OBSERVATIONS OF THE 21 CM LINE FROM THE MAGELLANIC CLOUDS

By F. J. Kerr,* J. V. Hindman,* and B. J. Robinson*

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Summary

A survey has been made of the 21 cm line from neutral interstellar hydrogen in the Magellanic Clouds. These are the first observations of this radiation from an extragalactic source.

The observations show that neutral hydrogen extends well beyond the easily visible regions of each Cloud, the gas being in each case less concentrated towards the nucleus than are the bright stars. From the total radiation received, the masses of neutral hydrogen are calculated to be 6×10^8 and 4×10^8 solar masses for the Large and Small Cloud respectively. Since the Small Cloud is believed to contain much less dust, this means that the ratio of gas to dust is very different in the two systems.

The measurement of Doppler frequency shifts has yielded extensive new information about radial velocities within the Clouds. The velocity distribution indicates that both Clouds are rotating. Detailed discussion of the velocities has been deferred for subsequent publication.

I. Introduction

The prediction (van de Hulst 1945) and subsequent detection (Ewen and Purcell 1951) of a radio-frequency line in the spectrum of interstellar hydrogen have opened up new possibilities in astronomical exploration. Extensive observations of 21 cm line radiation from the Galaxy have been reported by Christiansen and Hindman (1952) and van de Hulst (1953). This paper describes the first observations of the line from an extragalactic source.

Besides its immediate value in revealing the existence and some of the physical properties of the interstellar gas, this line radiation shares with the continuous spectrum radio-frequency radiation the ability to penetrate the clouds of interstellar dust which severely limit visibility in optical astronomy. In addition, it has the important advantage that it is a discrete line, so that recognizable frequency displacements are produced by the motions of the emitting gas. It thus combines for the first time in astronomy the " seeing power " of the radio wave with the possibility of measuring the (radial) velocities of the source regions. Hence both the motions and the distribution of gas in a large volume of space can be studied.

The radio observations do not by themselves provide sufficient information to deduce three-dimensional structure, because distance cannot be measured directly. It can in some cases, however, be inferred from other evidence.

* Division of Radiophysics, C.S.I.R.O., University Grounds, Sydney.

For instance, the systematic nature of galactic rotation effects has been used for this purpose by the Leiden group (van de Hulst 1953) to locate portion of the spiral structure of the Galaxy. For an external galaxy, there is the important simplification that all parts of the system are at substantially the same distance. Thus a low-resolution two-dimensional picture can be derived directly, and to some extent the details of the line profile can provide information about the distribution of the gas in depth.

The Magellanic Clouds, the nearest extragalactic systems, are specially suitable for study. They are sufficiently far away to be viewed as isolated systems, and yet are sufficiently near for their internal structure to be discerned in some detail. Studies of the Clouds have been very important in the development of optical astronomy.

An exploratory survey has been made over the region of the sky containing the Clouds.* The 21 cm line has been detected from each Cloud over a large area extending well beyond its previously known limits. Values have been derived for the total mass of neutral hydrogen in each Cloud, and information obtained about the two-dimensional distributions of intensity and velocity. The preliminary results indicate that observations of this line will be able to provide a detailed picture of the structure and dynamics of the Clouds, leading to a number of important inferences concerning galaxies of this type.

The present results are preliminary in character. They were obtained with a new type of receiver at present under development, and it should be possible to carry out a more complete and precise survey before long. Consequently, the scope of this paper is limited to the presentation of broad overall results, together with some discussion of the type of information which could be derived from more extensive data.

II. Receiving Technique

(a) *Equipment*

The energy received from any given direction is dispersed over a finite frequency band (typically $\frac{1}{4}$–$\frac{1}{2}$ Mc/s), owing to random and systematic motions of the gas. Thus both the frequency distribution and intensity of line radiation vary across the sky.

In the usual method of observing the line, the receiver frequency is swept slowly over an appropriate band. At the same time, the receiver is switched rapidly between two adjacent frequencies. This produces a modulated signal which is independent of the background radiation, and minimizes changes of zero level arising from gain variations. Since the intensity is very low, the output must be integrated over a period of time to reduce the noise fluctuations. In consequence, the frequency must be swept slowly.

A new receiving technique, which was proposed by Dr. J. L. Pawsey, is at present under development. In this system, the frequency-sweeping method is replaced by a fixed-frequency system, in which the output of a broad-band

* An account of this survey was presented to a meeting of the American Astronomical Society, held at Boulder, Colorado, in August 1953 (abstract, Kerr and Hindman 1953).

intermediate-frequency channel is analysed by filtering it through a number of parallel narrow-band channels, tuned to different frequencies across the range of interest. The outputs of these channels can all be displayed simultaneously, so that a picture of the whole frequency profile can be obtained in a single integration period. The suppression of zero-level variations and removal of the background are in this case effected by comparing the mean noise level from each narrow-band channel with that in the full receiver bandwidth.

Preliminary tests of the principles involved in this receiver are being carried out with a limited number of channels. The observations described in this paper were made for the most part with a single narrow channel of 40 kc/s bandwidth.

The use of this type of receiver leads to a different method of sweeping over the relevant coordinates. With the usual technique, the aerial follows a fixed point in the sky, while the receiver is swept slowly over the appropriate frequency range, thus tracing out the line profile at that point. The distribution over the sky is then obtained by fitting together a series of these profiles.

In the new system, the aerial remains in a fixed position, a continuous record being obtained at a constant frequency as the sky moves past the aerial beam. In the current observations, line profiles are derived by fitting together a series of these constant-frequency records. The later system will give a simultaneous output at a large number of separate frequencies, yielding the line profile directly as a function of position in the sky.

The parabolic aerial which is being used in this work is shown in Plate I. It has a diameter of 36 ft, and is mounted on an east-west axis as a transit instrument. The beam width between half-power points is 1·0°. This may be taken as the angular resolution of the equipment.

The resolution in frequency is also an important parameter. This depends on the bandwidth of the narrow channel, 40 kc/s, corresponding to a velocity spread of 9 km/s.

(b) *Method of Measurement*

An individual observation involves the measurement of a brightness temperature for a given region of the sky and a given frequency (or velocity). The methods used in measuring the brightness temperature, the direction of the aerial beam, and the frequency will be discussed in turn.

