlier taken the opportunity to lobby Bowen for assignment to Murraybank of the 60-ft Kennedy Dish that was being considered for purchase and was ultimately installed at the Fleurs field station in 1959 (Orchiston, 2004c). Pawsey discounted this idea and a specification was drawn up for a new aerial. It was agreed that this would be a modified design of a Chris Cross aerial (Figure 208) with its diameter increased to 21-ft and with additional strengthening and greater depth. The design was assigned to K. McAlister and a target date for production of February 1956 was agreed.

Figure 208: The Chris Cross at Fleurs Field station. The Murraybank aerial was based on this aerial design with an increased diameter and strengthened structure (Courtesy of the ATNF Historical Photographic Archive).

Progress with the multi-channel receiver continued to be problematic. On 3 July 1957 Pawsey held another review meeting. After considering the progress that was being made, Pawsey decided to suspend any further work at Murraybank for a period of five months so that the team could properly replan their approach under the supervision of McCready. McGee prepared an internal review paper of their progress implying that they would have been better off concentrating on improving the local oscillators and finishing off individual channels before attempting to take actual line profiles at Murraybank (McCready, 1957). The first twenty filters of the Murraybank receiver had been constructed in the laboratory using high-quality three inch diameter ceramic coil formers that had been found in the Radiophysics store. The remaining filters were constructed by cannibalising surplus aerial tuning units intended for commercial aircraft radio units. These were not as good a quality as the original filters. The original twenty filters were configured around the central H-line frequency with the new filters making up the outer channels (Murray, 2008). Much of the wiring and fitting for the receiver was performed by C.J. Ohlston and M.W. Sinclair (Murray and McGee, 1963).

Another source of delays was that the Chris Cross was under construction at Fleurs and operated at the same frequency. This meant that team had to compete for access to test equipment. For some time they operated with a 'wet-finger' approach without access to a wavemeter to measure the local oscillator frequency. When they finally managed to get access to a wave-meter for a whole day, they found that they had been operating on the wrong harmonic and so had been trying to observe at 1,200 MHz instead of 1,400 MHz (Murray, 2008).

The refocus of activity on the multi-channel receiver development and access to test equipment finally proved successful and the system became operational in mid- 1958.

### 11.3. Murraybank Equipment

As discussed in the earlier section, the Murraybank aerial was based on a modified Chris Cross design that had been increased in diameter to 21-ft and with increased structural rigidity. The ribs of the aerial were constructed of steel and the rings were made of aluminium (Murray, 2008). The design was performed by K. McAlister and construction was carried out in the Radiophysics workshops. The aerial was mounted on a simple alt-azimuth mount and installed at Murraybank in 1956 next to a comparatively large equipment hut. The mounting was built on an ex-British Army 200 MHz gun-laying radar trailer. This was the same trailer (Figure 209) that Bolton and Stanley had taken to New Zealand and which had been used in other Radiophysics projects (Murray, 2008).

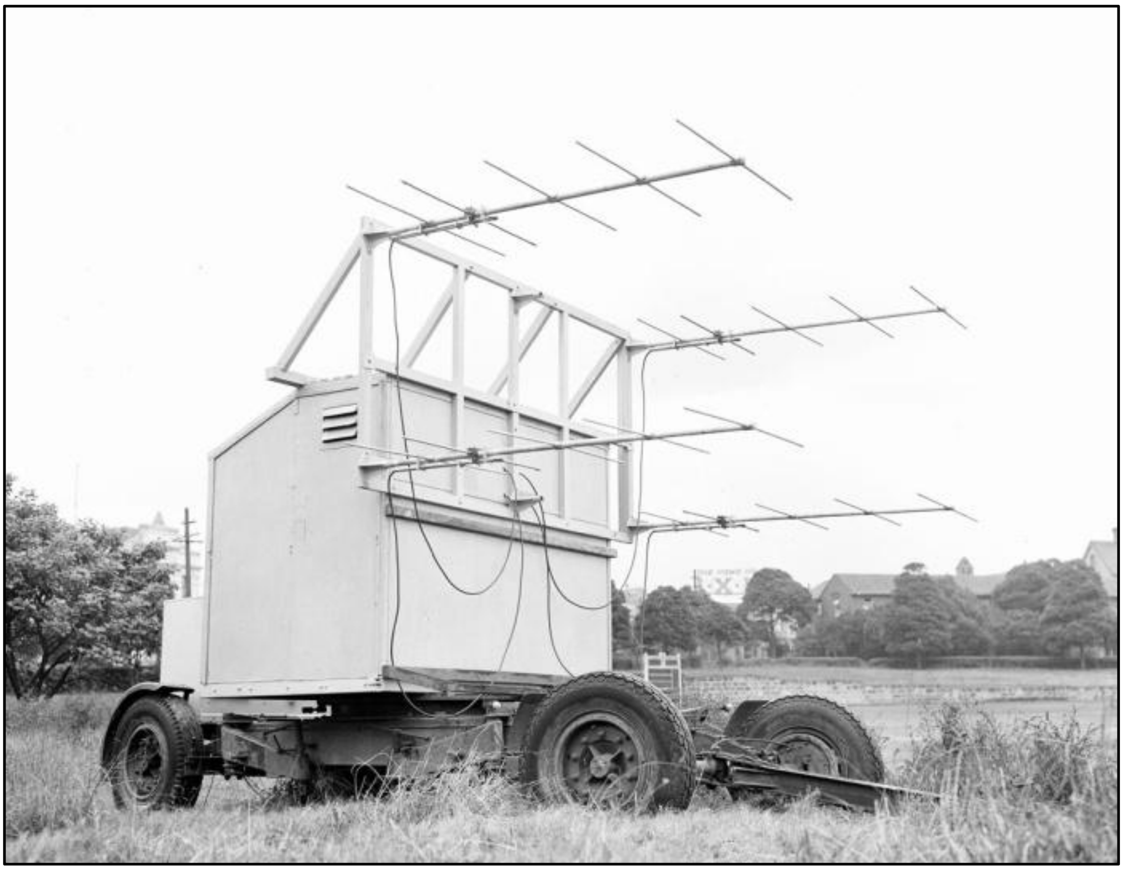

Figure 209: The ex-British Gun-laying trailer with the Yagi Array used by Bolton and Stanley (Courtesy of the ATNF Historical Photographic Archive: B1351 Image Date: 3 May 1948).

In its original configuration the trailer weighed some 6-7 tons and hence had a very solid framework including a set of elephant's feet for stability. Figure 210 shows a close-up of the trailer.

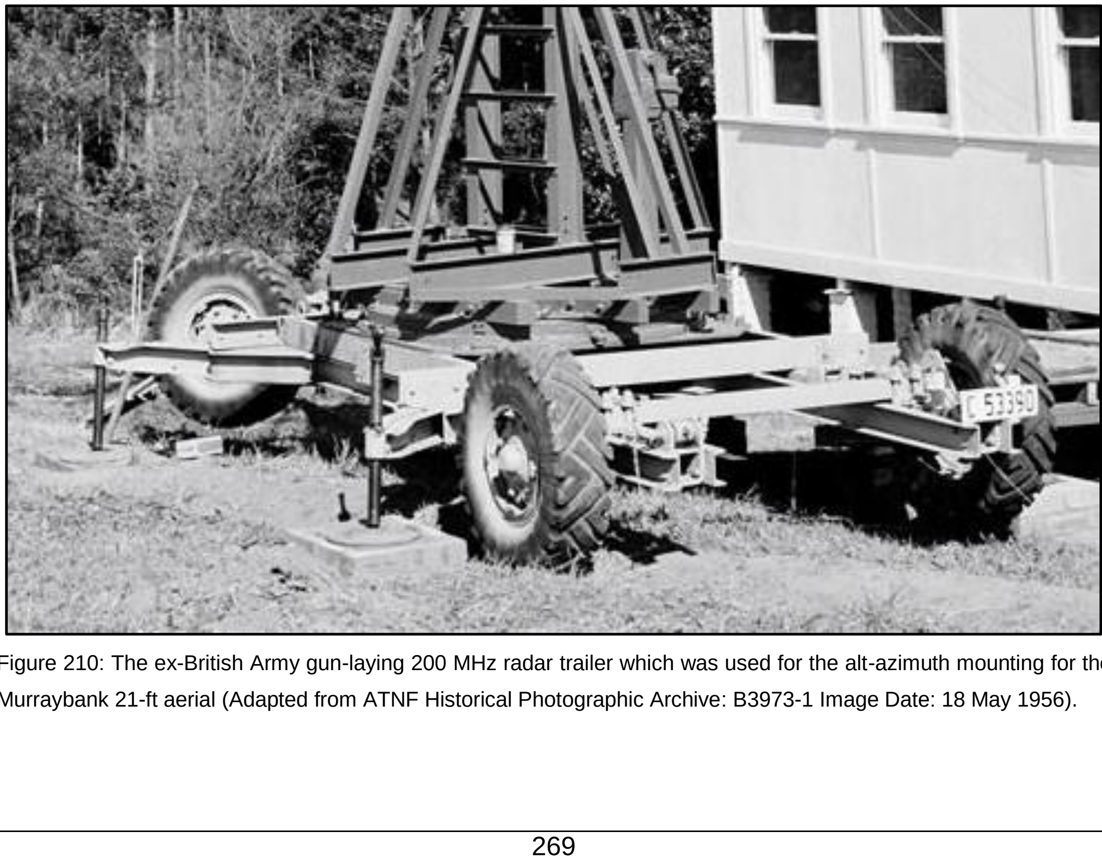

Figure 210: The ex-British Army gun-laying 200 MHz radar trailer which was used for the alt-azimuth mounting for the Murraybank 21-ft aerial (Adapted from ATNF Historical Photographic Archive: B3973-1 Image Date: 18 May 1956).

An aircraft propeller feather motor was cannibalised from an ex-WWII Liberator Bomber that was located at Tocumwal airfield. This motor was used for the elevation drive on the aerial mount (Murray, 2008), and although originally designed as a DC motor, it operated perfectly well on an AC supply. The azimuth control was provided by turning a hand crank which was part of the original gun-laying radar configuration and is visible just to the right of centre in the upper part of Figure 210.

Figure 211 shows the 21-ft aerial being lowered on to the mounting at Murraybank.

Figure 211: The 21-ft aerial being installed at Murraybank in 1956. The equipment hut is in the immediate background (Courtesy of the ATNF Historical Photographic Archive: B3973-4 Image Date: 18 May 1956).

In the original installation the primary feed was simply a long copper tube with a spilt bell and reflector, but this was soon abandoned and a new bipod feed mount was constructed which was supported by nylon guide ropes. The new feed front-end box contained the mixer, the final stage of the local oscillator and a pre-amplifier (Murray, 2008). Figure 212 shows the aerial after installation at Murraybank and with the new feed mount. The aerial was tilted toward the equipment hut and a platform ladder was placed on a small wooden ramp so that the primary feed could be accessed. Also visible in the background is the small reference aerial. This aerial had been transferred from Potts Hill with Joe Warburton when the solar program had been wound down. At one stage consideration had been given to using this aerial to provide a reference signal, but this configuration was not pursued (Murray, 2008). Warburton only stayed with the program for a short period before moving to Brisbane.

Figure 212: The 21-ft aerial at Murraybank with its new feed system. The smaller reference aerial is also visible in the background (Courtesy of the ATNF Historical Photographic Archive).

The Murraybank aerial in its initial configuration had a beamwidth of 2.8° at the half-power points. However, later changes to the primary feed of the aerial improved the beamwidth to 2.2°. Figure 213 shows McGee working on the primary feed of the aerial.

Figure 213: Dick McGee working on the primary feed of the 21-ft Murraybank aerial (Courtesy the ATNF Historical Photographic Archive: R5695-8).

Before discussing the multi-channel receiver in detail it is worth reflecting on the state of radio-frequency spectral-line receiver development when this project was first commenced. By early 1954, there were eight groups (excluding the Soviet Union) where spectral-line receivers were in development or use. Two of these were in Radiophysics, being Kerr's team at Potts Hill with the 4-channel H-line receiver project and the Dover Heights team attempting to detect the deuterium-line. Three groups were working in the U.S. at Harvard, NRL and the Carnegie Institute. In the U.K work was underway at Jodrell Bank and at Malvern. In the Netherlands a major effort was underway at the Kootwijk station. Up until this time, none of the overseas groups had initiated projects to construct large multi-channel receivers. While the Potts Hill group had considered having up to 20 channels, ultimately their design could not support more than four concurrent channels, and even this resulted in many practical difficulties in observations. Appendix C shows a summary of spectral-line receivers operating through-out the world as at February 1954 when the initial design of the Murraybank multi-channel receiver was being considered. This position would change fairly quickly. Department of Terrestrial Magnetism (D.T.M.) of the Carnegie Institute in Washington developed a 54-channel H-line receiver which they had operational before Radiophysics and were making observations by early 1957 using this receiver on an 8-m Würzburg antenna (Burke et al., 1959).

The first operating version of the Murraybank multi-channel receiver used as its first stage a crystal diode mounted in a tuned cavity. This signal was then passed to a double-conversion superheterodyne using intermediate frequencies of 31.8 and 6.74 MHz. The receiver output was switched at a rate of 385 Hz between the signal frequency of 1420 MHz and a reference frequency of 1424 MHz (Murray and McGee, 1959: 127). The reference frequency was selected as being outside of the largest Doppler shift expected in the Galaxy for the H-line. The output from the second intermediate frequency amplifier was passed into 48 double-tuned filters that were spaced at intervals of 32 KHz. The individual band pass filters had an approximately Gaussian response with a half-power bandwidth of 40 KHz which equates to a H-line radial velocity coverage of 8.4 kms$^{-1}$. A second detector was attached to each individual filter. The detected outputs, including contributions from the two switched frequencies, were then passed through audio amplifiers and synchronous detectors to produce the hydrogen-line signal. Signal fluctuations were smoothed by the using a two minute time constant. A telephone-type uni-selector switch allowed sampling of each of the synchronous detector outputs once every two minutes. The noise temperature of the receiver was ~800 °K. The output was recorded on a Speedomax chart-recorder as a 48-point profile with frequency on the x-axis and aerial temperature on the y-axis.

Figure 214 shows a view inside the receiver hut at Murraybank. On the left is the bank of 400 MHz amplifiers for the 48-channels. In the next rack to the right, starting from the top is an oscilloscope and receiver used to check the frequency against the WWV signal. Below this are the main local oscillator multiplier chain, the local oscillators and the local oscillator switch. The chart-recorder is in the back right of the hut.

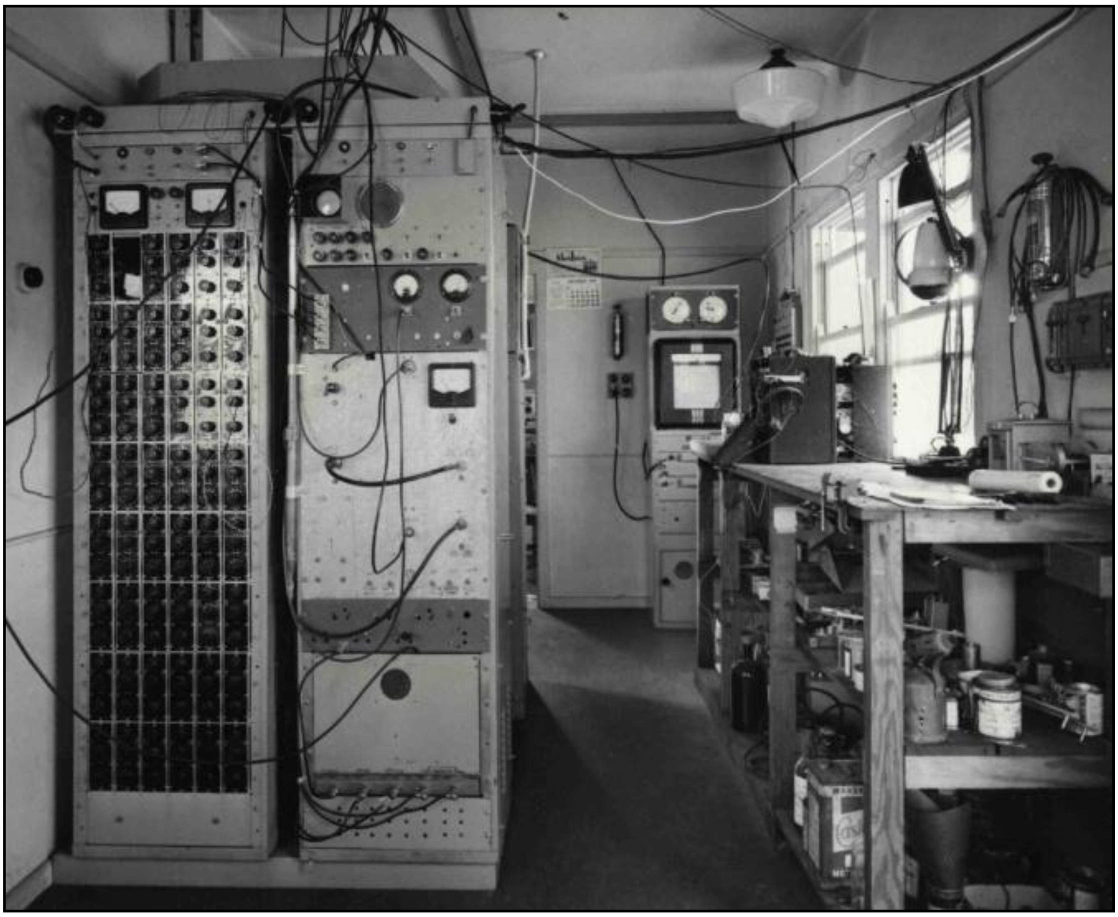

Figure 214: A view of the multi-channel receiver equipment inside the receiver hut at Murraybank (Courtesy of ATNF Historical Photographic Archive: R5695-18).