(i) *Brightness Temperature*.—The noise fluctuations appearing in the receiver output have been used as a means of calibrating the output scale in terms of aerial temperature. For a receiver of the type described above, the temperature change, ΔT, which corresponds to the r.m.s. noise fluctuation, is related to the noise factor by the expression

$$\Delta T=\frac{2^{\frac{1}{2}}(N-1)T_0}{(\tau B_c)^{\frac{1}{2}}},$$

where N is the noise factor for the continuous spectrum, T_0 the ambient temperature, τ the output time constant, and B_c the bandwidth of a single narrow channel. When the total receiver bandwidth is much greater than B_c, the noise arising in the wide comparison band can be neglected in comparison with that due to the narrow band.

The derivation of the above equation, and its relation to the corresponding equations for the systems used by Dicke (1946) and by Ewen and Purcell (1951) will be given in a later paper.

The noise factor of the receiver was measured by means of a gas-discharge noise generator, whose characteristics had been checked against the standards established at a wavelength of 10 cm by the Division of Electrotechnology, C.S.I.R.O.

During the observations described in this paper, the receiver parameters were $N=6$, $\tau=15$ sec, $B_c=40$ kc/s, giving a calculated temperature fluctuation of 2·4 °K. Some unwanted slow variations were, however, superposed on the noise fluctuations, reducing the effective receiver sensitivity. For calibration a smaller value of τ was used in order to generate larger noise fluctuations, comparable in amplitude with the observed signals. Use of the larger calibrating signal also minimized errors arising from receiver instability. During the observations, a relative zero point was established at frequent intervals throughout each run by moving to the south celestial pole. At the frequencies used for observation of the Magellanic Clouds, the radiation in the polar region is negligibly small.

Since the mixer and 30 Mc/s preamplifier were mounted at the aerial feed point, it was not convenient to measure the receiver noise factor at frequent intervals. The relative sensitivity of the receiver was therefore checked after each day's run by observing the intensities at a number of points near the galactic plane.

In deriving temperatures by the procedure outlined above, there are two types of uncertainty. The percentage error of the scale calibration is about ±20 per cent. Relative values are, however, mainly affected by the uncertainty of the zero level. In this case the estimated probable error is ±3 °K.

All values quoted refer to the " aerial temperature ", and the small correction to allow for losses in the aerial and reception from directions other than that of the main beam has not yet been determined.

Temperatures measured in the differential output of the receiver are subject to a further correction. The wide channel in the present equipment has a bandwidth of only 1·7 Mc/s, so that the presence of line radiation will produce a small increase in the wide-band output in addition to the increase in the narrow-band output. This effect must be allowed for in deriving the " true " profile.

(ii) *Direction of Aerial Beam*.—The declination scale, which was attached to the mechanical axis of the aerial, was set by making radio observations of the Sun. If the aerial structure maintains the same shape in all positions, such a single-point calibration will suffice for all declinations. It was found however that structural distortions in the framework and in the feed support resulted in directional errors of up to 1°. Such errors are of course serious for a 1° beam. Two types of measurement were made to determine the distortion. Firstly, the transit of stars at various declinations was observed visually, using a small telescope rigidly attached to a point on the aerial framework. Secondly, direct measurements were made of the relative movements occurring during rotation of the aerial, by sighting with a telescope from one part of the moving structure to another.

The indicated declinations were corrected according to the results of these measurements. There may still, however, be small systematic errors in both declination and Right Ascension.

(iii) *Frequency*.—The receiver is of superheterodyne type with a double frequency change. A simplified block diagram is shown in Figure 1. The first intermediate-frequency channel is at 30 Mc/s, the second at 7 Mc/s. The overall bandwidth is 1·7 Mc/s, and a portion of this, 40 kc/s wide, is selected

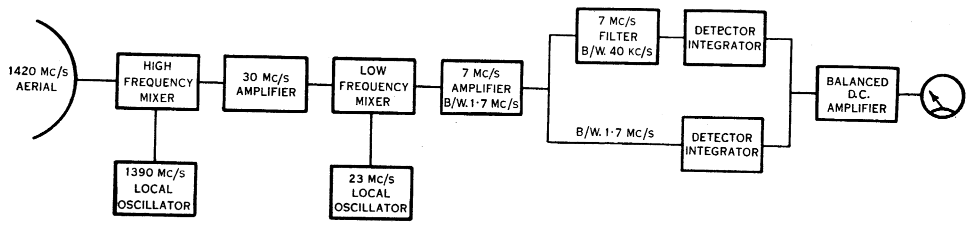


Fig. 1.—Block diagram of receiver.

by the narrow-band filter. Although normally fixed, the operating frequency of the receiver can be varied over a range of several megacycles per second by tuning the first local oscillator, whose frequency is approximately 1390 Mc/s. This frequency is derived from a temperature-stabilized self-excited oscillator operating at 5·7 Mc/s.

Measurement of the receiver frequency involves measurement of its three components, the frequencies of the two local oscillators (1390 Mc/s and 23 Mc/s) and the narrow-band filter (7 Mc/s). With an overall passband of 40 kc/s, an accuracy of several kilocycles per second is required in each case. Thus only the first of the three measurements offers any difficulty. The method adopted makes use of a crystal-controlled oscillator (occasionally checked against WWV) as a local reference standard, to set the self-excited oscillator controlling the first injection frequency.

The latter frequency is determined by a measurement of the audible beat note between these two oscillators. A convenient arrangement is to adjust the various frequencies involved to give zero beat when the receiver frequency corresponds to zero radial velocity (1420·405 Mc/s). Then, for other settings of the receiver, the beat note is a direct measure of the radial velocity at which observations are being made.

III. Observational Results

(a) *Method of Scanning*

In each run, the receiver was kept on a constant frequency and observations made as the sky moved past the aerial beam. Since the motion is quite slow near the pole, relative to the beam width, it was possible to vary the declination in steps throughout each run. The result of each run was therefore a map showing the brightness distribution over one or both Clouds at a single frequency, that is, the distribution of the radiation from that part of the gas which is moving with a particular radial velocity. Figure 2 shows in contour form some samples of these maps for the Small Cloud.* The series illustrates the striking change in the appearance of the Cloud for different radial velocities. The values of radial velocity have been referred to the Sun.

In these observations, the galactic foreground makes no contribution in the frequency range of interest ; the great difference in radial velocity completely separates the radiation from the Clouds and the Galaxy.

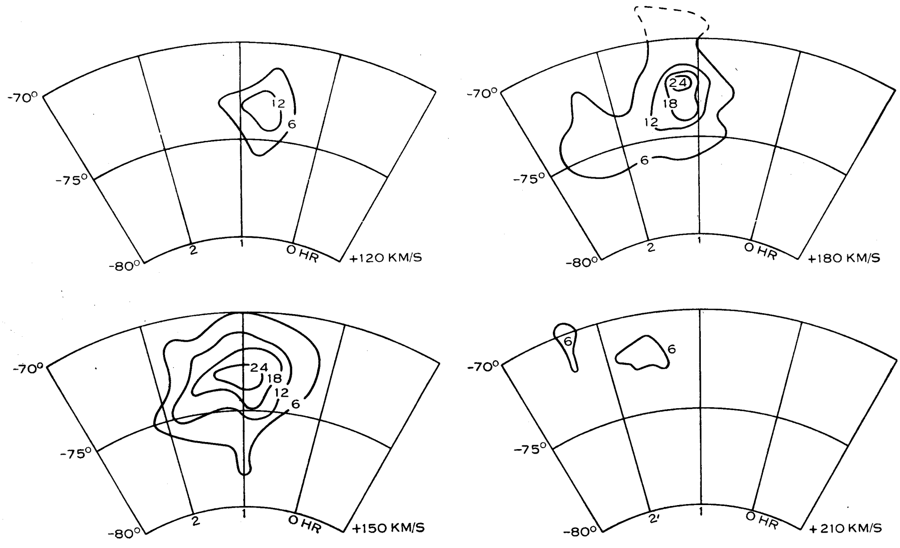


Fig. 2.—Distribution of brightness temperature over the Small Cloud at four radial velocities. (Unit = 1 °K.)

(b) *Line Profiles*

From a set of maps of this type, line profiles were drawn for 250 points of a lattice, spaced 1° in declination and 10 min in Right Ascension. A number of sample profiles are shown in Figure 3,* indicating the main features of the variation over the Small Cloud.

It can be seen that the brightness temperatures are in all cases low. The highest value observed is about 30 °K, a quarter of the peak brightness temperature at the galactic anticentre.

The group of profiles illustrates the progressive change of velocity across the Clouds, and also shows the different shapes which were obtained. The profiles are fairly smooth and symmetrical over a small region in the immediate centre of the Small Cloud, but elsewhere are generally complex. They are in

* The correction for the contribution of the line to the wide-band output has not been applied in these two figures. The true profiles will be very similar in shape, but the brightness temperatures and linewidths should both be increased by about 15 per cent.

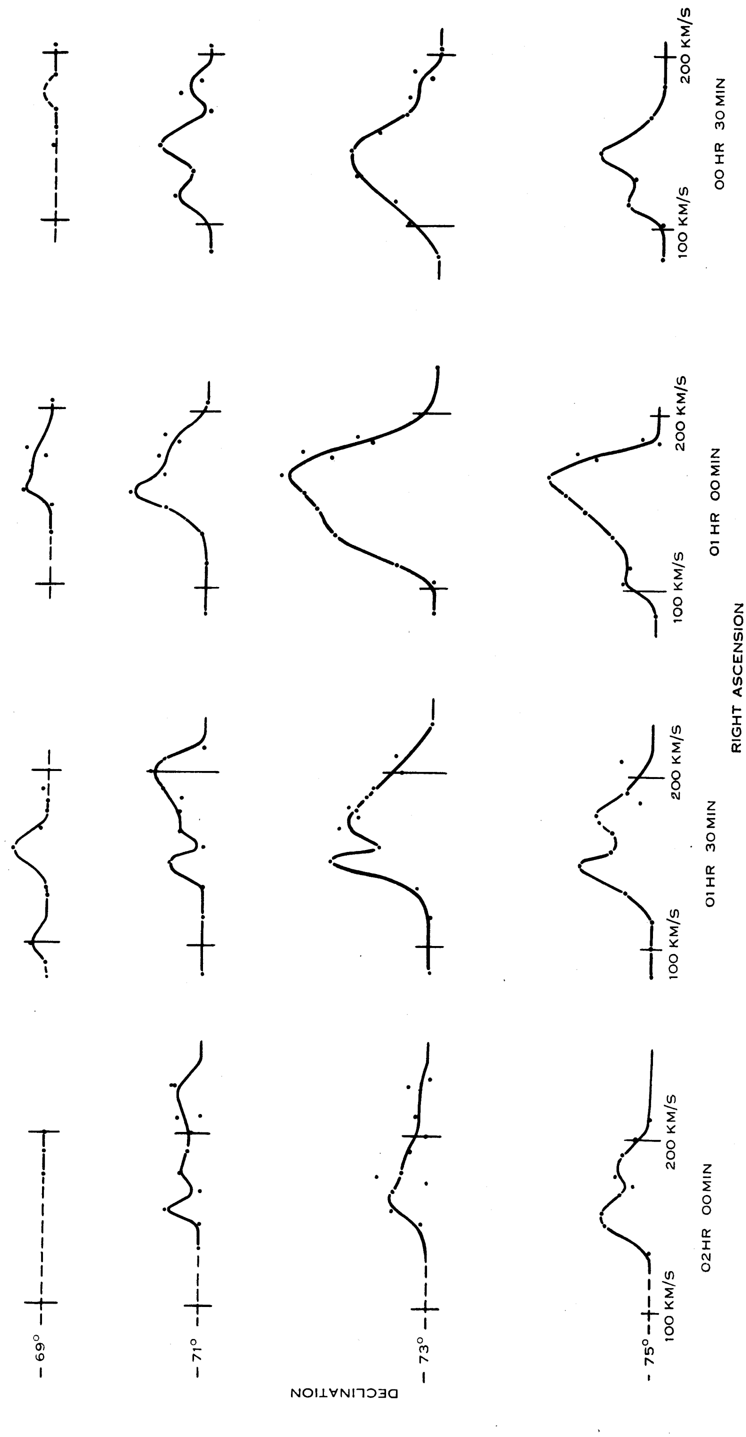


Fig. 3.—Samples of the line profiles obtained for the Small Cloud. The maximum value of the brightness temperature is 30 °K.

general more irregular for the Large Cloud than for the Small Cloud, presumably indicating a greater degree of fine structure in the space distribution.