The workbench visible in the right of Figure 214 was later moved and the chart-recorder was relocated next to the other rack equipment as shown in Figure 215.

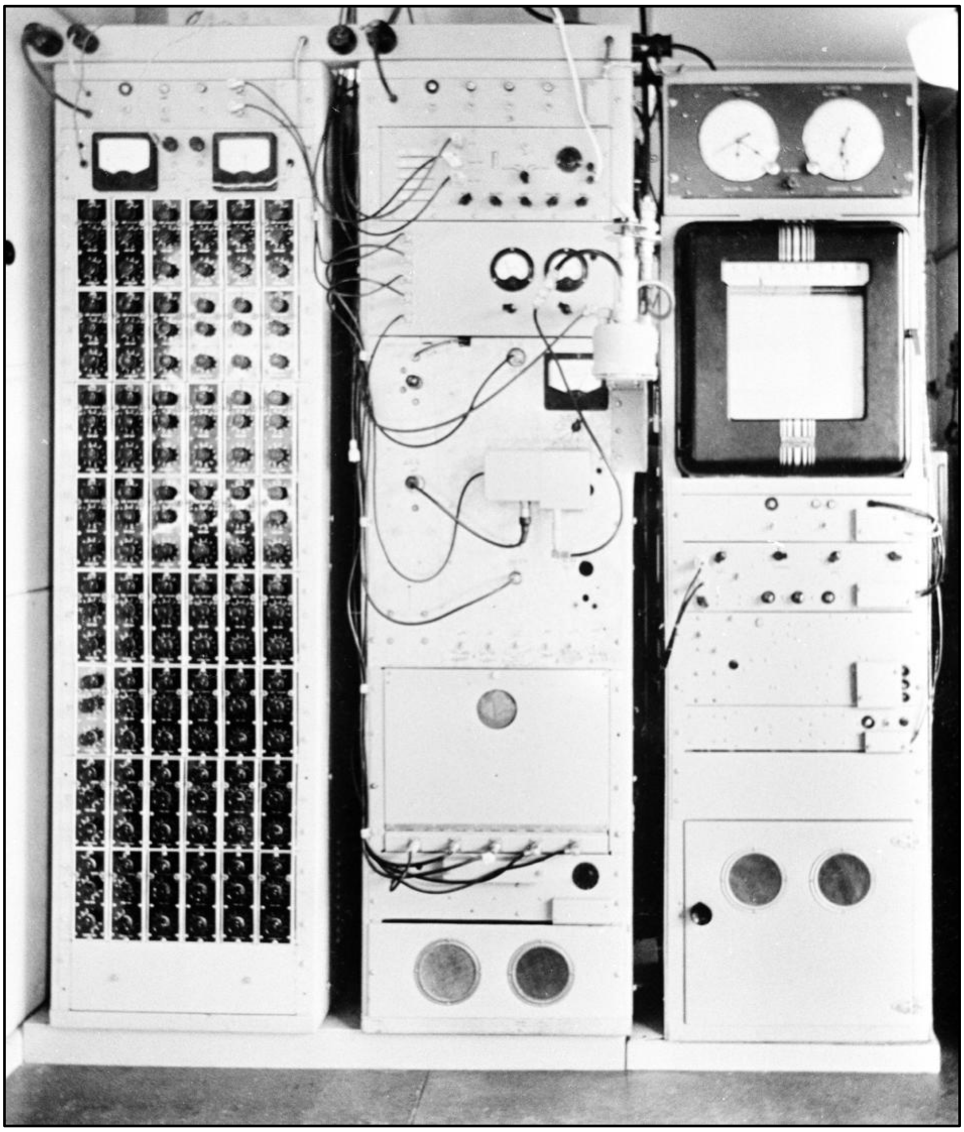

Figure 215: A later view of the receiver and recording equipment following the relocation of the recorder (Courtesy of ATNF Historical Photographic Archive: B6222-1 Image Date: 28 September 1960).

Given Murray's experiences with the problem of temperature control at Potts Hill, careful attention was paid to construction of the equipment hut. The hut was heavily insulated using 3-inch slag sheets on the walls, floor and ceiling. The roof had open eaves to allow airflow, but was shielded with netting to keep animals and birds out. The filters themselves were located inside another insulated structure inside the hut. This was accessed through a butcher's cold-room store door. Figure 216 shows a view of the filter bank.

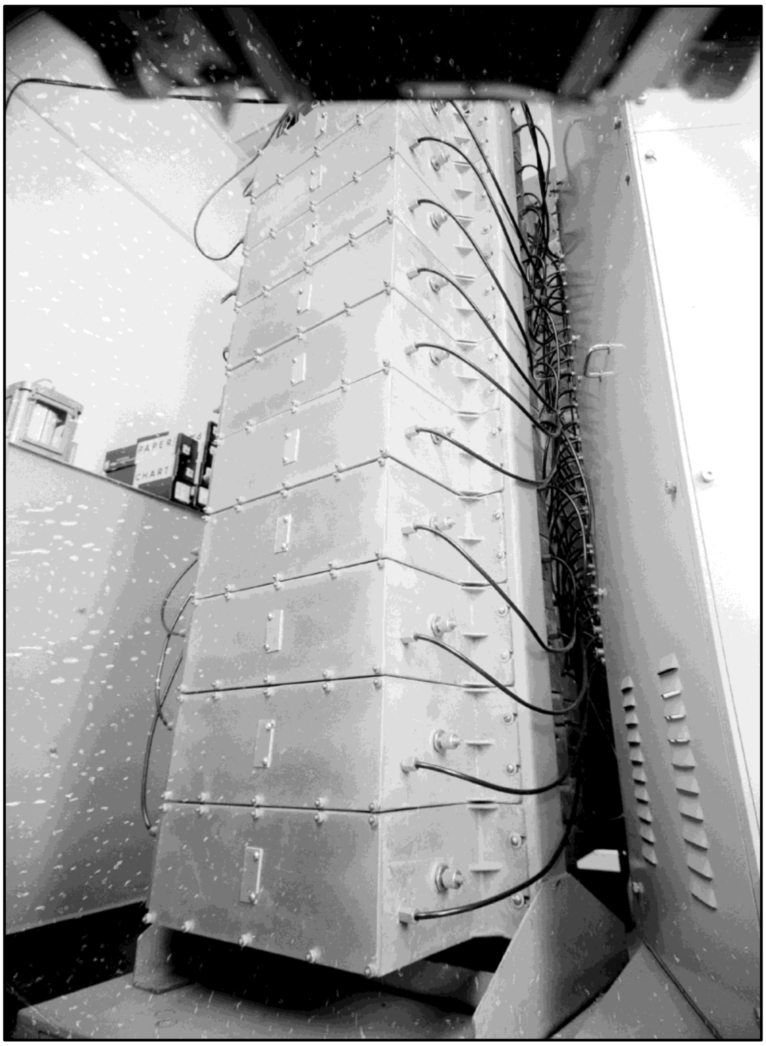

Figure 216: The filters used in the Murraybank receiver (Courtesy of ATNF Historical Photographic Archive: B5985-1 Image Date: 17 December 1959).

The filters were housed in heavy aluminium casings. To the left in Figure 216, a large water tank can been seen. This was used as a heat-sink. On top of this a recording thermometer can also be seen. With this set-up it was found that the temperature varied less than half a degree even on a hot days (Murray, 2008).

Figure 217 shows John Murray standing at the chart-recorder inside the receiver hut at Murraybank. The clocks visible above the recorder show solar and sidereal time. All of this equipment including the mounting racks and sheet metal work was constructed in the Radiophysics workshop (Murray, 2008).

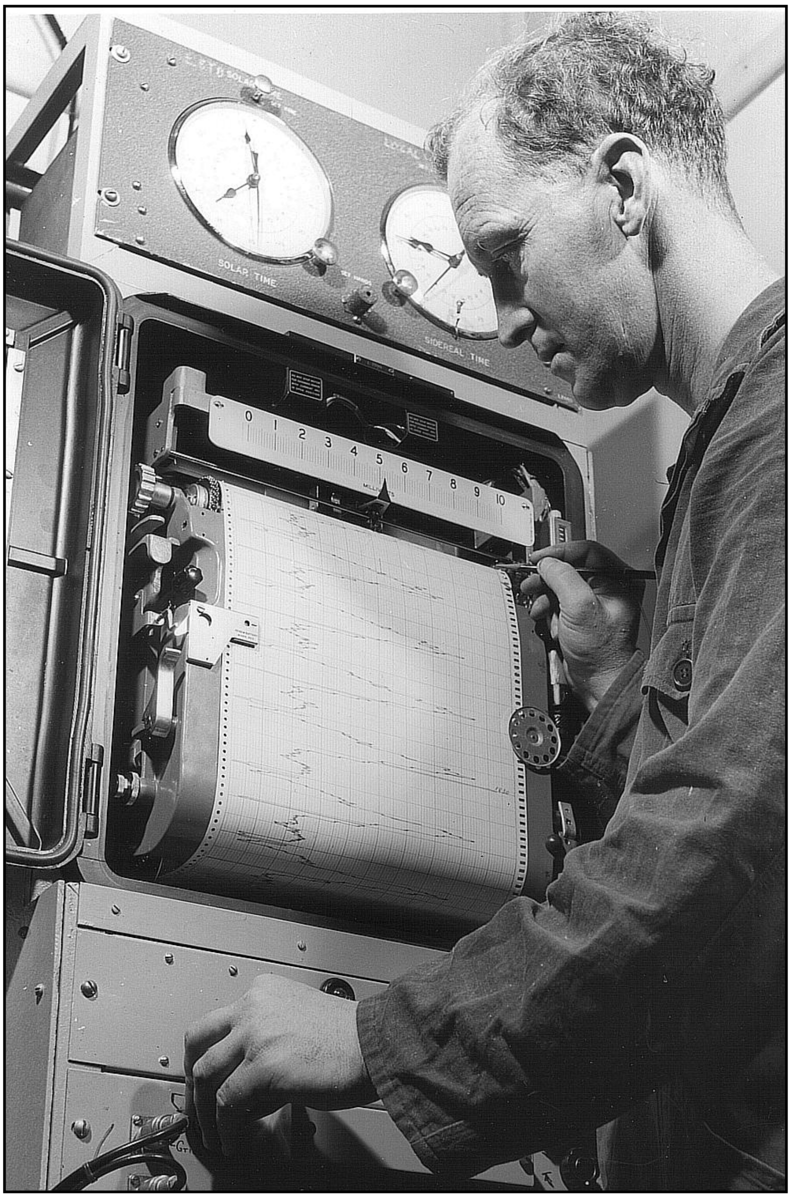

Figure 217: John Murray at the Speedomax recorder in the receiver hut at Murraybank (Courtesy of ATNF Historical Photographic Archive: R5695-9).

Figure 218 shows an example of the raw output of seven successive two-minute profiles on the Speedomax recorder.

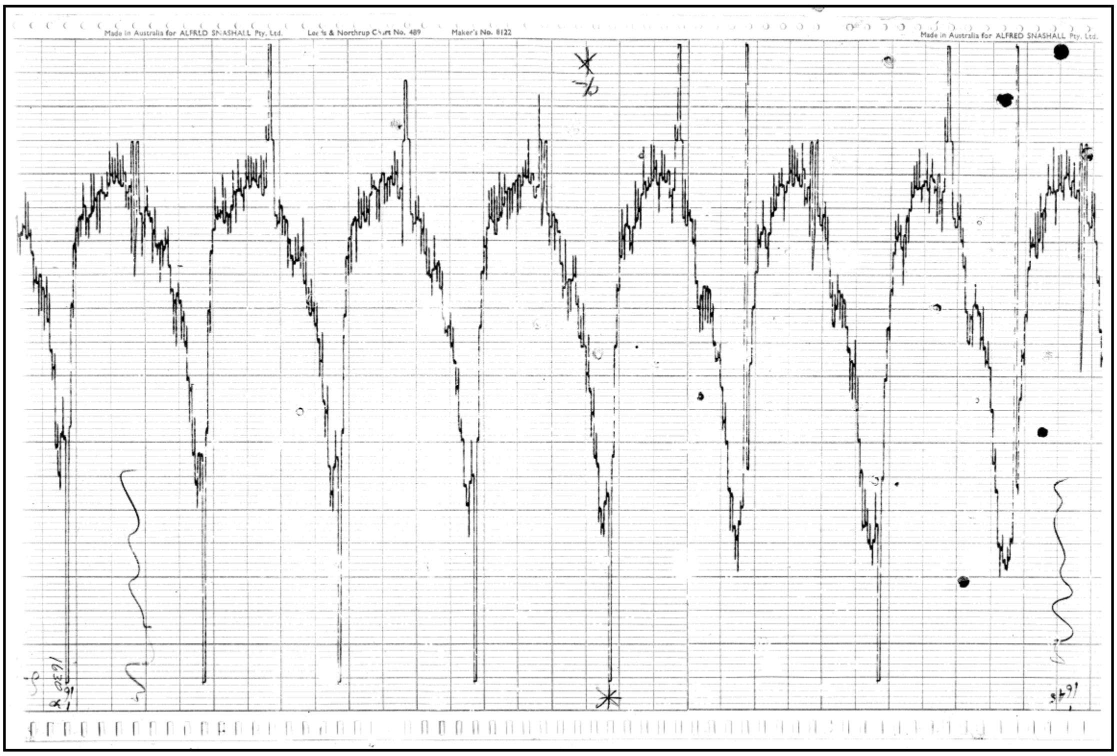

Figure 218: An example of the two minute H-line profiles produced as an output on the Speedomax chart-recorder (Courtesy of the ATNF Historical Photographic Archive: B5849-1 Image Date: 22 June 1959).

Figure 219 shows an example of a composite profile obtained from six successive two minute scans while the aerial was held in a meridian transit position set at a declination of +14° and the profiles recorded from $03^h\ 44^m$ to $03^h\ 54^m$ as the Earth rotated.

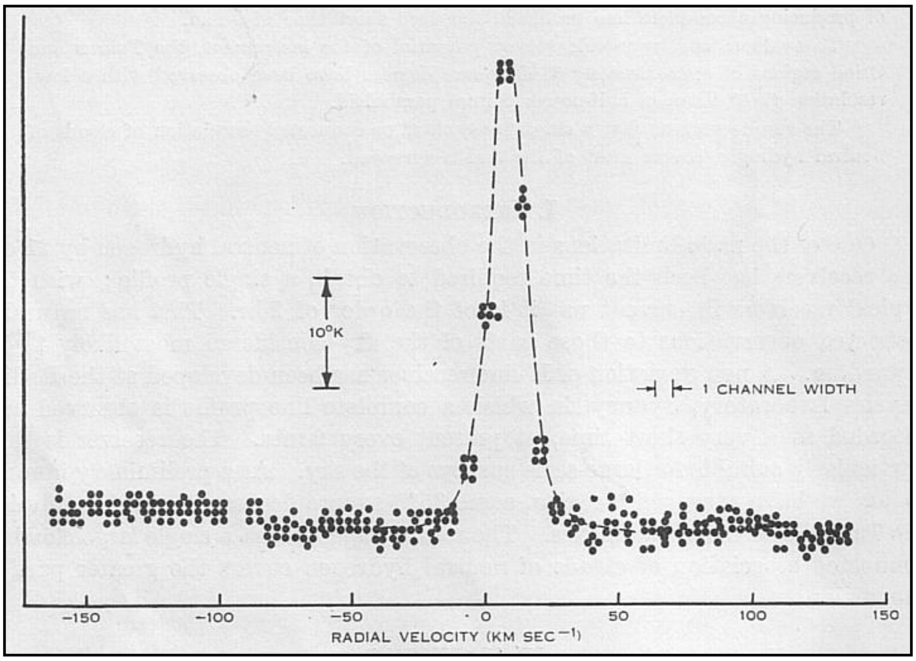


Figure 219: An example of a composite H-line profile produced by the Murraybank multi-channel receiver. The profile consists of 6, two-minute profiles taken over a period of 12 minutes while the aerial was held at a fixed declination in a meridian transit position (after Murray and McGee, 1959: 128).

As can been seen from Figure 219, the baseline showed some inherent unevenness due to individual differences between channel filters. After some initial trial surveys, the receiver was modified to add an additional two wide-band channels, taking the total to fifty. These additional channels were added to each end of the existing 48-channel bank and were used as zero-line markers. The filters in each of these channels had a bandwidth 0.5 MHz between half power points and were setup so that so that they covered the same frequency range as the first 24 and last 24 channels filters so that complete coverage of the profile frequency range was provided.

A calibration system was also added to the multi-channel receiver. A switched noise source was located at the vertex of the main aerial paraboloid. The noise signal was generated from a dipole located at the vertex of the aerial by switching alternatively on and off a high tension voltage supply to a noise diode mounted across the dipole feed point. This was used to provide a relative intensity calibration. The switching was performed in synchronisation with the frequency switching of the receiver so that the noise signal appeared only in the signal band of the receiver. In this way, the signal appeared equally in all channels and served as a means of calibrating the relative gain of each channel. The system was capable of measuring deflections of up to 200 °K aerial temperature. Frequency monitoring was made by comparison of the harmonics of the crystal-controlled local oscillator signals with signals from the radio station WWV. The team found that when a beat signal between WWV and another station JJY could be heard, it was likely that propagation effects would impact the quality of the recordings (Murray, 2008). Tests were also later performed using a laboratory frequency counter and these tests indicated the local oscillators had frequency stability better than the equivalent of 0.03 km/s.

For surveys the aerial was placed at a fixed declination in a meridian transit position. Recordings were then taken for a period of 24 hours. With a beamwidth of 2.2°, four complete profiles were produced per beamwidth and a total of 720 were produced in each 24 hour declination strip observing run. It was clear that the multi-channel receiver would produce a very large body of data in a short period of time. As the multi-channel receiver was proving successful in operation, it also became clear that much larger amounts of data would be produced when the receiver was later installed on the 210-ft (64-m) Parkes radio telescope. To deal with these very large amounts of data, a new project was launched under Hindman's leadership to develop a digital recording and data reduction system. M. Beard, who had been involved with the development of Radiophysics' original digital computer, joined the team to develop the Division's first digital recording system for radio astronomy. This was also to be the Division's first application of digital computers to the reduction of observational data. It was intended that this project should conduct a pilot survey to develop the techniques prior to the introduction of the system on the Parkes radio telescope.

The digital recording system used only 46 of the 48 channels for the original pilot. It consisted of five major components, being: an analogue to digital converter, a ten binary digit data store, a paper hole-punch control unit a paper tape hole-punch unit, and a program control unit with digital clock (Hindman et al., 1963b). Figure 220 shows a block diagram of the recorder system and an example of the paper hole-punch tape output.

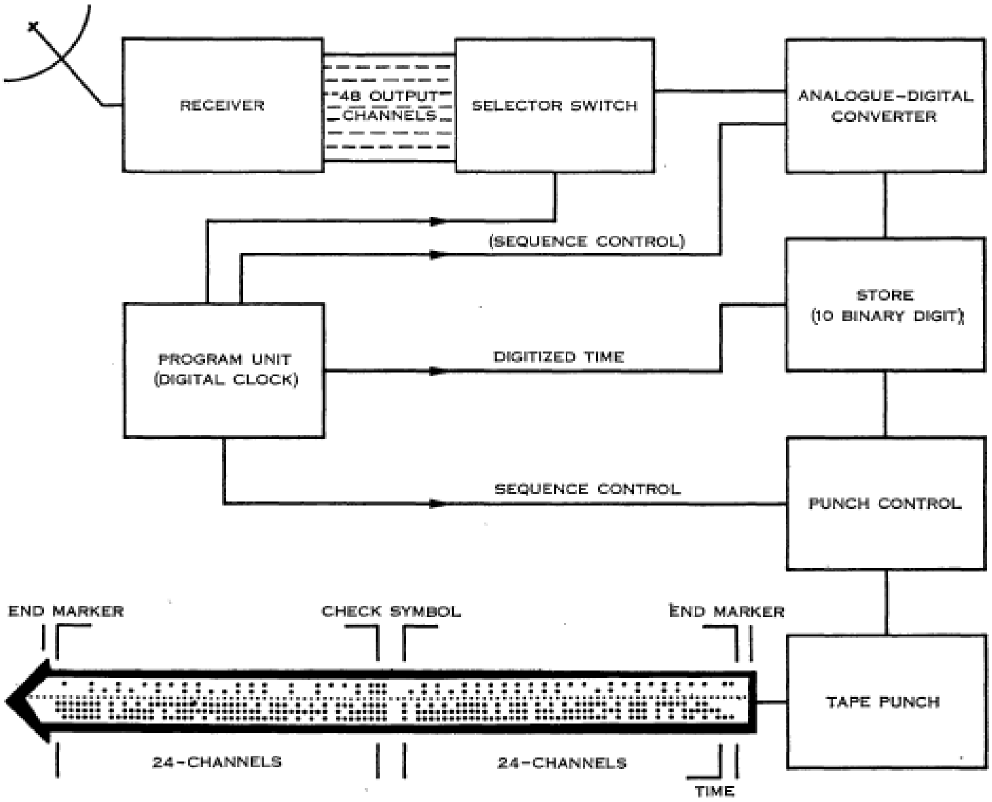


Figure 220: A block diagram of the digital recording system used at Murraybank together with the 48-channel hydrogen-line receiver (after Hindman et al., 1963b: 554).

The output produced by the digital recorder was a block of 53 pairs of characters representing the output of a single 2 minute line profile together with the sidereal time of the observation, marker characters and check characters.

In this example, the first pair of characters are blanks (or zeros) used to mark both the start and end of a single H-line profile block. This is immediately followed by 24-pairs of characters that record the relative intensity of each of the first 24 channels of the receiver, being channel numbers 0 to 23. A control symbol is then inserted represented by 2-pairs of control characters, one pair with all holes punched and the other with no holes punched. This control symbol was used to check that the paper hole-punch was functioning correctly. Following the control symbol are the next 24 pairs of characters representing channels 24 to 47. This is immediately followed by a pair of characters recording the sidereal time of the observation, and finally by the blank character pair indicating the end of the block.

The program control unit contained a clock driven at the sidereal rate with a number of shafts to achieve four revolution rates: 52 revs in 2 minutes, 1 rev in 2 minutes, 1 rev in 1 hour and 1 rev in 24 hours. Figure 221 shows a schematic diagram of the digital shaft encoder that was used to convert the shaft rotation to digital signal using a flash lamp and photoelectric readout.

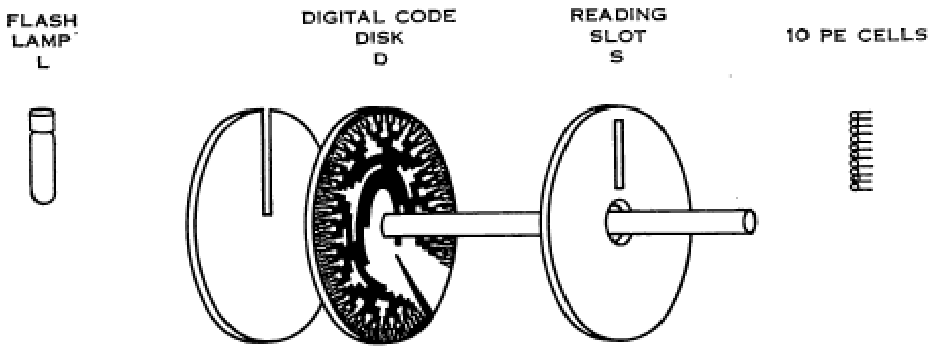


Figure 221: A schematic diagram of the digital shaft encoder in the Murraybank digital recorder program control unit (after Hindman et al., 1963b: 556).

A reading from the digital converter was obtained by flashing the lamp and a number corresponding to the shaft position was detected through the disk reading slot by the ten photo-transistors. The 1-hour and 24-hour shafts were read every two minutes to record the sidereal time of the observation and recorded as two characters in the paper tape data block. Figure 222 shows a close-up view of the digital code disk which gives 1024 numbers from 324° of rotation.

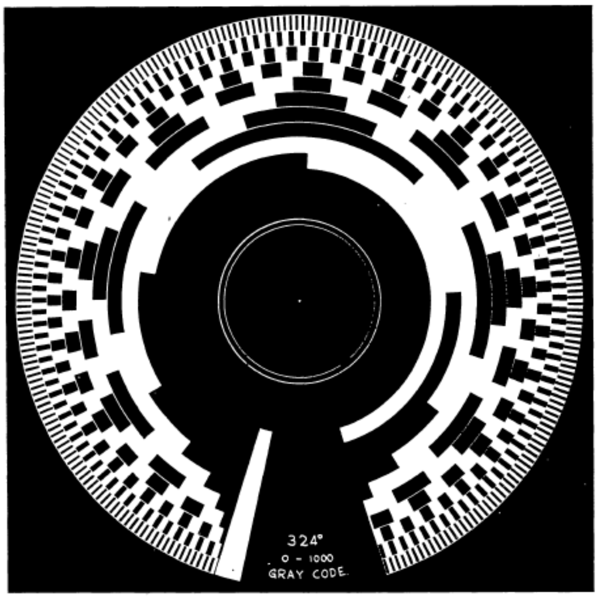


Figure 222: A close-up view of the encoding disk pattern which divided the 324° of shaft rotation into 1024 steps (after Hindman et al., 1963b: 557).

Once a number had been read by the photo-transistor cells, it was stored in the binary store which consisted of 10 bistable multivibrators. The program control unit then initiated a pulse which triggered the number to be punched on the five-hole paper tape, which used two characters to represent a number with the most significant digit being the first.

Before beginning any data reduction, each tape was checked visually to ensure that the block markers and central check characters were present. Further, each tape was passed through a reader as a check count of the number of characters per block. These checks were put in place to avoid more obvious downstream errors in the batch computer reductions. The usual chart record was recorded at the same time as digital encoding to provide a cross check.

Another feature of the digital recording method was that it made it possible to apply individual gain and zero level corrections to each individual channel. To do this a calibration tape was prepared for each data recording tape. The calibration tape had selected sections of the high and low level calibration and a base-level run that was usually the same as the low level. The calibration tape could then be fed into the computer at the beginning of the reduction process for each observation run. The calibration tape produced the base-level corrections and individual channel gain factors which were then stored in the working memory of the computer for use in reducing the observational data. Prior to the use of digital recording, manual data reductions were performed by estimating an average figure for gain corrections. In each calibration run, ten or twelve blocks of data were averaged to produce a set of calibration factors which were substantially smoothed from the receiver noise fluctuations.

The data reductions were performed using the SILLIAC (Sydney version of the Illinois Automatic Computer) computer of the Adolph Basser Computing Laboratory of the School of Physics at the University of Sydney, which had entered service in July 1956 (Figure 223).

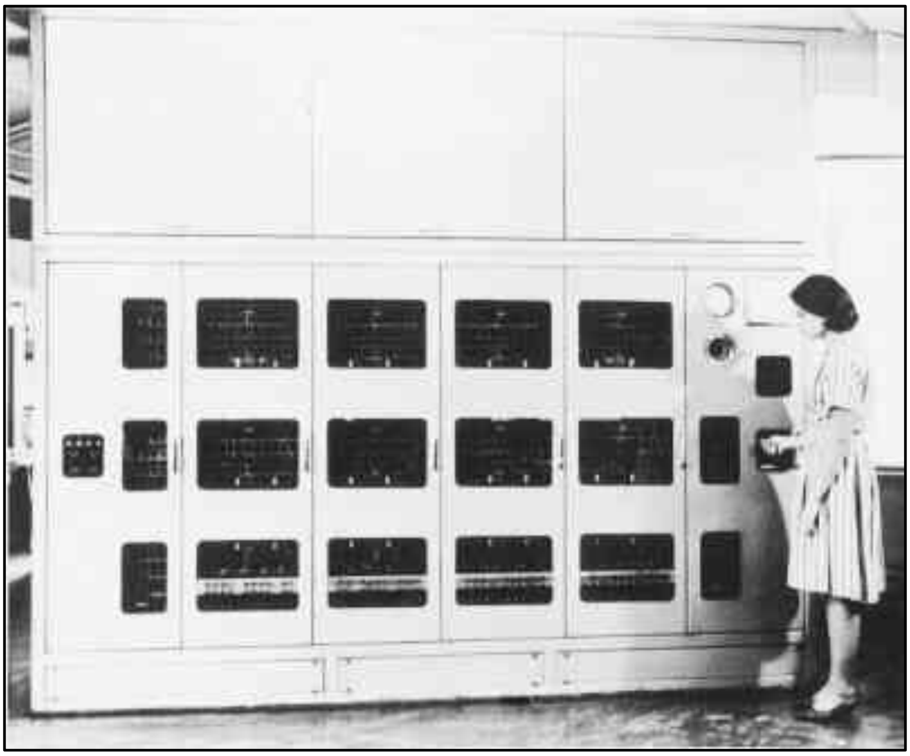

Figure 223: The SILLIAC computer of the Adolph Basser Computing Laboratory of the School of Physics at the University of Sydney (Courtesy of the Science Foundation for Physics, Univesity of Sydney).

Radiophysics had abandoned their own computer development program in 1955 and therefore it was necessary to purchase computing time from the University of Sydney. Even after negotiating a half price discount, a 'block' of 400 hours of computing time on SILLIAC cost £16,000 (Deane, 2006). As well as reducing the recorded data, the integrated brightness and median radial velocity of each profile was calculated together with the first and third quartile median velocities as channel numbers. Finally the average right ascension of the profile, corrected for the receiver time constant effect, was calculated and all the data were then recorded on an output tape. Velocity corrections to account for the Earth's rotation and then Earth's orbit about the Sun were not performed as part of the initial data reduction, but were calculated in a separate run. The computer time required to reduce 250 hours of observations was approximately 8 hours, with a further 15 minutes required to calculate the velocity corrections. Plotting of the results was still performed by hand, but this was the next obvious step for automation. Figure 224 shows a simplified flow chart of the reduction program.

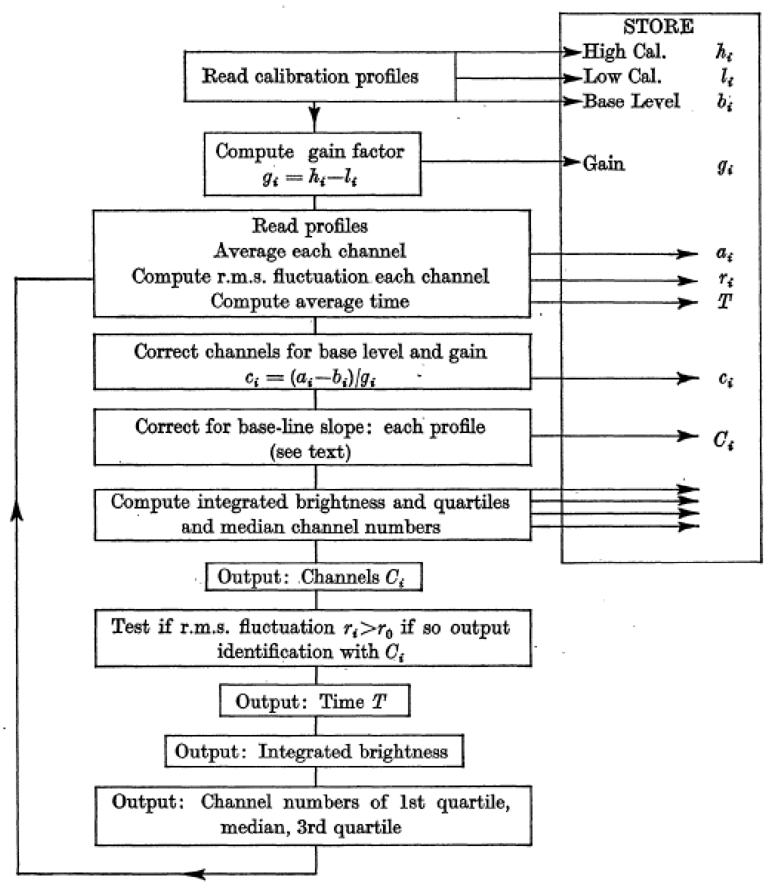


Figure 224: A simplified flow chart of the reduction program run on the SILLIAC computer (after Hindman et al., 1963b: 562).

The use of digital recording not only greatly reduced the time necessary for reduction of the initial observations, but the more rigid application of calibration data lead to the detection of a second-order receiver effect due to diurnal temperature variations which had not previously been detected. It also allowed the detection of lower level signals that had previously been averaged out in manual reductions. The pilot program was considered highly successful and allowed digital recording to be introduced when the Parkes radio telescope became operational.

### 11.4. Murraybank Research

Appendix B contains a listing of published material that was based on research carried out at Murraybank. The first published research appeared in *The Observatory* (Murray and McGee, 1958). This was based on a set of trial observations in the Pyxis-Hydra region in the mid galactic latitudes between longitudes 210° and 230°. The observations were made prior to the adjustment of the aerial feed so that the beamwidth at half power points was still 2.8°. At this time no absolute brightness temperature calibration had been performed, so the temperature scale was based on a comparison to Muller and Westerhout's (1957) observations in nearby regions. Observations were made by holding the aerial at a constant declination with a spacing of two degrees or less between scans. Approximately 700 profiles were recorded covering an area of ~500 square degrees.

The profiles observed in the Pyxis-Hydra region were single-peaked and therefore the distribution of neutral hydrogen was reasonably represented by the peak profile brightness temperatures and the radial velocities at this point. Figure 225 shows a contour diagram of peak H-line brightness temperatures at intervals of 5°K, together with radial velocities and an indication of HII regions from optical observations.