The linewidths, between half-power points, average about 250 kc/s, corresponding to a velocity spread of 50 km/s. There is no great variation in the linewidth over the region of the Clouds, but the average width for the Small Cloud is a little greater than that for the Large Cloud.

In this paper we have neglected the fine details shown by some of the profiles. The conclusions presented are based on the broader features, as specified by two quantities, " integrated brightness " and " mean radial velocity ", defined below.

(*c*) *Contours of Integrated Brightness*

The total energy received from a particular direction can be measured in terms of the area under the line profile. This quantity, which corresponds to the " integrated intensity " of optical spectroscopy, we call integrated brightness. In conformity with the general system of units used in radio astronomy, the integrated brightness, $B_{\text{int.}}$, is defined here as

$$B_{\text{int.}}=\frac{2k}{\lambda^2}\int T_\nu \mathrm{d}\nu,$$

where the factor 2 covers the two polarizations of the total radiation, and k is Boltzmann's constant, λ the wavelength, T_ν the brightness temperature, and ν the frequency. The m.k.s. unit is the watt(metre)$^{-2}$(steradian)$^{-1}$. For example, a brightness temperature of 10 °K over a frequency range of 200 kc/s gives $B_{\text{int.}}=12\times10^{-16}$ W m^{-2} sterad^{-1}.

A diagram showing the contours of integrated brightness is given in Plate 2, Figure 1, where the contour interval is 7×10^{-16} W m^{-2} sterad^{-1}. The values have been increased by 35 per cent. to allow for the contribution of the line to the wide-band output. A dashed line is also included in the figure to indicate the approximate outer limits from which radiation could be detected with the present sensitivity. The limiting factor in these observations was the uncertainty in the position of the zero level.

(*d*) *Contours of Radial Velocity*

The mean radial velocity for each profile is defined in the sense of the weighted mean, as the velocity for which the ordinate halves the area under the profile. Contours of mean radial velocity, in kilometres per second, are given in Plate 2, Figures 3 and 4. Positive values of radial velocity indicate recession.

The velocities are least accurate where the radiation is very weak. These contours are restricted to the region in which the integrated brightness exceeds 7×10^{-16} W m^{-2} sterad^{-1}.

IV. The Magellanic Clouds

Before discussing the radio observations we shall briefly review the results of optical studies of the Clouds.

The Magellanic Clouds are the nearest external galaxies. Subtending angles of several degrees, they are prominent features of the southern sky, but are invisible from the greater part of the northern hemisphere. The mean of several recent determinations of their distance (Gum and de Vaucouleurs 1953 ; Shapley 1953 ; Thackeray and Wesselink 1953 ; Shapley and Nail 1954) is 46 kpc, in the new cosmic distance scale.* The two Clouds appear to be at practically the same distance from the Sun, to within the observational uncertainty.

The distances of all other members of the local group of galaxies are considerably greater than this. Hence the two Clouds and the Galaxy appear to form a close group of their own. The Clouds have in fact often been referred to as " satellites " of our Galaxy. de Vaucouleurs (1954) has collected evidence suggesting the existence of a connexion between the Large Cloud and the Galaxy. This would be analogous to the cases reported recently by Zwicky (1953), in which filaments of intergalactic matter connect neighbour members in pairs or groups of galaxies.

A photograph of the Clouds is shown in Plate 2, Figure 2. The Large Cloud has a central elongated section, known as the " axis ", surrounded by a number of irregularly situated luminous patches. The small Cloud is more concentrated into a single body, but it too shows some irregularities of structure.

To the unaided eye, the diameters of the Large and Small Clouds are approximately 7 and $3\frac{1}{2}°$. Microdensitometer studies and star counts have considerably extended the recognized dimensions of the Clouds. Shapley and Mohr (1932) obtained 12 and 8° respectively for the diameters averaged over all position angles. The outer isophotes of the Large Cloud are reasonably smooth, but those of the Small Cloud show an extension or " wing " towards the Large Cloud. Shapley (1940) showed from star counts that this feature is at least 1·5° in width (in declination), and extends 3 or 4° in Right Ascension to a distance of 6·5° from the centre of the Small Cloud, that is, one-third of the way to the centre of the Large Cloud. Star counts by McCuskey (1935) confirmed the increased dimensions of the Large Cloud. He obtained a mean diameter of 11°, and this has recently been extended to 20° by de Vaucouleurs (1954).

Holmberg (1952) has made estimates of the masses of the Clouds. His values, reduced to the new distance scale, are as follows : for the Large Cloud, 2×10^9 solar masses as derived from the velocity dispersion of nebulae observed by Wilson (1917), and $2 \cdot 5 \times 10^9$ solar masses from the estimated mass/luminosity ratio for a type I population and the Shapley-Ames magnitude ; for the Small Cloud, by the latter method, 6×10^8 solar masses. These values must, however, all be taken as rather uncertain.

In the standard classification of galaxies, the Magellanic Clouds are the typical examples of a class of irregular galaxies, which comprises about half of the systems classified as " irregular ". H. C. Russell (1890) first reported evidence of spiral structure in the Clouds. Shapley (1931, 1950) described similarities in the Large Cloud and the barred spirals, but he considered that the evidence was not yet clear as to whether the Clouds are flattened or spherical.

* As recently revised, following the discussion presented by Baade at the Rome Assembly of the International Astronomical Union, September 1952.

A more detailed study has been made by de Vaucouleurs (1954) from star counts and multiply printed photographs. He has been able to show the existence of an extensive spiral structure in the outer parts of the Large Cloud. From the shape of the intermediate and outer isophotes, he suggested that both Clouds are flattened systems with different inclinations to the line of sight. The Large Cloud appears to have an inclination of 65°, with its major axis in position angles* 160–340°, the Small Cloud an inclination of 35°, and major axis in position angles 40–220°.

The stellar population types of the Clouds have been the subject of considerable recent discussion. Baade (1950) has given the Large Cloud as an example of a system with a population of pure type I. Thackeray and Wesselink (1953) have shown, however, that it contains some variables which belong to type II. It is therefore not of pure type I, but appears to be predominantly so—its colour is that of a type I system.