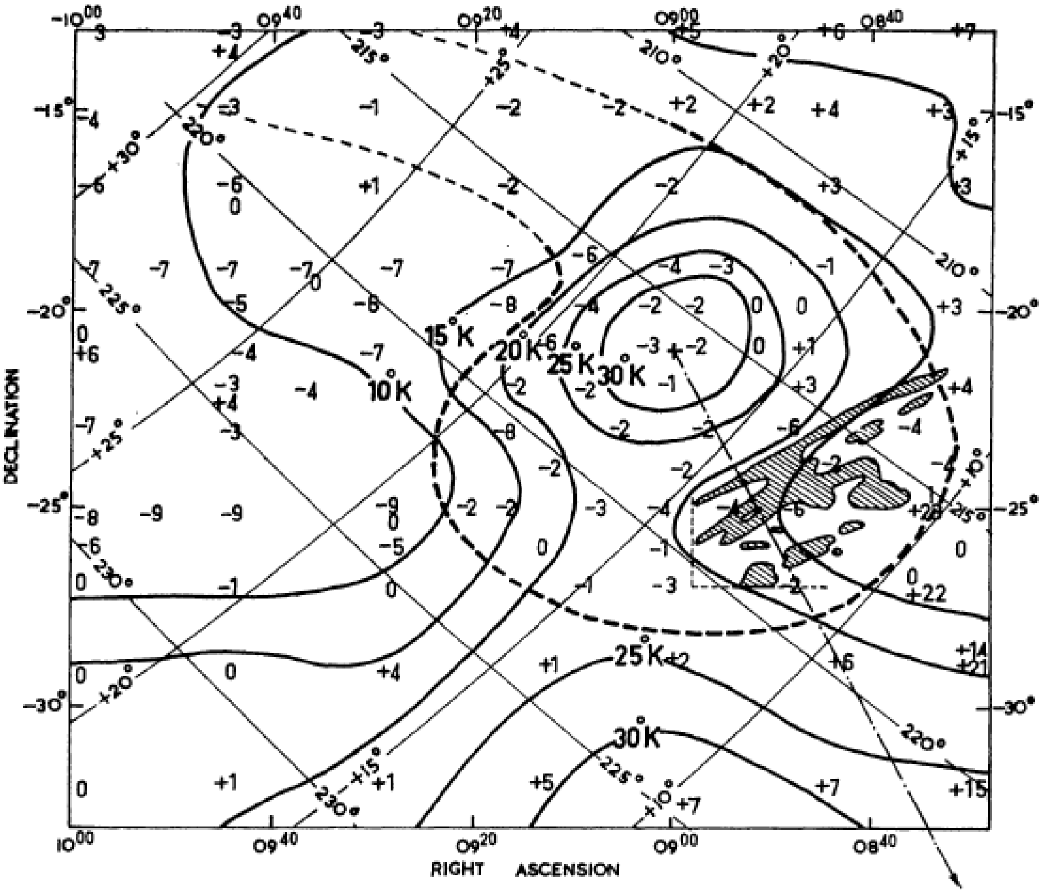


Figure 225: A contour diagram of the H-line brightness temperature in the Taurus-Orion region Contour spacing is 7.5 degrees of peak temperature. The large numbers represent the mean radial velocity in kms$^{-1}$ over areas 10° by 10° (after Murray and McGee, 1959: 130).

Based on these observations, Murray and McGee deduced the presence of a large discrete neutral hydrogen cloud centred at right ascension 09$^h$ 00$^m$ and declination -21°. This was supported not only by the peak brightness contours, but also by the fact that the radial velocities immediately to the Cloud's left (East) in Figure 225 had a large step change in velocity indicating that the cloud appeared not to be associated with other HI in that region. The dotted line in the diagram encompasses the possible area of the cloud based on the radial velocity measurements. The extension in the upper left is speculative and based only on the velocity measurements. Gum (1956) had shown that the two stars $\gamma^2$ Vel and $\zeta$ Pup were the source of the ionisation radiation forming the HII region. The location of the HII region on the leading edge of the HI cloud facing these stars appeared to lend support to the idea that the two were indeed part of the same complex. Using a distance determination from Gum (1956) they reached the following conclusions:

| | |
|---|---|
| Position of Cloud centre (max H-line brightness): | $\alpha = 09^h\ 00^m$, $\delta = -21°$<br>$l = 216°$, $b = +17.5°$ (1950) |
| Cloud Diameter: | 12° |
| Average Peculiar Radial Velocity: | -2.5 km $sec^{-1}$ |
| Maximum H-line brightness Temperature: | 35° K |
| Average number of H atoms in line-of-sight column of 1 $cm^2$ section: | $1.0 \times 10^{21}$ H atoms |

The next preliminary survey was made of the Taurus and Orion complexes which covered approximately 3,500 square degrees. Again the survey was conducted by holding the aerial at a fixed declination and then the next scan taken with two degree spacing. Some 3,500 profiles were taken in this manner. Nearly all the line profiles were single peaked with an average half-width of 19 $kms^{-1}$ with a standard deviation of 2 $kms^{-1}$. As no flattening of line profiles was observed it was concluded that the gas was optically thin at all points in the region.

To investigate the radial velocity distribution in the Taurus-Orion region, over 350 uniformly distributed velocity values, corrected to the local rest standard, were calculated. Figure 226 shows a contour diagram of brightness temperature and the mean radial velocities in a grid of 10° by 10°.

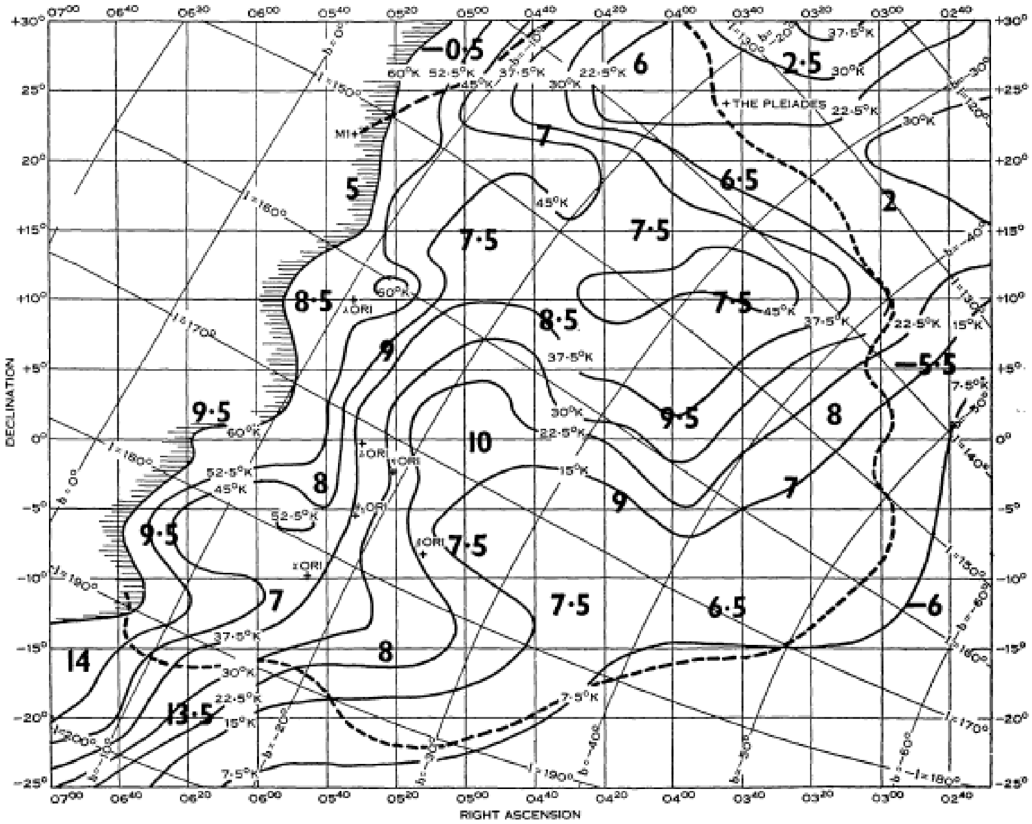

Figure 226: A contour diagram of peak H-line brightness temperature at intervals of 5° K. Radial velocity in km/sec is indicated as integers on the chart. The shaded area represents a HII region sketched from the National Geographic-Palomar Sky Survey. The arrow indicates the direction from the centre of the contours of two stars believed to be responsible for the ionisation of the HII region (after Murray and McGee, 1958: 243).

As for the Pyxis-Hydra region, both the peak temperature contours and the radial velocity profiles supported the presence of a large cloud, or connected clouds, in the Taurus-Orion region. Figure 227 shows a comparison of neutral hydrogen density in a line-of-sight column compared to dust regions defined by Hubble's zone of avoidance where there are high levels of optical extinction.

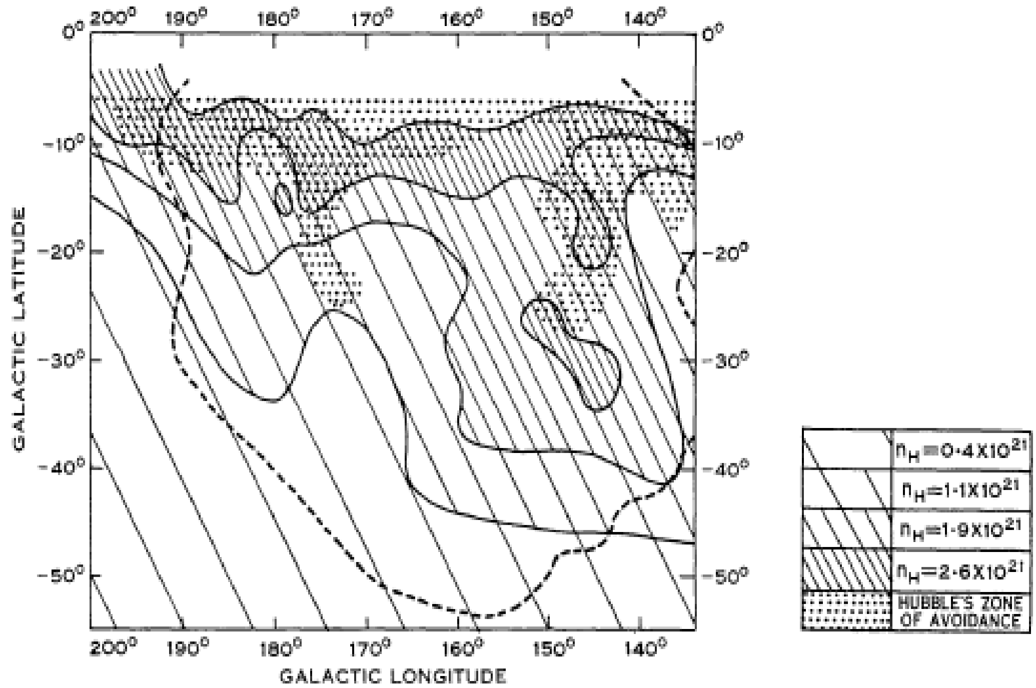


Figure 227: A comparison of neutral hydrogen density and Hubble's zone of avoidance (after Murray and McGee, 1959: 132).

The distance to the clouds estimated from a galactic rotation model (Kwee et al., 1954) was 430 parsec, however if the neutral hydrogen clouds were associated with the optically observed dust clouds in the region, as suggested by Figure 226, then there was a large distance discrepancy as these had previously been determined to be at a distance of 145 parsecs (Greenstein, 1937). A more recent VBLA measurement of the trigonometric parallax of several member stars of the Orion Nebula Cluster, showing non-thermal radio emission, has determined the distance to the cluster to be 414± 7 pc (Menten et al., 2007).

Both of the pilot surveys conducted by Murray and McGee demonstrated the viability of the multi-channel receiver coupled with the relatively low resolution 21-ft aerial. With this arrangement, large areas of the sky could be surveyed in relatively short periods. The initial surveys also demonstrated the value that could be gained in examining not only the large-scale structures of the Galaxy, but also the more detailed study of specific regions.

With the pilot surveys completed, the focus now turned to a large scale survey of the sky visible from Sydney. This survey was completed during 1960 and the first publication of results appeared in *Nature* and the *Astronomical Journal* (McGee and Murray, 1961a; McGee et al., 1961). These dealt with the large-scale streaming of neutral hydrogen in the vicinity of the Sun.

Figure 228 shows a radial velocity contour diagram of the H-line peak profiles from the Murraybank survey. The diagram shows the positive and negative peak velocities along the galactic equator associated with differential rotation of neutral hydrogen in a disk about the galactic centre. However, the interesting features evident in the diagram are the large areas of negative velocity at high galactic latitudes. Areas of negative velocity near the galactic poles had previously been reported by Erickson et al. (1959), but they had not noted the overall disposition.

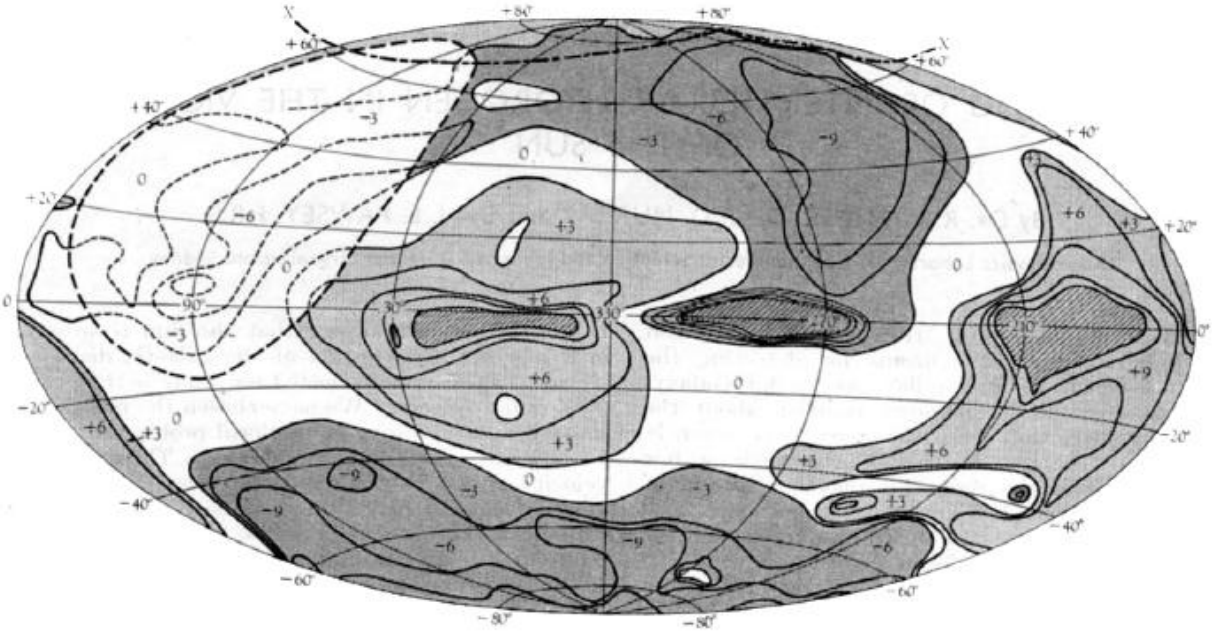

Figure 228: A contour diagram of peak H-line radial velocities from the Murraybank southern sky survey. Dark grey areas represent negative velocities. Light grey areas represent positive velocity areas. The hatching denotes areas where the radial velocity exceeds 15 kmsec$^{-1}$. Co-ordinates are in the old 1950 Ohlsson scheme (after McGee et al., 1961: 958).

These areas appeared to be associated with a general in-streaming of neutral hydrogen, at least within the general area of the Sun, but possibly more generally. Figure 229 compares the observed peak velocities to a derived curved based on a differential galactic rotation model. The diagram shows areas of positive velocity toward the galactic centre where negative values would be expected indicating that the gas in this region has an additional component of outwards motion.

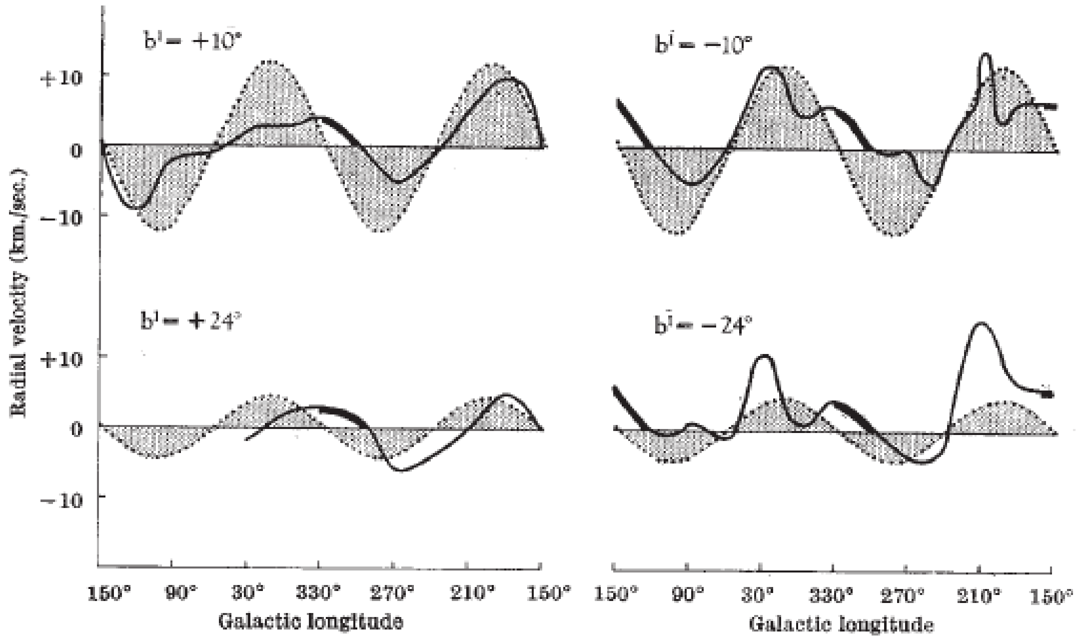


Figure 229: A comparison of observed velocity curves to the predicted velocity curve assuming differential galactic rotation. The dotted line and shading represent the predicted curve. The solid line represents the actual observations. The thickened sections of the line represent the main deviations from the prediction (after McGee et al., 1961: 958).

Without being able to determine the distance of observed peaks, other than through an assumed differential rotation model, they were unable to state whether the streaming was a more general phenomenon. However, they noted that if the observed flow was representative of the general flow over the galactic disk then the quantities of hydrogen involved would be sufficient to make this a major feature of galactic dynamics.

A further series of three detailed papers was published in the *Australian Journal of Physics* from 1961 to 1964 based on the Murraybank southern sky survey (McGee and Milton, 1964; McGee and Murray, 1961b; McGee et al., 1963). For the analysis of the southern sky survey, McGee and Murray were joined by Janice A. Milton who conducted a major part of the data reduction. She was a co-author on the later two papers and was acknowledged for her contribution in the first paper. The third paper in the series was prepared solely by McGee and Milton as by this stage Murray was working in the Netherlands.

The Murraybank southern sky survey was performed by taking observations at meridian transit with intervals of one degree in declination from -90° to +42° over a period of 24 hours for each observing run. The limit of sensitivity was believed to be set by an r.m.s. fluctuation level of the system of approximately 0.7 °K. Prior to the Murraybank survey there had been only three extensive H-line surveys that dealt with the region away from the galactic plane. The first was the pioneering survey at Potts Hill by Christiansen and Hindman (1952b) which included galactic latitudes of ±50°. The next was by Erickson et al. (1959) at

D.T.M in Washington using the 54-channel receiver and covering galactic latitudes outside of ±20°. This survey was based on profiles taken at intervals of 10° in both galactic longitude and latitude. Finally, Davies (1960) at Jodrell Bank had covered the same region and extended observations to include ±20° with observations at 5° intervals.

In the first detailed paper in their series, McGee and Murray (1961b) dealt with the general distribution and motions of the local neutral hydrogen as had been reported in summary form in *Nature*. The paper established that in the vicinity of the Sun, neutral hydrogen was flowing outwards at a mean radial velocity of +6kms$^{-1}$ in those latitudes in the direction of the galactic centre and anti-centre, and was flowing inwards at a mean velocity of -6kms$^{-1}$ from above and below in the high galactic latitudes.

McGee and Murray found that the recorded profiles could be divided into three broad classes. The first class was believed to be the local neutral hydrogen distributed over a wide area of the southern sky with line profile half-widths from the instrumental lower resolution limit of 12 kms$^{-1}$ to a maximum observed value of 35 kms$^{-1}$. In most cases the profiles were single peaked with radial velocities not in excess of ±12 kms$^{-1}$ and with maximum brightness temperature ~50 °K. The second class was believed to emanate from the galactic spiral structure and fell within ±12° of the galactic equator. These profiles were wide and usually multi-peaked and of much greater intensity than those of any other regions. The third class mainly occurred in low intensity regions at high galactic latitudes. These had half-widths that ranged from 36 to 140 kms$^{-1}$ and in some cases exhibited two or three distinct peaks. McGee and Murray considered the possibility that the wide profiles may be due to hydrogen from the galactic corona but discounted this idea, as a much greater dispersion would be expected from randomly moving and highly dispersed gas clouds.

The optical depth of the neutral hydrogen was calculated based on the method from Wild (1952):

$$N_H = 1.84 \times 10^{18} \int_{-\infty}^{\infty} T(v)\,dv \qquad (19)$$

where

$N_H$ is the number of hydrogen atoms in a 1 cm$^2$ line-of-sight column;
$T$ is the H-line brightness temperature; and
$v$ is the radial velocity in km/second.

Figure 230 shows the calculated local distribution of neutral hydrogen density as the number of atoms/cm$^2$ in a line-of-sight column.

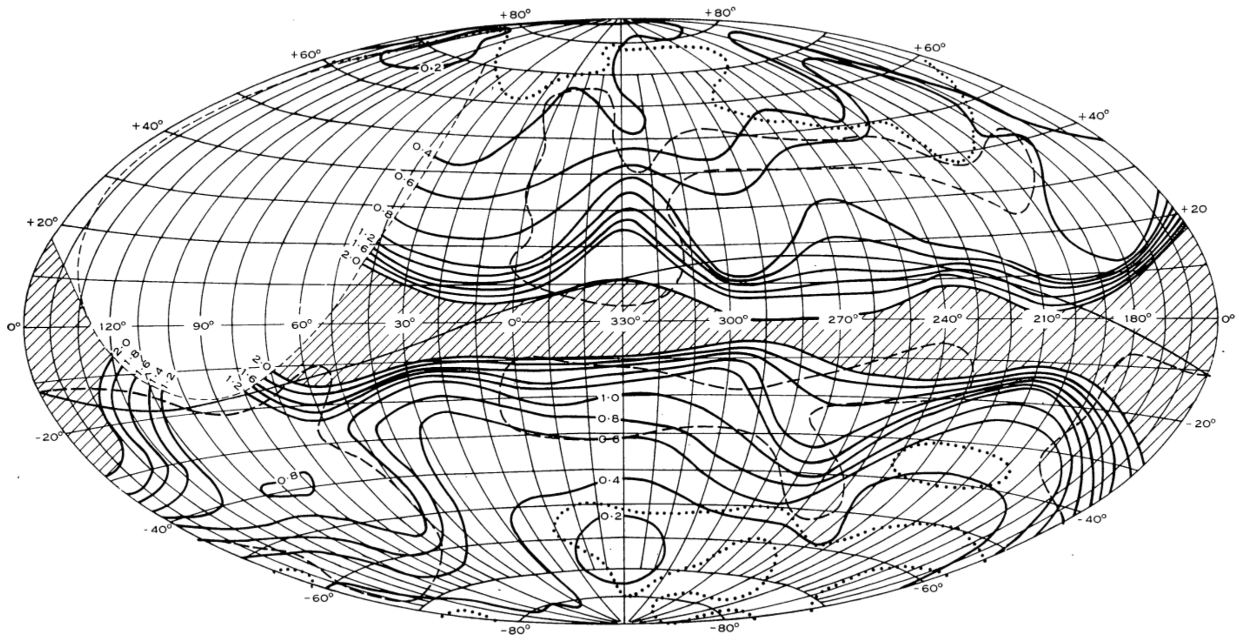


Figure 230: A contour diagram of the local distribution of neutral hydrogen shown as the number of hydrogen atoms/cm$^3$ in a line-of-sight column. The contour interval is $0.2 \times 10^{21}$ H atoms cm$^{-2}$. The hatched area encloses regions where the profile half-widths were in the range 12-20 km/s. The Galactic co-ordinates are the old system after Ohlsson (after McGee and Murray, 1961b: 264).

The hatched area in Figure 230 indicates the area along the galactic plane where the neutral hydrogen density exceeds $2.0 \times 10^{21}$ hydrogen atoms cm$^{-2}$. Also evident are a number of large scale features. The northern galactic hemisphere showed two spurs; one in the Scorpius-Ophiuchus region, and the second in Sextan's region. A weaker ridge is also visible in the southern hemisphere. McGee and Murray noted that the mean longitudes of the major northern spur, the southern galactic minimum, the northern minimum and southern spur were approximately the same. Dr. W.C. Erickson had also alerted McGee and Murray to the fact that the position of the northern minimum agreed exactly with that of the D.T.M survey and was also the pole corresponding to the plane of the general magnetic field in the solar vicinity as derived by Shain (1957). No conclusion was drawn from the coincidence of this alignment.

McGee and Murray noted that if the neutral hydrogen is stratified parallel to the galactic plane, then the observed density should vary as the cosecant of the galactic latitude. Figure 231 and Figure 232 show the density of neutral hydrogen plotted against twelve galactic longitudes as a function of latitude.

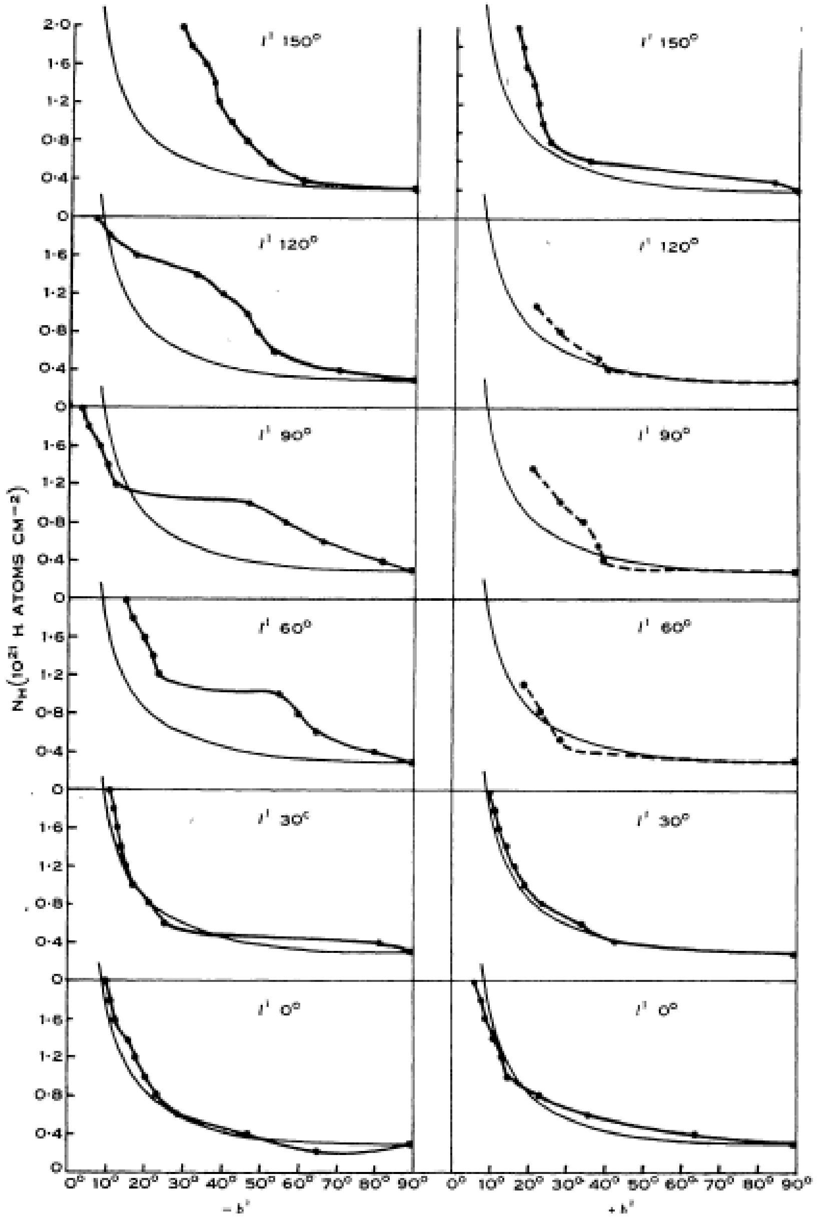


Figure 231: The variation of neutral hydrogen ($N_H$) density compared to the cosecant curve $N_H$ = $\left|0.3\times10^{21} \text{ cosec } b^I\right|$. The left-hand column are +ve latitudes and the right-hand column are –ve. Longitudes 0° to 150° (after McGee and Murray, 1961b: 269).

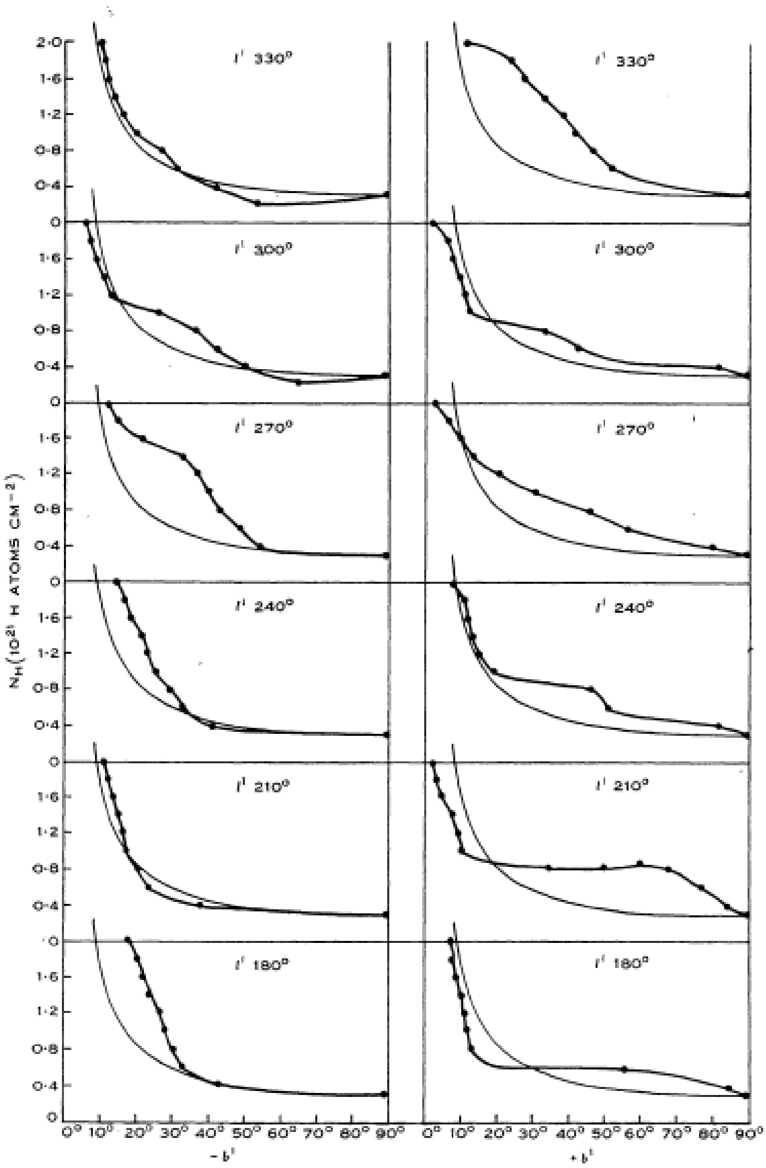


Figure 232: The variation of neutral hydrogen ($N_H$) density compared to the cosecant curve $N_H = |0.3\times10^{21} \text{ cosec } b^I|$. The left-hand column are +ve latitudes and the right-hand column are –ve. Longitudes 180° to 330° (after McGee and Murray, 1961b: 269).

The conclusion drawn from these diagrams was that the neutral hydrogen was substantially horizontally stratified in the plane of the galaxy and that there were a number of concentrations of neutral hydrogen embedded in the plane. The estimated density of neutral hydrogen in the solar vicinity was approximately $0.40\times10^{21}$ hydrogen atoms cm$^{-2}$. Davies (1960) had found a variation in density in the southern galactic hemisphere, however McGee and Murray suggested that this discrepancy was most likely due to averaging effects over different areas of the sky. Their results suggested that there was little difference between hemispheres, indicating that the Sun lies at the centre of the hydrogen layer in the galactic plane.

Much of the data on the radial velocity distribution had been discussed in the *Nature* summary paper. In their paper that appeared in the *Australia Journal of Physics* a more detailed analysis was made of the departures of measured radial velocities from the predicted velocities due to differential galactic rotation. Figure 233 shows a summary of these for both northern and southern galactic hemispheres from ±20° to ±60°. The predicted curve was based on the following formula for points 11 kpc above and below the galactic plane:

$$v_g = 0.11 \times 19.5 \sin 2l' \cos b' \cot b' \qquad (20)$$

It is clear from Figure 233 that at high galactic latitudes the velocity of neutral hydrogen is not influenced by differential rotation. Based on this evidence it was concluded that neutral hydrogen was flowing toward the Sun from above and below latitudes ±90° to ±40°.

The second paper in the series (McGee et al., 1963) dealt in detail with the low velocity gas observations. Some 95,000 H-line profiles were obtained in the survey, of which about 40,000 were redundant, being for the same region of the sky. The redundant profiles were however still useful for cross-checking of the observations. By this stage they were using the term "low velocity" in place of "local" as it became clear that the low velocity areas while predominantly local were not the only regions with low velocity characteristics. In the area of the Milky Way the observations showed a close adherence to the velocities of a simple double sine curve assuming differential galactic rotation. They compared the neutral hydrogen measurements to ionised calcium optical observations (Feast et al., 1957) and found good agreement in radial velocities and distance estimates. However, as shown in Figure 233 it was apparent that a more reliable value for Oort's constant A = 19.5 $kms^{-1}$ $kpc^{-1}$ may be required. Adjustment of the value of Oort's constant to A = 13.8 $kms^{-1}$ $kpc^{-1}$ and assuming a distance of 2 kpc would bring the optical and radio observations into alignment. Over time the value for Oort's constant has been refined to a current value of A = 14.8 $kms^{-1}$ $kpc^{-1}$ (Sparke and Gallagher, 2000: 81).

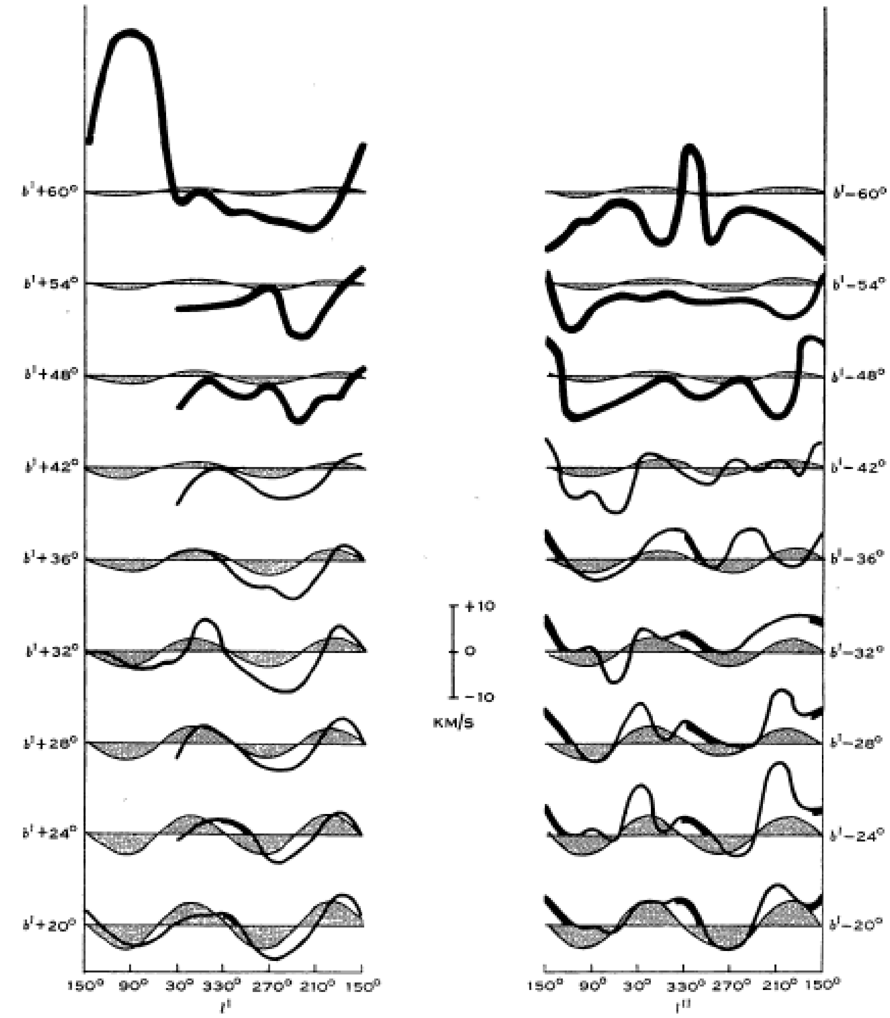


Figure 233: Radial velocity as a function of galactic longitude compared to predicted velocities at points 11 kpc above and below the galactic plane. The thick lines indicate areas of major discrepancies between the prediction and observations (after McGee and Murray, 1961b: 276).