Shapley (1950 and personal communication) has pointed out that the Small Cloud approaches in character the irregular dwarf galaxies and it may be evolving towards the spheroidal type of galaxy, that is, it may be more developed towards one of the Population II subdivisions than is the Large Cloud. Gascoigne and Kron (1953), from colour measurements of the Clouds and some of their variables, concluded that the Small Cloud might be predominantly of type II. Gascoigne (personal communication) now considers that further measurements suggest that this view should be substantially modified, and that the Small Cloud appears to differ in important respects from both Population I and Population II. Shapley (1950) suggests that the population of the Small Cloud, at its centre, may be intermediate between Populations I and II.

The dust content of the two Clouds appears to be very different. Photographs show many more dark patches in the Large Cloud than in the Small Cloud. Shapley (1951) has made counts of the numbers of distant galaxies visible through various parts of the Clouds, and finds that the Small Cloud is essentially transparent, whereas the Large Cloud contains a considerable amount of obscuring dust. He points out, however, (personal communication) that, while the Large Cloud undoubtedly contains more dust, no quantitative comparison is possible because of irregularities in the distribution of the faint galaxies themselves. In particular, there is probably some obscuration in a small region at the centre of the Small Cloud. Recent colour measurements of B stars and cepheids by Gascoigne (personal communication) do not support the presence of appreciable quantities of dust in the Small Cloud ; they cannot be said, however, definitely to exclude this possibility.

Ionized hydrogen is known to be present in both Clouds. Studies of emission nebulosities have been reported by Henize and Miller (1950) for both Clouds, and by Shapley and Wilson (1925) and Nail, Whitney, and Wade (1953) for the Small Cloud. Hydrogen emission appears to be more prominent in the case of the Large Cloud.

* The position angle is the inclination to the hour circle passing through the centre of the object, measured from north towards east.

In addition, the H and K lines of interstellar calcium in the Large Cloud have recently been observed by Feast (1953) in the light of S Dor, the brightest star in the Cloud. This is the first observation of absorption by interstellar gas in an extragalactic system.

The information available from optical sources about the motions of the Clouds is scanty. So far, radial velocities have been measured for only 17 bright nebulae in the Large Cloud, and one in the small Cloud (Wilson 1917). The values obtained are in the range +251 to +309 km/s in the Large Cloud, and +168 km/s in the Small Cloud. Proper motions have not yet been measurable.

Wilson examined the radial velocities for evidence of rotation of the Large Cloud, but the data were too few for a clear result. Hertzsprung (1920) then suggested that the data could be interpreted more simply as indicating a translational motion of the two Clouds through space. A more recent analysis has been made by Wilson (1944), leading to a suggested space motion of about 550 km/s.

There are still many gaps in present knowledge and the solution of some pressing problems requires more data. Radio and optical observations are to a great extent complementary. It seems likely that the detailed data of both types, which can be expected in the near future, should lead to a much better understanding of the two systems.

V. Discussion of the Brightness Observations

We can now discuss the current radio observations in the light of the present optical knowledge of the Clouds. Since this is a preliminary survey, the discussion will largely indicate the type of information which radio studies can provide, rather than derive final results.

(a) *The Size of the Clouds*

The most striking aspect of the brightness contour diagram (Plate 2, Fig. 1) is the large size of the Clouds, in comparison with the size of the easily visible regions (see Plate 2, Fig. 2). Also the large amount of radiation from the Small Cloud, relative to that from the Large Cloud, would not have been expected from its smaller optical luminosity and lower dust content.

Features such as the wing of the Small Cloud and the axis of the Large Cloud can be clearly seen in the diagram. Another noticeable characteristic is that the contour pattern is smoother in the case of the Small Cloud. This conforms with the optical evidence for a more regular structure.

(b) *The Degree of Central Concentration*

The radio brightness is seen to decrease less rapidly than the optical brightness in going outwards from the centre, demonstrating that the gas is less concentrated towards the centre than the bright stars. This result is made more evident by comparing radio and optical brightnesses along sections through the Clouds. Such a comparison is shown in Figure 4, which gives sections at constant declination and constant Right Ascension through the optically brightest part of each Cloud.* The optical curves have been derived from data obtained by van Herk (1930). These observations are not good by modern standards, but they are the only systematic data available so far. A major weakness is that the brightness at points in the Clouds has been referred to the brightness at nearby points, which were at that time considered to be outside the Clouds. Present knowledge of the size of the Clouds indicates that the reference level cannot be taken as a true zero level. The shape of the optical sections in the figure may therefore be considerably in error in the outer parts, but the central regions will not be greatly affected.

To facilitate the comparison of the radio and optical data, the resolution of the latter has been degraded by " smoothing " the data with a directional characteristic equivalent to that given by an aerial with a beam width of 1° between half-power points. Thus the radio and optical results have been made directly comparable. The two brightness scales have been adjusted to make the maxima coincide for the Large Cloud.

The greater spread of the radio distribution can be clearly seen in both sections through the Small Cloud and in the section at constant Right Ascension through the Large Cloud. Thus the hydrogen appears in each case as a large envelope surrounding a core of bright stars. However, the radio and optical distributions are more similar for the section at constant declination through the Large Cloud, passing along the axis. The elongated axis, which is a feature of the optical picture, appears to be less marked in the radio observations. This suggests that the gas is disposed in a broad distribution, with an approach to circular symmetry, on which the axis of bright stars is superposed.

Detailed studies of brightness distributions of this type are important in relation to the dynamics and the gravitational equilibrium of the Clouds. When more radio data are available it will be possible to study the Clouds in the way which has been applied to globular clusters (for example, Camm 1952) and ellipsoidal galaxies (de Vaucouleurs 1953). These studies are expected to show the extent to which the Clouds have reached a state of equilibrium under their own gravitation and internal motions.

Differences in distribution, similar to that now reported for the hydrogen and the bright stars, are already known in other galactic systems for stars of different sizes. The internal structure of galaxies and clusters was at first deduced solely from studies of the light distribution across their surfaces. As in the case of the Magellanic Clouds, refinements of technique have revealed more and more of the outlying regions, and thus increased the apparent sizes of the systems. In some galaxies the distribution of rotational velocity has now been observed, leading to the mass distribution. In each case the mass and light distribution are found to be quite different (Oort 1940 ; Wyse and Mayall 1942), with the ratio of mass to luminosity increasing steadily on going out from the nucleus.