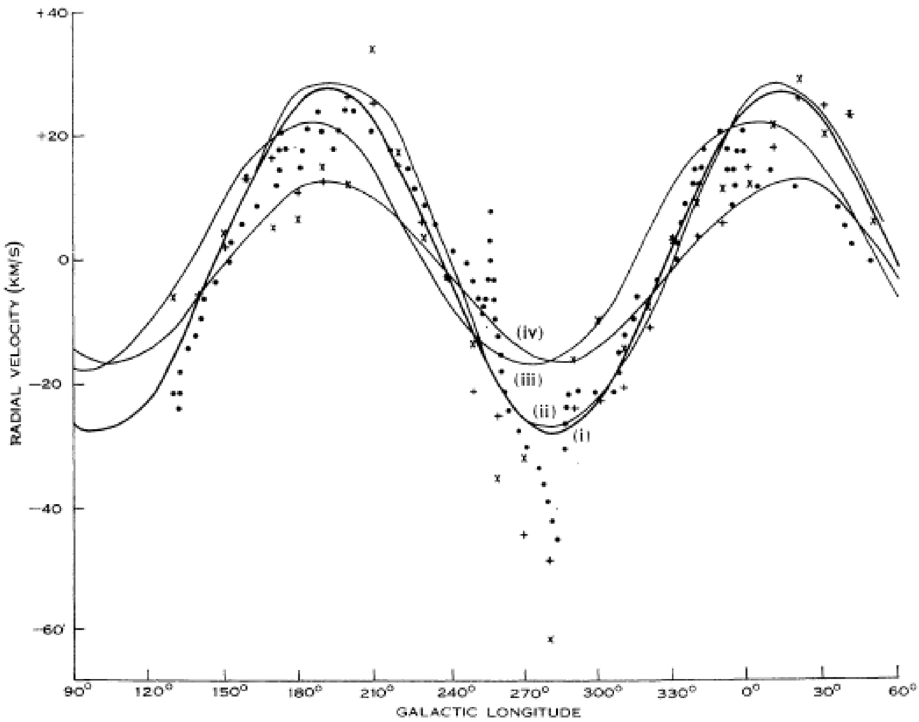


Figure 234: Radial velocity observations as a function of galactic longitude. The dots represent neutral hydrogen observations. The + points and X points are derived radial velocities using the relation $v_g = 19.5r \sin 2(l^I - 238°)$. The + points are positive latitudes the X negative. Curve (i) is the theoretical differential rotation curve assuming a 1.4 kpc estimated mean distance of hydrogen in the galactic plane. Curve (ii), (iii) and (iv) are those derived by Feast and Thackeray based on ionised calcium (Ca II) absorption lines in the spectra of B-type stars reduced to mean distances of 2, 1.15 and 0.75 kpc respectively (after McGee et al., 1963: 154).

A detailed comparison was made between the neutral hydrogen distribution and the other radio-frequency emission distribution. A catalogue of concentrations, depression and column density deficiencies of low velocity neutral hydrogen was produced and this was compared to surveys by Westerhout (1958) at 1,390 MHz and by Mathewson et al. (1962) at 1440 MHz. These were continuum rather than H-line surveys. The general findings from this comparison were that there was evidence of absorption by neutral hydrogen from some intense and extended sources. For some nearby thermal radio sources, strong HI and HII emissions are related. The neutral hydrogen emission along the Milky Way on the other hand, can be very intense in places where the radio continuum drops to a negligible level. The survey also confirmed that Hα emitting regions occur where there are areas of intense neutral hydrogen emission. It was noted that deficiencies in neutral hydrogen of about 8 °K occur where the position coincides with HII regions. Although the association of neutral hydrogen with dust had previously been demonstrated, the detailed survey provided very strong evidence to support this association. There were a number of outstanding examples of this correspondence in the regions of the Great Rift, the Ophiuchus Complex and the spurs in the Orion-Taurus-Perseus region, although this association was not present in all cases, for example for the Southern Coal-sack. Figure 235 and Figure 236 are examples produced from the survey of the contour diagrams of peak temperatures and the corresponding radial velocities for similar areas of the sky.

Figure 237 shows a summary diagram of the of the peak temperature from declinations +42° to -80°. In this diagram the contours have been limited to 4, 8, 16, 32 and 64 °K for simplicity. This diagram should be compared to the general radio continuum shown in Figure 156.

The third paper in the series (McGee and Milton, 1964) on the Murraybank H-line survey, addressed the high velocity neutral hydrogen believed to be associated with the Galaxy’s spiral arms. Again, the detailed data was presented with a minimal amount of reduction and correction. The distribution of neutral hydrogen in the Milky Way had previously been extensively studied in Leiden (Muller and Westerhout, 1957; Ollongren and van de Hulst, 1957; Schmidt, 1957; van de Hulst et al., 1954) and at Potts Hill as discussed in section 10.5.2.2. The new IAU System of Galactic Coordinates (Blaauw et al., 1960) had been determined principally from neutral hydrogen observations in the inner part of the galaxy. The third paper therefore dealt mainly with the outer parts of the Galaxy beyond the solar orbit and within galactic latitudes of ±10°. In this region the H-line profiles exhibited multiple peaks. Figure 238 shows examples of some triple-peaked profiles.

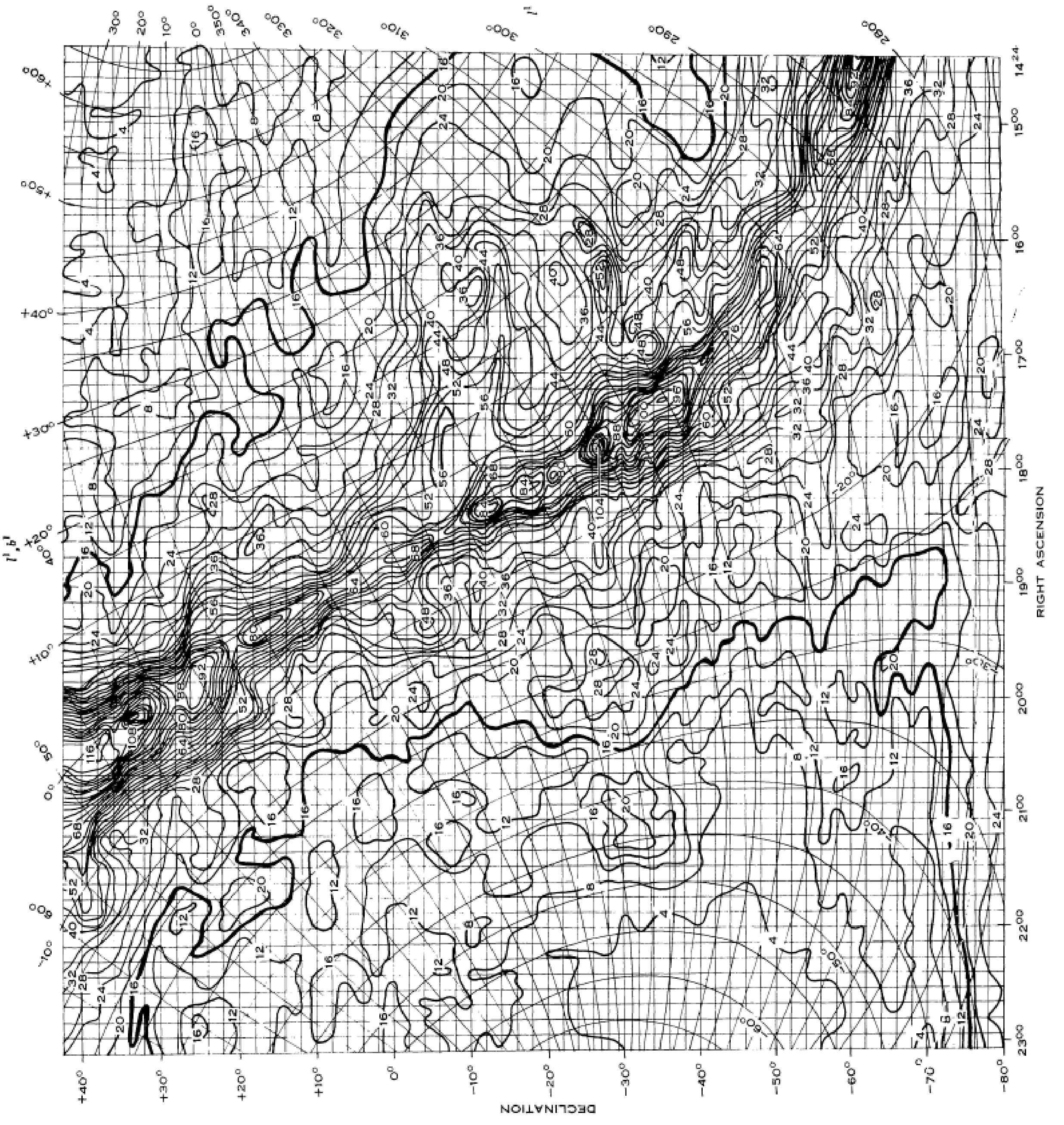


Figure 235: An example of the peak temperature of neutral hydrogen contour diagram produced in the Murraybank survey (after McGee et al., 1963: 139).

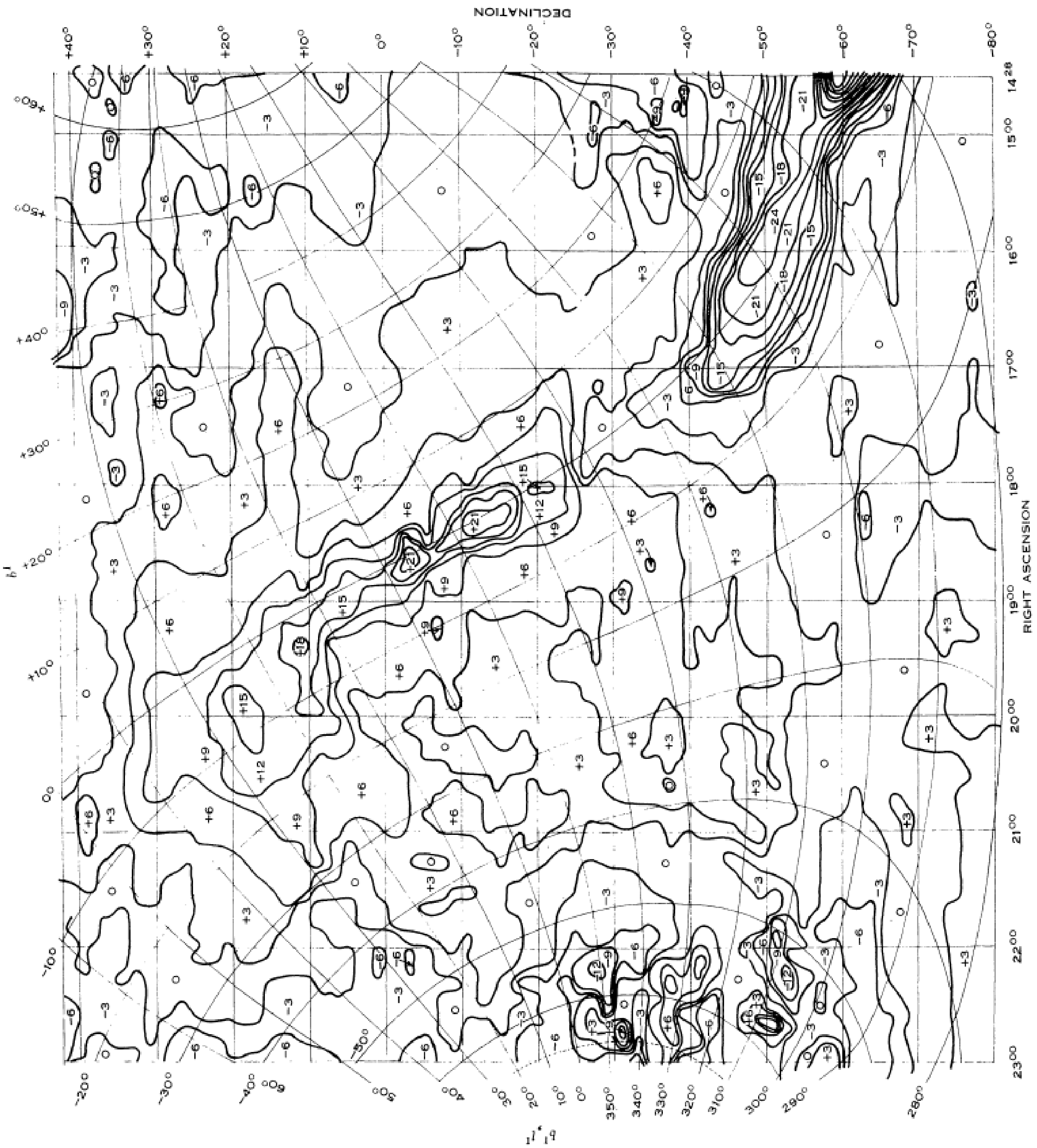


Figure 236: An example of the radial velocity contour diagram corresponding to the brightness peak of neutral hydrogen from the Murraybank survey (after McGee et al., 1963: 147).

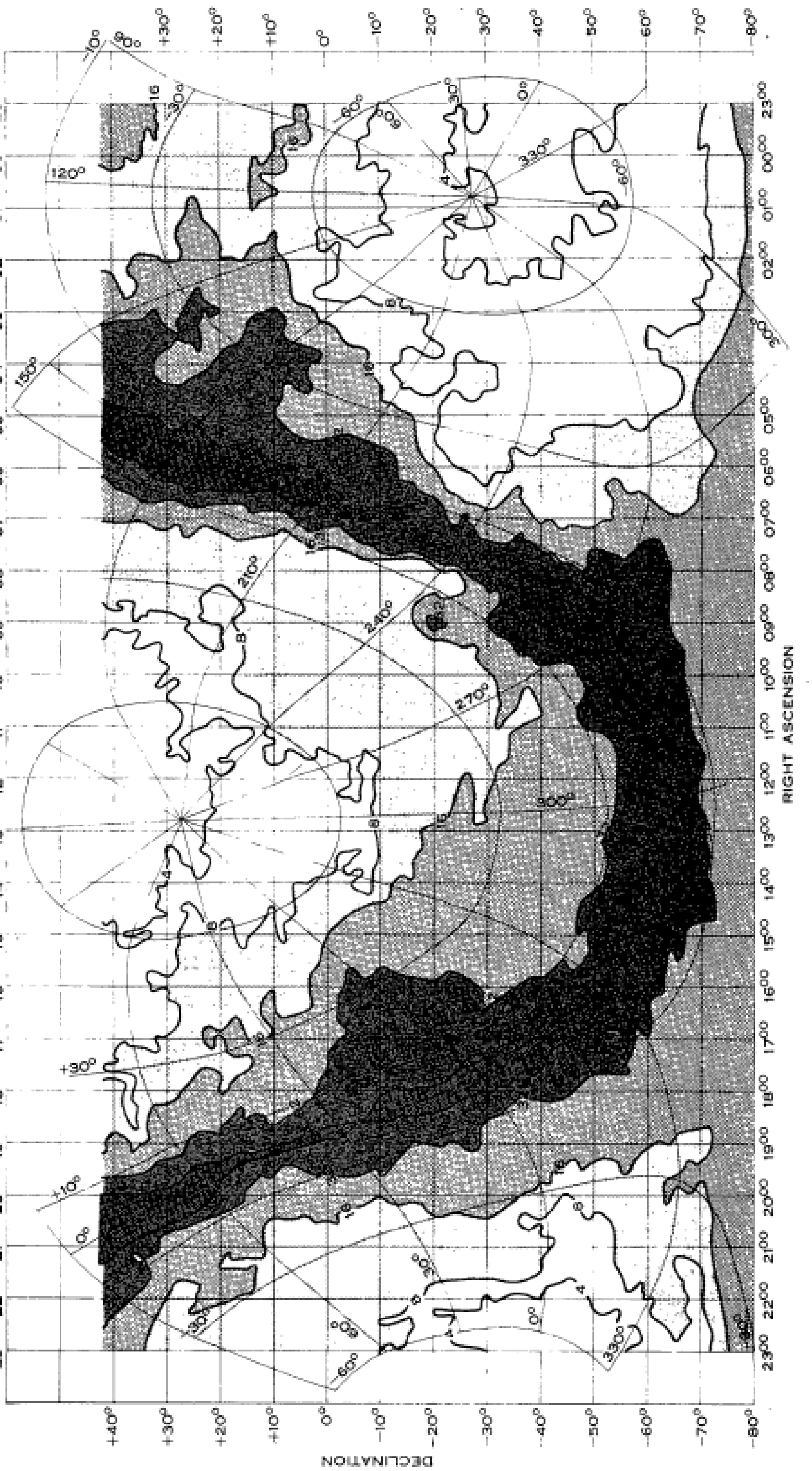


Figure 237: A composite contour diagram of peak temperature with contours limited to 4, 8, 16, 32 and 64 °K (after McGee et al., 1963: 156).

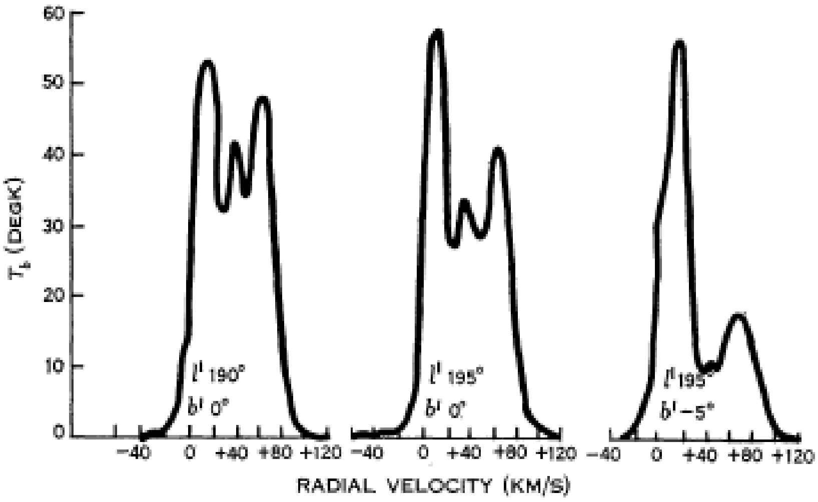


Figure 238: Examples of triple-peaked H-line profiles from the Murraybank survey (after McGee and Milton, 1964: 129).

Figure 239 shows an example of the contour diagrams produced for both peak brightness temperature and radial velocity of the peak.

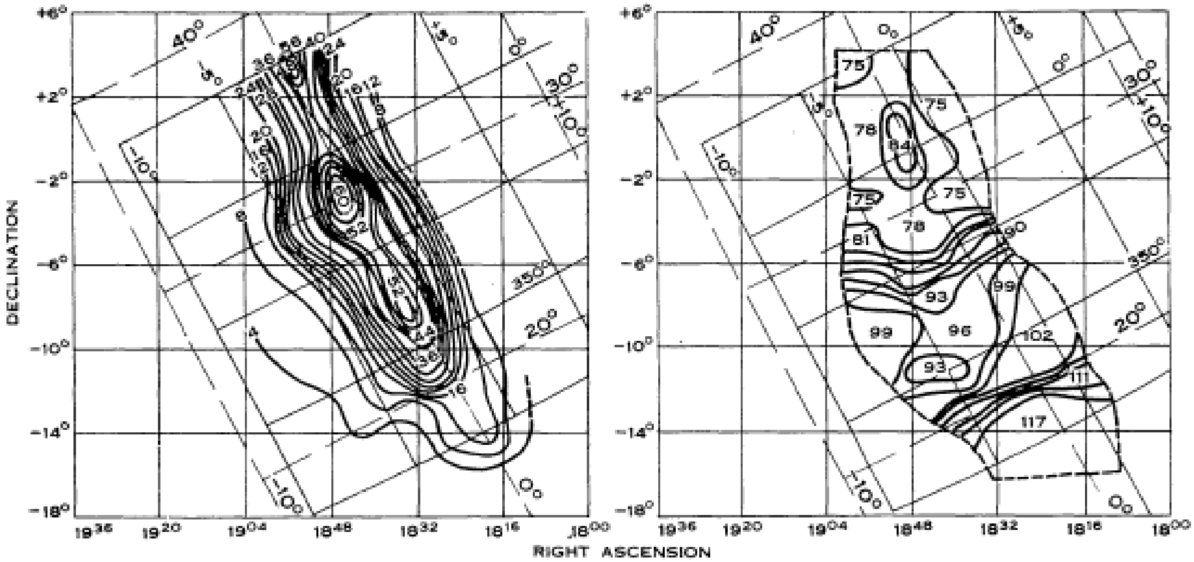


Figure 239: Examples of the peak brightness temperature (left) and radial velocity (right) contour diagrams along the galactic equator from the Murraybank survey (after McGee and Milton, 1964: 143).

To enable comparisons with previous surveys, McGee and Milton adopted the radial velocity-distance model used by Kerr (1962). This included adjustments for both the northern and southern sets of data to include the galactic rotation and an expansion component. For positions inside the solar orbit, an ambiguity of position exists and therefore no general comparisons were made for this region. Figure 240 shows the overlay of their positions of maxima (open circles) and minima (crosses) of hydrogen concentrations on Kerr's (1962) map of the distribution of neutral hydrogen. The dark line joining the positions marks the ridges of maximum intensity of four spiral arms.

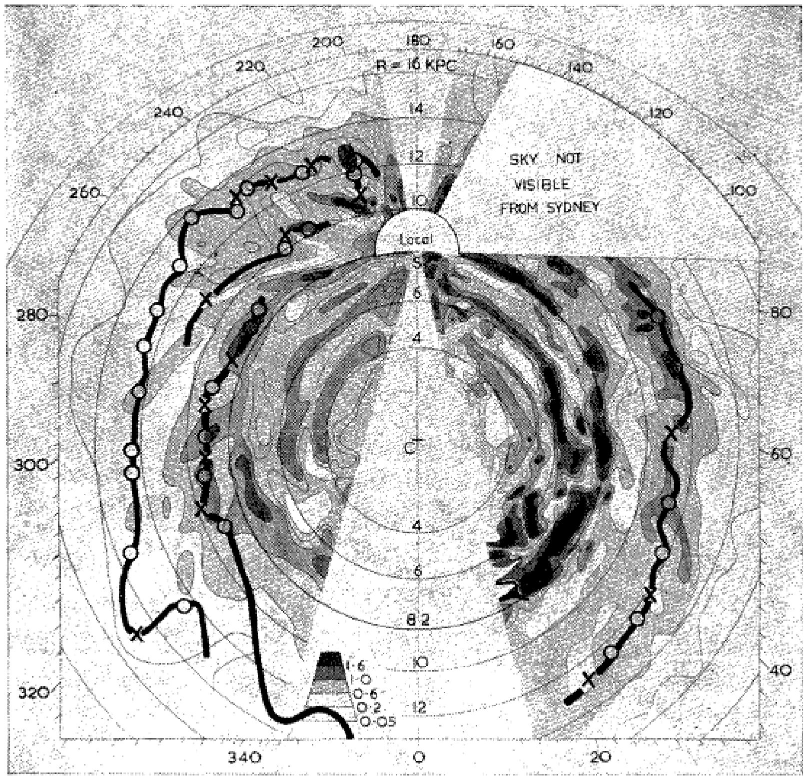


Figure 240: The ridges of maximum intensity of neutral hydrogen for four spiral arm outside of the Sun's galactic orbit over-laid on Kerr's (1962) map of hydrogen distribution (after McGee and Milton, 1964: 149).

Van de Hulst (1958) had earlier published estimates for hydrogen cloud sizes summarised as follows:

| Class | Size in pc |
|---|---|
| Diameter of spiral arms in plane | 500-1000 |
| Diameter of spiral arms 90º to plane | 200 |
| Condensations in spiral arms | 100 |
| Large emission regions | 60 |
| Typical cloud, Ca+ absorption | 30 |
| Typical cloud, 21-cm emission | 20-70 |

McGee (1964) had drawn attention to the existence of two further classes based on the Murraybank observations. The first of these was typically of 100-150 parsec and contained two or more of van de Hulst's 'typical clouds, 21-cm emission'. They were generally observed in the solar vicinity. The second class was HI clouds that were several times larger and are found in the region outside of the solar orbit. Twenty nine examples of these clouds were recorded that ranged in size from 350-1330 parsecs. The average mass of these clouds was estimated to in the order of $10^7$ solar masses. McGee and Milton noted that the hydrogen in our own local neighbourhood could well be considered to form one of the large clouds with the major components being of the 100-150 parsec class, such as the Scorpius-Ophiuchus, Pupis-Vela and Orion-Taurus-Perseus clouds.

One of the major findings from this section of the Murraybank survey was that although there was good agreement with earlier surveys on the possible thickness of the hydrogen layer in the galactic plane, outside of the radius of the Sun's galactic orbit the thickness of four of the spiral arms increases with increasing distance from the galactic centre. At a radius of 13 kpc the half-power thickness of the arms was estimated to be 1,300 parsecs. This phenomenon had not previously received a great deal of attention. Van de Hulst et al. (1954) had found "...a distant arm..." had a "...true half-thickness of 750 parsecs". Westerhout (1957) in discussing a "...faint outer arm..." stated that "...its mean height between +500 and +1000 parsecs is very peculiar". In discussing their result with the Potts Hill team, Hindman had "...informed us that he had noticed the great increase in the thickness of outer arms", however this interpretation was discounted at the time. Figure 241 illustrates the observed rapid increase in cloud thickness outside of the radius of the Sun's galactic orbit.

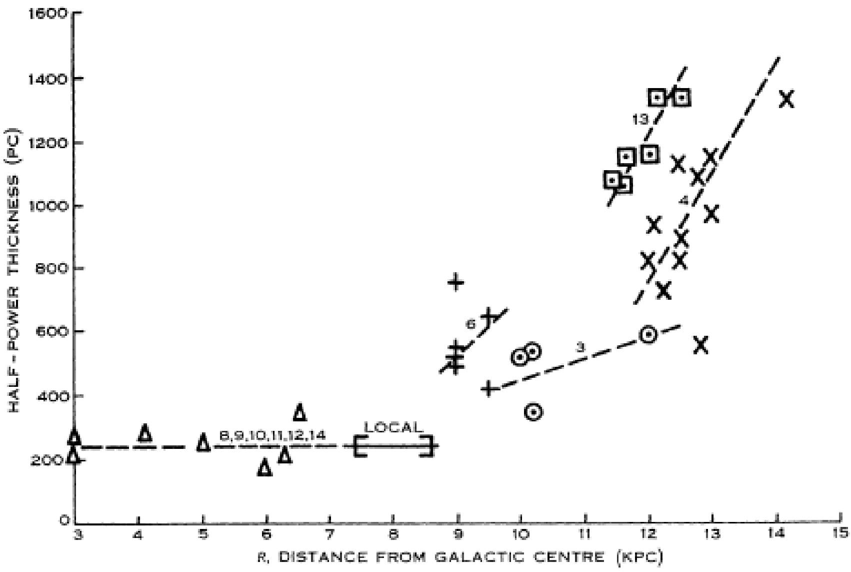


Figure 241: HI Cloud thickness at half-power points plotted as a function of distance from the galactic centre. The different symbols and associated numbers refer to the groups of observations. The triangles are from within the solar orbit. The other represents the four different spiral arms (after McGee and Milton, 1964: 152).

The third paper was the final paper in the series on the Murraybank H-line galactic survey. McGee also co-authored a paper (Howard et al., 1963) that used the Murraybank data for a study of the correlation between radial velocities of optical Ca II line and H-line observations.

The next step for the Murraybank program was a trial of a new digital recording system. For this purpose it was decided to conduct a survey of the Magellanic Clouds to test the recording system prior to its use at Parkes. This survey was conducted in late 1960. For this work McGee was joined by Jim Hindman from Potts Hill. By this time Murray had moved to the Netherlands and was working on the construction of the Benelux Cross.

The introduction of digital recording and data reduction was the first time that Radiophysics had used a digital computer in this role. The Murraybank team consisted of Hindman, McGee, Alan Carter, Eric Holmes and Maston Beard. The survey of the Magellanic Clouds was chosen as it represented a self-contained project, but with the increased sensitivity of the 48-channel receiver also provided a worthwhile extension of the earlier Potts Hill work by Kerr, Hindman and Robinson (1954).

The low resolution survey of the Magellanic Clouds proved extremely successful, not only demonstrating the value of the digital recording and computer based reduction techniques, but also resulting in two major discoveries about the Magellanic Cloud system. Two papers on the survey were published in the *Australian Journal of Physics* (Hindman et al., 1963a; Hindman et al., 1963b). The first of these covered the observations and a description of the digital recording technique, reduction procedure and equipment. The second paper provided an interpretation of the results. This paper was the first research effort that formally bought together the Potts Hill and Murraybank H-line teams prior to the move to Parkes.

The first of the major discoveries produced by the Murraybank survey is clearly evident in the contour diagram of integrated brightness of the neutral hydrogen in the Magellanic system (Figure 242).

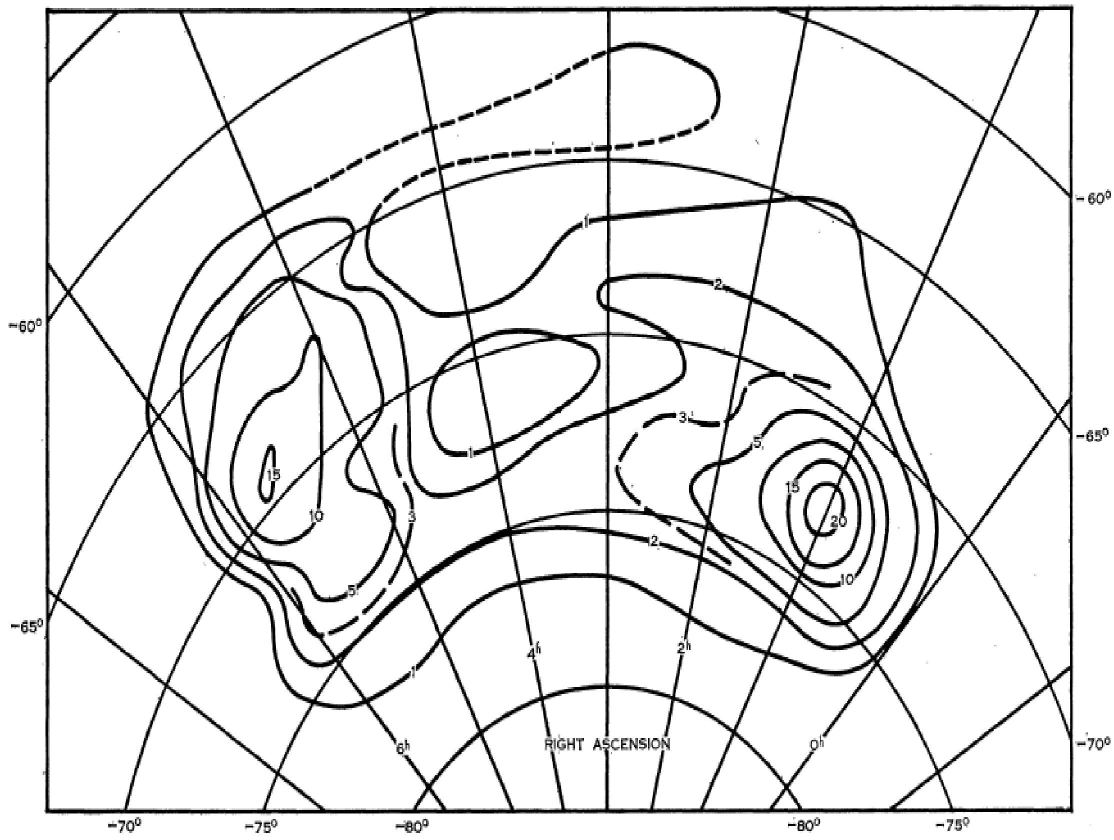


Figure 242: The contours of integrated brightness of neutral hydrogen in the Magellanic System from the Murraybank survey. The contour units = $2 \times 10^{-16}$ $Wm^{-2}$ $sr^{-1}$ (after Hindman et al., 1963a: 572).

The brightness distribution showed that the two Clouds were joined by a bridge of neutral hydrogen gas, and that they were also within a common envelope of this gas. This detection was made possible by the increased sensitivity of the Murraybank receiver, coupled with the effect of digital integration which raised the sensitivity to a level where the low density region between the clouds could be detected. The system was estimated to be some three times more sensitive than the Potts Hill equipment. The team ruled out the possibility that the effect was caused by overlapping clouds in the line-of-sight at different distances by observing the continuity of the general radial velocity gradient across the cloud system. Although the observations had no sign of a link between the Magellanic Clouds and the Galaxy, the team noted:

> "Such a link would, however, be quite difficult to detect, because it would probably be spread widely on the sky and in velocity, and a different observing technique would be desirable in searching for it." (Hindman et al., 1963a: 577).

With the benefit of hindsight this statement proved insightful, with the Magellanic Stream (Figure 243) being discovered by a team, including Murray, using observations from Parkes (Mathewson et al., 1974). HI velocity anomalies near the South Galactic Pole had been noted as early as 1965 (Deiter, 1965) and subsequently van Kuilenburg (1972) and Wannier and Wrixon (1972) noted a large area of HI emission, but it was Mathewson et al. who recognised its full extent and associated the stream with the Magellanic Clouds. De Vaucouleurs (1954a,b) had been the first to propose a link between the Magellanic Clouds and our Galaxy some twenty years before the discovery of the stream. More recent studies (McClure-Griffiths et al., 2008) have shown that the leading arm of the stream is intersecting the Galactic disk approximately 21 kpc from Earth at a point in the sky near the Southern Cross.