* This is not the same as the centroid of the hydrogen distribution, which is at R.A. 05 hr 35 min, Dec. —68·5° for the Large Cloud, and R.A. 01 hr 20 min, Dec. —72·5° for the Small Cloud.

This appears to indicate that most of the mass is contained in dwarf stars, widely distributed around the nucleus. Since the luminosity of a star increases

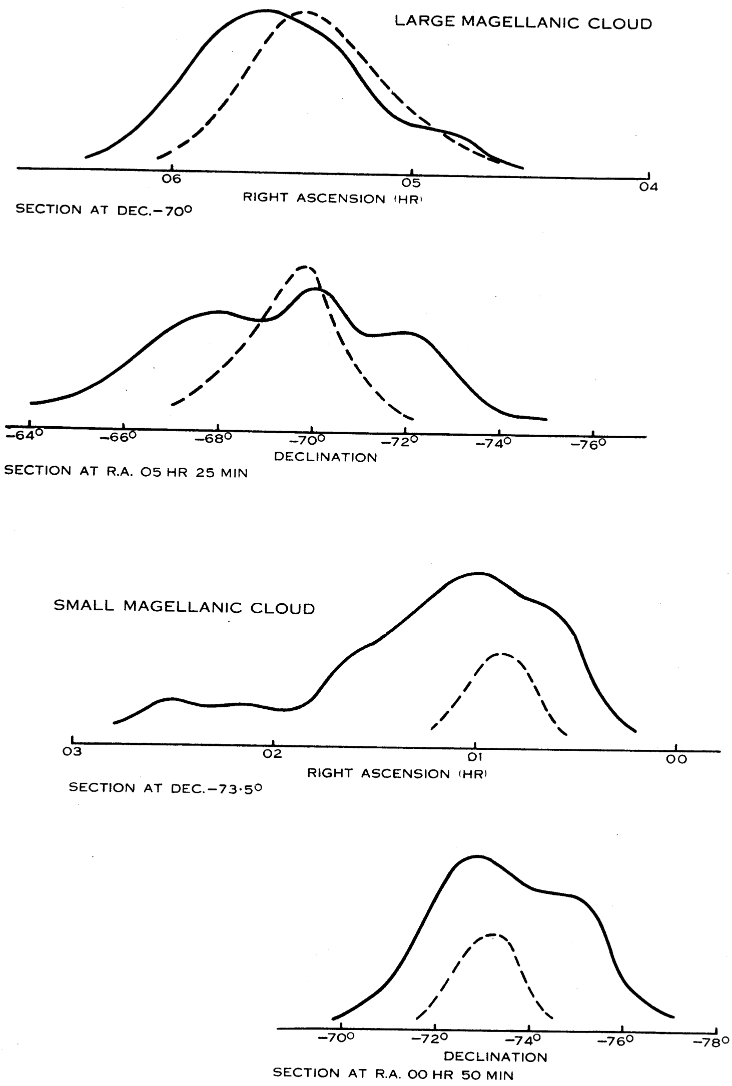


Fig. 4.—Comparison of radio and optical brightness distributions along sections through the Clouds. The brightness scales are the same for the two Clouds, and the radio and optical scales have been adjusted to equalize the peak values for the Large Cloud.

——— Radio. – – – – Optical.

much more rapidly than its mass ($L \propto M^{3 \cdot 8}$), optical observations tend to pick out the brighter stars, in spite of their smaller number. Evidently these are more concentrated towards the centre than the dwarf stars. Dynamical arguments are used to account for these observed differences in the distribution of stars of different masses.

In the case of the Clouds, then, the main mass is likely to be in dwarf stars, more spread out than the bright stars which mainly contribute to the observed luminosity. The hydrogen distribution may therefore approximate to the mass distribution, but later work should enable a detailed comparison to be made.

(c) *Quantity of Neutral Hydrogen*

Unless the source region is opaque, the observed integrated brightness (the area under the profile) will increase with an increase in the number of hydrogen atoms in the line of sight. When the optical depth is small, the relationship is nearly linear, and is also independent of the excitation temperature of the source. (This latter result follows from the fact that the absorption coefficient is inversely proportional to the excitation temperature.) In these circumstances, the quantity of hydrogen in the line of sight can be derived directly from the observational data and an integration over the brightness contours can lead to the total mass of neutral hydrogen in each Cloud.

This method cannot be used, however, when the number of atoms—and so the optical depth—is very great, because then the presence of additional atoms does not increase the brightness temperature. The line is then said to be " saturated ", the increased emission due to the additional atoms being balanced by increased self-absorption. In the case where the radiating gas is at a uniform temperature, the resulting profile would be " flat-topped ", though this may not be so in the general case.

The shapes of the observed profiles and the low values of the brightness temperatures provide some evidence that the Clouds are optically thin. Therefore the values for the quantity of hydrogen which are derived below from the integrated brightness are probably the correct figures and are certainly lower limits.

The required expression for the number of atoms in the line of sight can be derived from the equation for the absorption coefficient (after Wild 1952),

$$\varkappa = 2\cdot 6\times 10^{-15}\cdot\frac{n}{\theta}\cdot f(\nu)\ \text{cm}^{-1},$$

where n is the number of ground-state hydrogen atoms per cubic centimetre, θ is the excitation temperature in degrees Kelvin, and $f(\nu)$ is the " line-shape " function, normalized so that

$$\int_0^\infty f(\nu)\mathrm{d}\nu = 1.$$

The optical depth is then

$$\tau = \int_0^\infty \varkappa \mathrm{d}s = 2\cdot 6\times 10^{-15}\int_0^\infty \frac{n}{\theta} f(\nu)\mathrm{d}s,$$

and, if θ and $f(\nu)$ are assumed to be constant throughout the depth s of the gas in the line of sight,

$$\tau = 2\cdot 6\times 10^{-15}\frac{f(\nu)}{\theta}N,$$

where N is the total number of atoms in the line of sight in a cylinder of 1 cm² section.