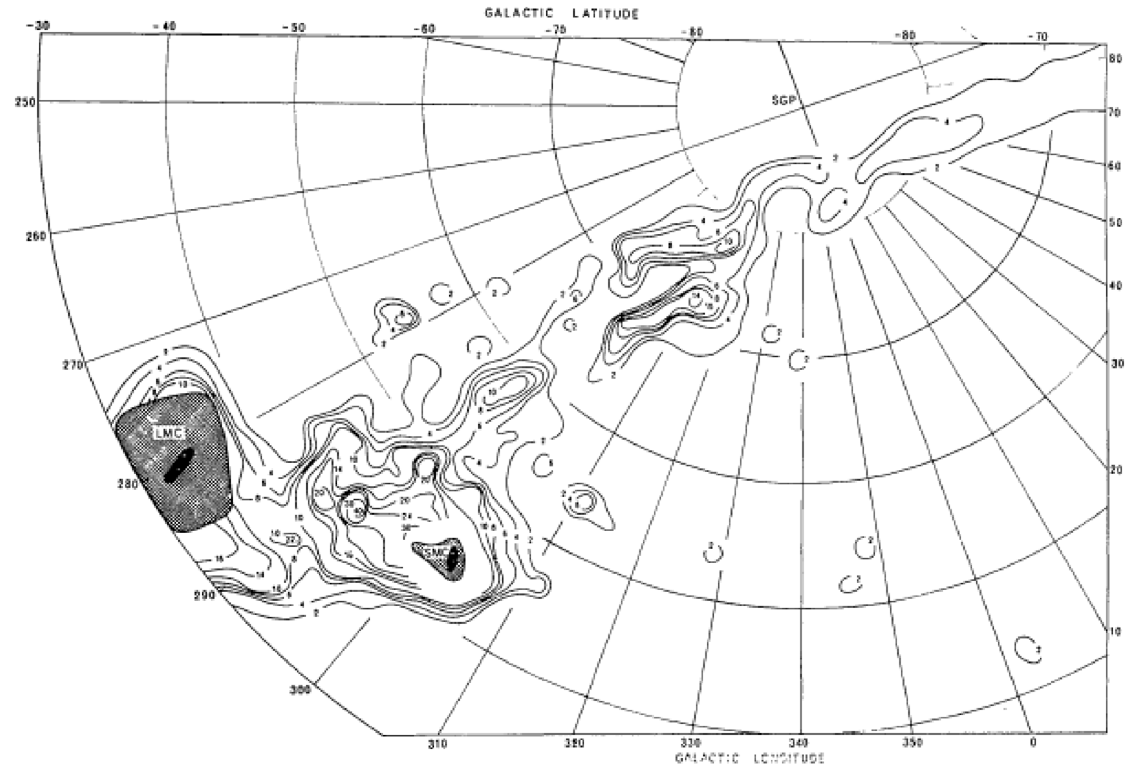


Figure 243: Contours of surface density of neutral hydrogen from Parkes 18-m (ex-Kennedy dish). The Magellanic Stream is seen extending from the Magellanic Clouds (left) across the sky (after Mathewson et al., 1974: Plate 6).

Using Wild’s (1952) method for estimating the number of atoms in a line-of-sight column of optically thin gas, the team was able to estimate the following masses of neutral hydrogen:

| | Solar Masses |
|---|---|
| Large Cloud (inside contour 3, Figure 242) | $3.2 \times 10^8$ |
| Small Could (inside contour 3, Figure 242) | $2.8 \times 10^8$ |
| Whole Magellanic System | $1 \times 10^9$ |

A comparison was made between the neutral hydrogen distribution and the distribution of HII regions (Henize, 1956), globular clusters (Hodge, 1960, 1961), SMC Clusters (Lindsay, 1958) and SMC emission-line objects (Lindsay, 1961). No significant conclusion could be drawn from these comparisons other than that all the objects tended to concentrate in the main bodies of the Clouds.

Based on the observations, a rotation curve for the Large Cloud was derived (Figure 244). This curve was largely similar to the findings of the earlier survey by Kerr et.al. (1954). No clear curve could be derived for the Small Cloud.

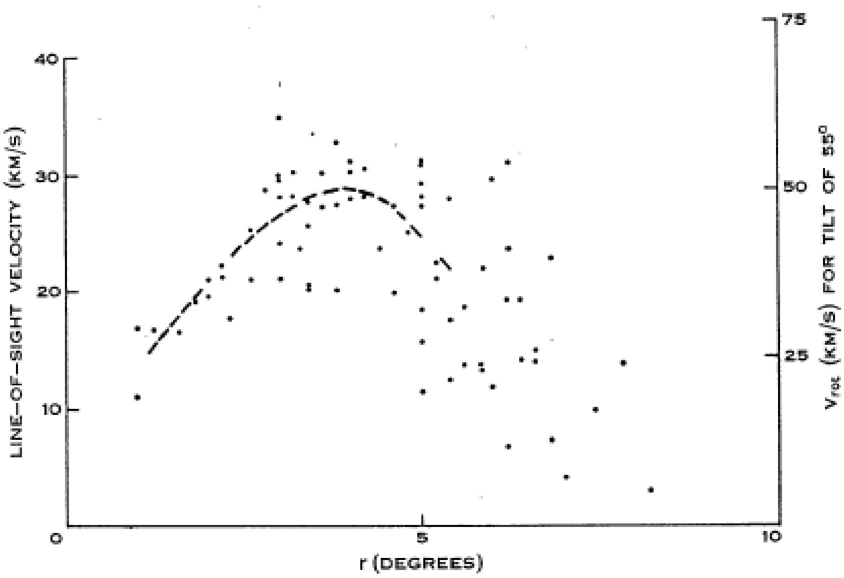


Figure 244: The rotation curve for the LMC derived from median velocities of neutral hydrogen profiles. The centre of rotation was R.A. 05:25, Dec. -68º (1960). The position angle of major axis: 5º-185º. A tilt of 55º was assumed. Note that both sides of the curve are plotted together (after Hindman et al., 1963a: 580).

Based on this rotation curve a mass estimate for the Large Cloud was found to be in the range 7-10 × $10^9$ solar masses. Note this is a factor of 10 larger than the mass derived from Wild's method and could have been another of the early clues to the "missing mass problem" generally identified with galaxies and examined in detail in the late 1960s (e.g. see Freeman, 1970; Rubin and Ford, 1970).

The second major discovery came from the radial velocity measurements of the Small Magellanic Cloud. Figure 245 shows the contours of median radial velocity of the neutral hydrogen profiles from the Magellanic System that has been corrected for both the motion of the Earth's orbit and the Sun's orbit about the Galaxy.

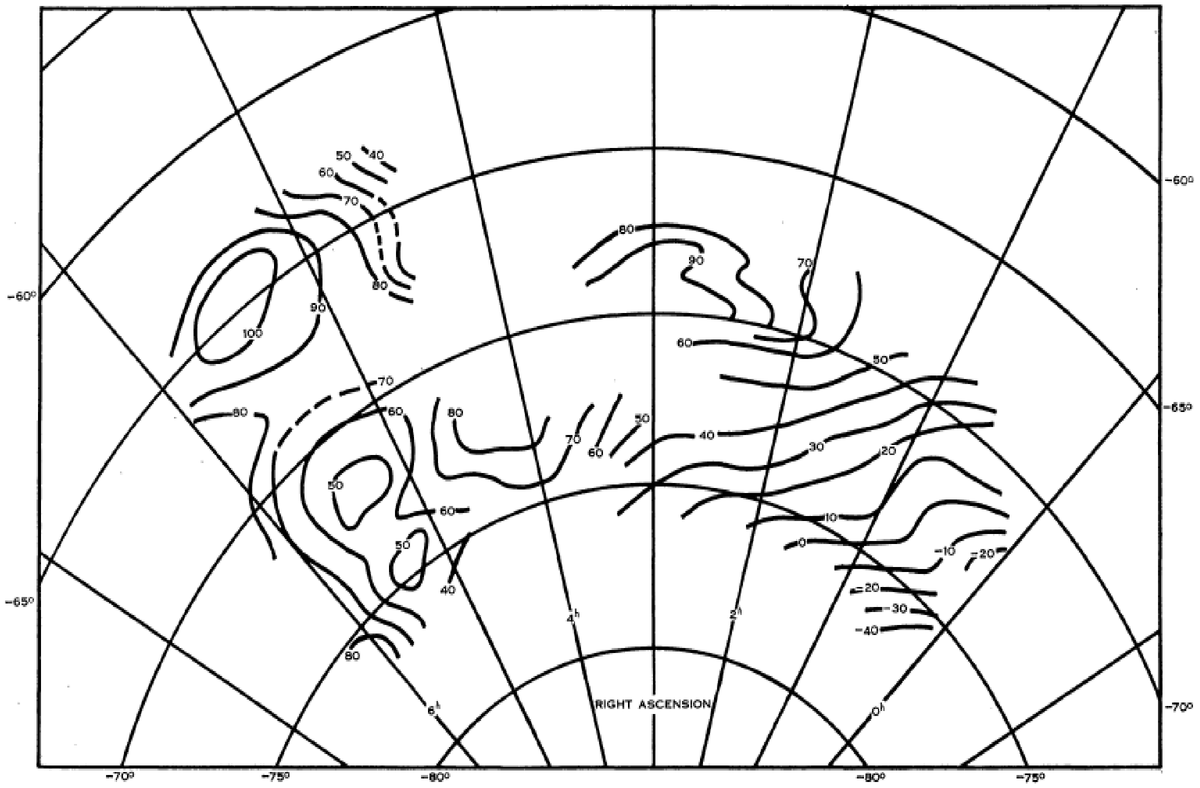


Figure 245: The contours of median radial velocity of the Magellanic System. The contour interval is 10 Km/s (after Hindman et al., 1963a: 579).

To allow for correction due to the Sun's orbital velocity, a rotational velocity of 216 km/s was assumed. This value was adopted to simplify comparison to the earlier survey which used this value. By this time evidence was building for a much higher value (i.e. 300 km/s by de Vaucouleurs, (1961)).

Figure 246 and Figure 247 show a summary of H-line profiles for the Large and Small Clouds respectively. The Small Cloud shows large areas where double-peaked line profiles are evident. The double-peak nature of some of the Small Magellanic Cloud line profiles had previously been noted by Johnson (1961) based on an examination of the original survey data from Kerr et al. (1954), although few conclusions could be drawn due to the quality of these records.

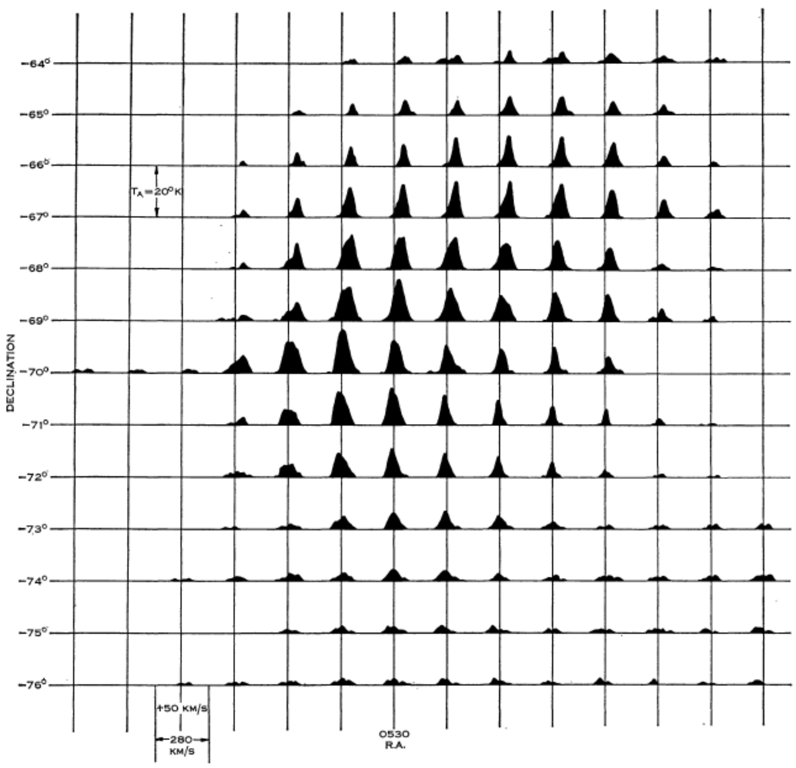


Figure 246: Line profile per square degree of sky from the LMC. The vertical line on each profile is +50 km/s (after Hindman et al., 1963b: 568).

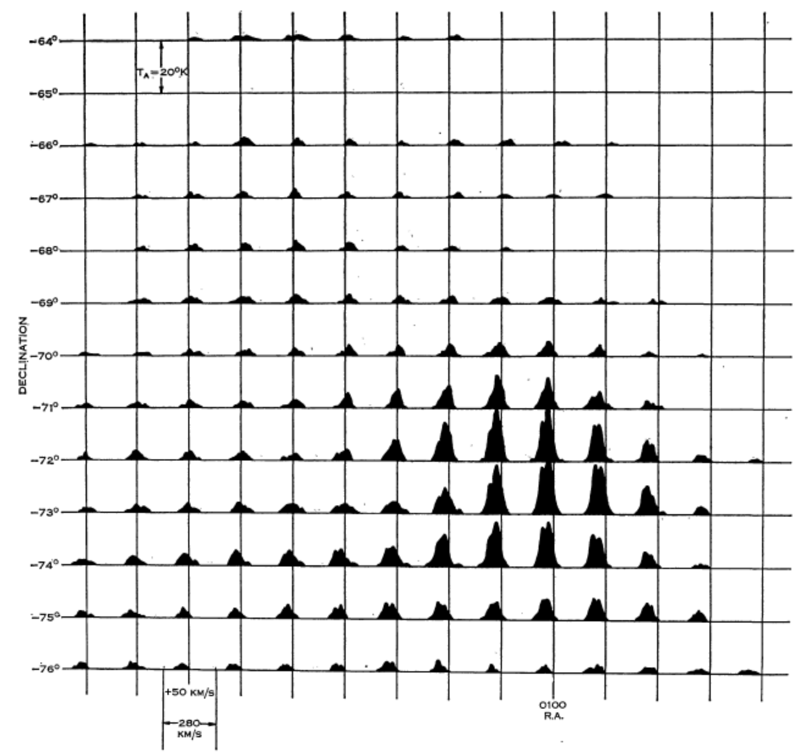


Figure 247: Line profile per square degree of sky from the SMC. The vertical line on each profile is +50 km/s. Note the large area of double-peaks. (after Hindman et al., 1963b: 568).

The splitting of the H-line profiles into two distinct groups is best illustrated in Figure 248. The difference between peaks is consistently between 25-30 km/s over a large area. This "splitting" of the Small Magellanic Cloud had not been observed in any other optical or radio observations before this time.

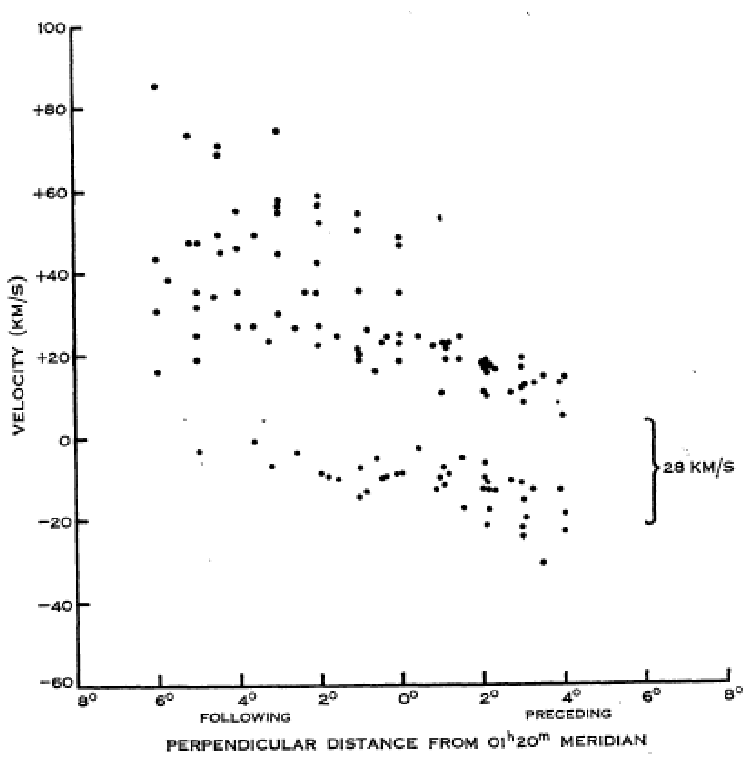


Figure 248: Velocities of the main peaks of neutral hydrogen in the SMC showing the systematic separation into two groups separated consistently by ~28 km/s (after Hindman et al., 1963a: 581).

Many years later the 'splitting' of the Small Cloud was seen as providing an important clue to the origin of the Magellanic Stream. Mathewson et al. (1987) found that by integrating backward in time, the Small Cloud could have collided with the Large Cloud ~4 $\times 10^8$ years ago. This could mean that the Stream originated from this collision and the split of the Small Cloud indicated it was breaking up following the interaction with the Large Cloud.

Over the period 1962 to 1964, Hindman (1967) used the 64-m Parkes telescope together with the Murraybank multi-channel receiver for a high resolution (~15 arc seconds at 1,420 MHz) survey of the Small Magellanic Cloud. At this much higher resolution, Hindman concluded that the double-peaked profiles that had earlier been observed were related to at least three broad structural features which may represent expanding shells of gas within the main body of the cloud, which itself appeared to be a flattened system, rotating in a plane observed near edge-on to the observer. This conclusion was supported some years later when data from Parkes and the Australia Telescope Compact Array were combined in a detailed study of the Small Magellanic Cloud (Stanimirovic et al., 1999).