The brightness temperature of the line is then given by

$$T_\nu = \theta(1-e^{-\tau})$$
$$\simeq \theta\tau, \quad \text{when } \tau \ll 1.$$

Integrating the brightness temperature over the full range of ν, we have

$$N = \frac{\int_0^\infty T_\nu d\nu}{2\cdot 6\times 10^{-15}} = \frac{\lambda^2 B_{\text{int.}}}{5\cdot 2\times 10^{-15}k}$$

(from the definition of integrated brightness)

$$= 6\cdot 2\times 10^{35} B_{\text{int.}}$$

This is the number of atoms in a projected area of 1 cm². An area of 1 deg² on the celestial sphere at a distance of 46 kpc is equal to $6\cdot 2\times 10^{42}$ cm². Thus the number of atoms corresponding to an integrated brightness $B_{\text{int.}}$ extending over an area δA deg² is

$$\delta N = 3\cdot 8\times 10^{78} B_{\text{int.}}\delta A.$$

The total number of neutral hydrogen atoms in each Cloud can now be found by integrating the product $(B_{\text{int.}}\delta A)$ over the contour diagram for the Cloud. The values obtained are 7×10^{65} and 5×10^{65} for the Large and Small Cloud respectively. The corresponding masses of hydrogen are 6×10^{8} and 4×10^{8} units of solar mass.

These results may be compared with Holmberg's estimates of the masses of the Clouds (see Section IV), 2×10^{9} and $2\cdot 5\times 10^{9}$ solar masses for the Large Cloud by two methods, and 6×10^{8} solar masses for the Small Cloud.

In addition to the mass of neutral hydrogen, better values for the total mass of each Cloud should be obtainable from hydrogen line observations (see Section VI). The present data lead to a tentative value of 20 per cent. for the proportion of hydrogen, by mass, in both Clouds. This may be compared with a recent estimate of 15 per cent. for this ratio in the solar neighbourhood (Oort 1952).

More reliable data will make possible a detailed comparison between the distribution of the gas through the Cloud and the distribution of (total) mass. The latter would be derived from the velocity distribution.

An important result from this survey is that the amount of gas in the two Clouds is about the same, whereas the Large Cloud is believed to contain much more dust than the Small Cloud. Thus the ratio of gas to dust, which has often been held to be constant everywhere, is very different in the two systems. Better optical data are required to put this result on a quantitative basis, but qualitatively it appears to be well established.

The mean gas density can also be derived. In the central regions of the two Clouds the number of atoms in a cylinder of 1 cm² section in the line of sight is about 3×10^{21}. The mean density of neutral hydrogen is then of the order of $10^3/d$ atoms/cm^3, where d is the " depth " of either Cloud in parsecs. The mean diameter of the hydrogen distribution for the Large Cloud, in a plane perpendicular to the line of sight, is 5 kpc between half-intensity points. Thus, if the Cloud has an approximately spherical shape, the mean density in the central region would be about $0 \cdot 2$ atoms/cm^3. On the other hand, if we take the conventional value of 1 atom/cm^3 derived from observations in the solar neighbourhood, we obtain a value of 1 kpc for the line-of-sight depth. The corresponding values for the Small Cloud are very similar.

VI. Discussion of the Velocity Observations.

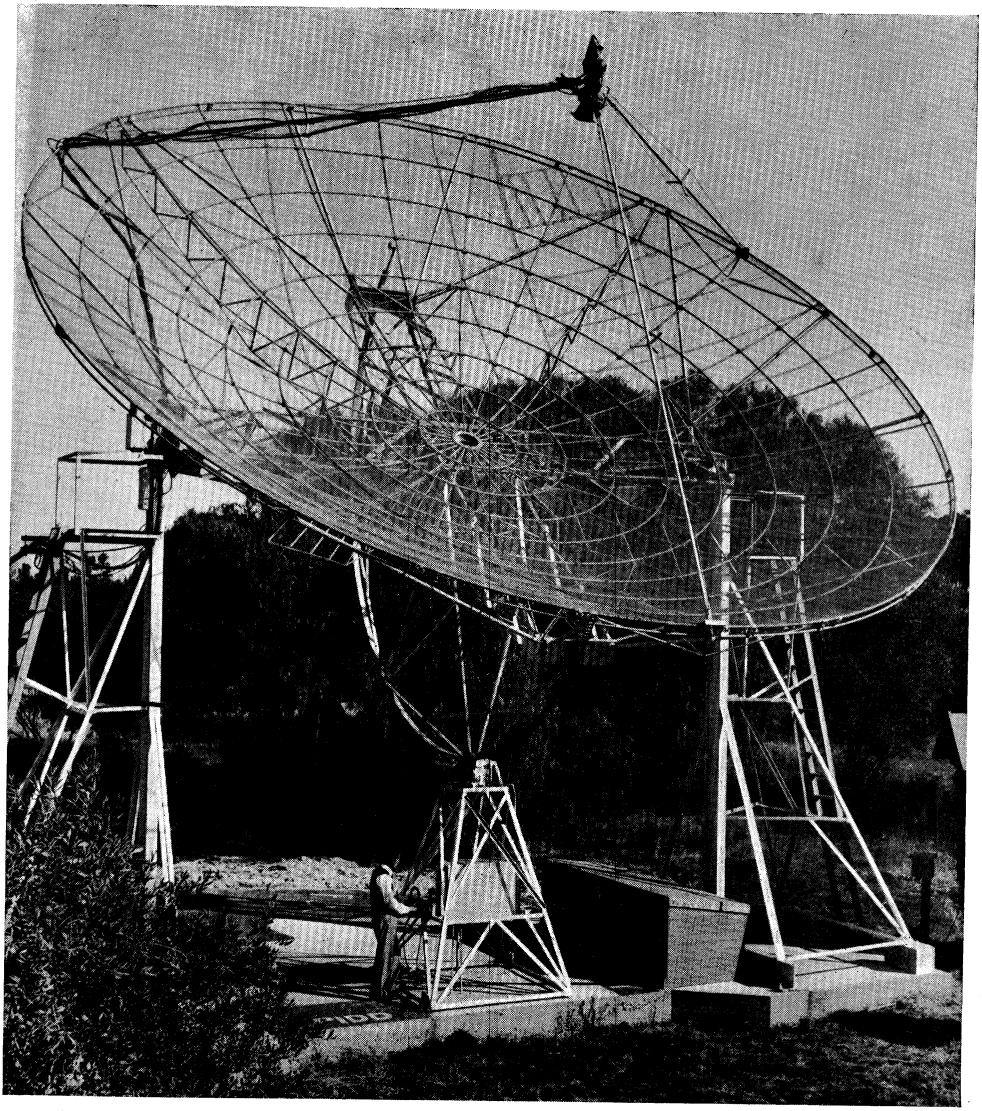
The observations on velocities will now be considered. The radio observations have added enormously to the available information on velocities in the Clouds. Optical measurements to date only give radial velocities for 17 bright nebulae in the Large Cloud, and one in the Small Cloud. The present radio data give velocities for more than 200 independent points across the Clouds, and for each point a full velocity profile can be obtained. The spread of velocity in a profile (about 50 km/s between half-intensity points) can be due to random, or peculiar, motions in the Clouds, and also to systematic variation of velocity with depth in the Cloud, along the line of sight.

The present survey was not sufficiently detailed to give the fine structure of the velocity profiles. Systematic motions can, however, be studied through the mean radial velocity, defined in Section III (d). The significance of this quantity is that, provided the optical depth is small, it gives the motion of the centre of mass of the material in the line of sight. In the particular case of a flattened system it corresponds, on the average, to the mean motion in the equatorial plane.

The contour diagram of mean radial velocity, presented in Plate 2, Figure 3, shows a systematic pattern, with velocity increasing from right to left. The greater part of these velocities, and of their variation across the Clouds, arise from the Sun's rotation about the centre of the Galaxy. The next step is therefore to remove the known motions.

Plate 2, Figure 4, shows the detailed mean radial velocity data, after removal of the galactic rotation velocity (taken as 270 km/s towards $l=57°$, $b=0°$) and the solar motion relative to the local centre of mass (20 km/s towards R.A. 270°, Dec. $30 \cdot 0°$ (1900)). The residual velocities are found to cover a range between -45 and $+60$ km/s. Analysis of the distribution of these residual velocities indicates that each Cloud is rotating. The orientation of the major axis agrees with that derived from the shape of the optical isophotes (see Section IV). The rotational parameters lead to values for the total masses of the Clouds. Thus we can obtain from hydrogen line observations both the mass of neutral hydrogen and the total mass.

Weighted mean radial velocities have been calculated, representing the velocity of the centre of mass of the neutral hydrogen in each Cloud. The



The 36-ft. paraboloid at Potts Hill, near Sydney.
The aerial is mounted as a transit instrument.

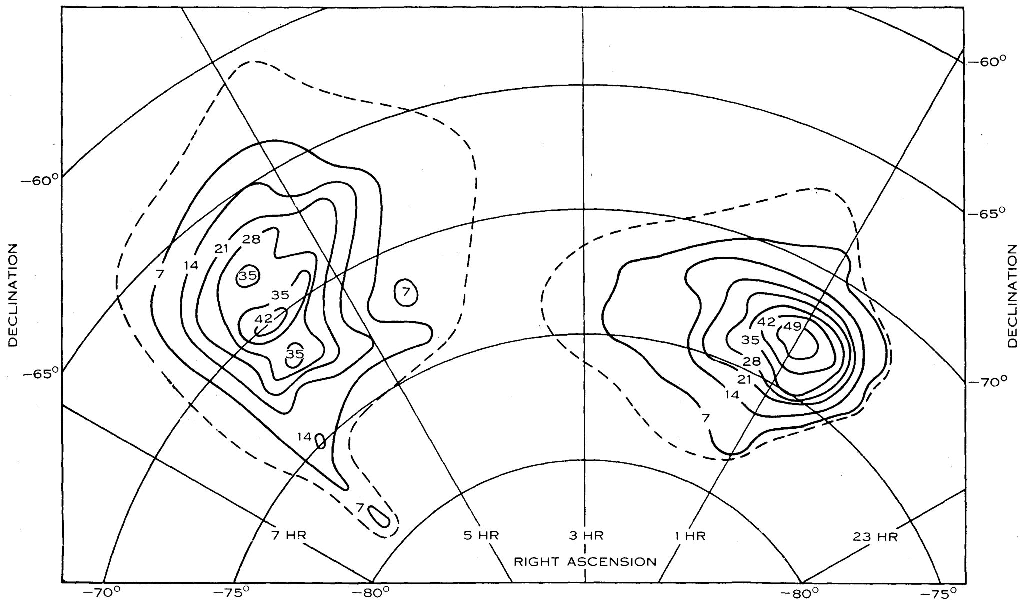


Fig. 1.—Contours of integrated brightness. (Unit $=10^{-16}$ W m^{-2} $sterad^{-1}$.) The dashed line approximately encloses the areas within which radiation was detected.

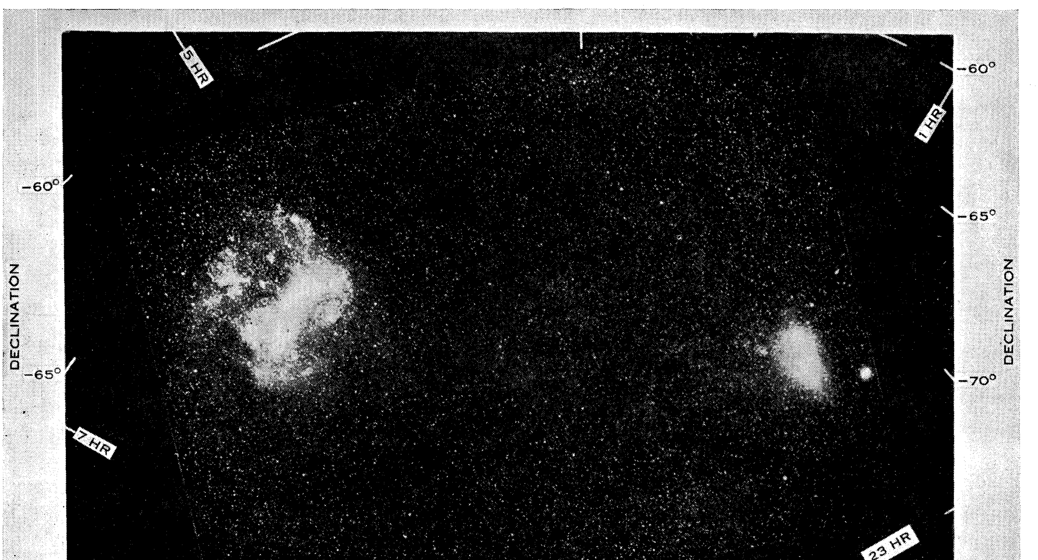


Fig. 2.—The portion of the southern sky containing the Magellanic Clouds. It covers the same area as the contour diagrams.

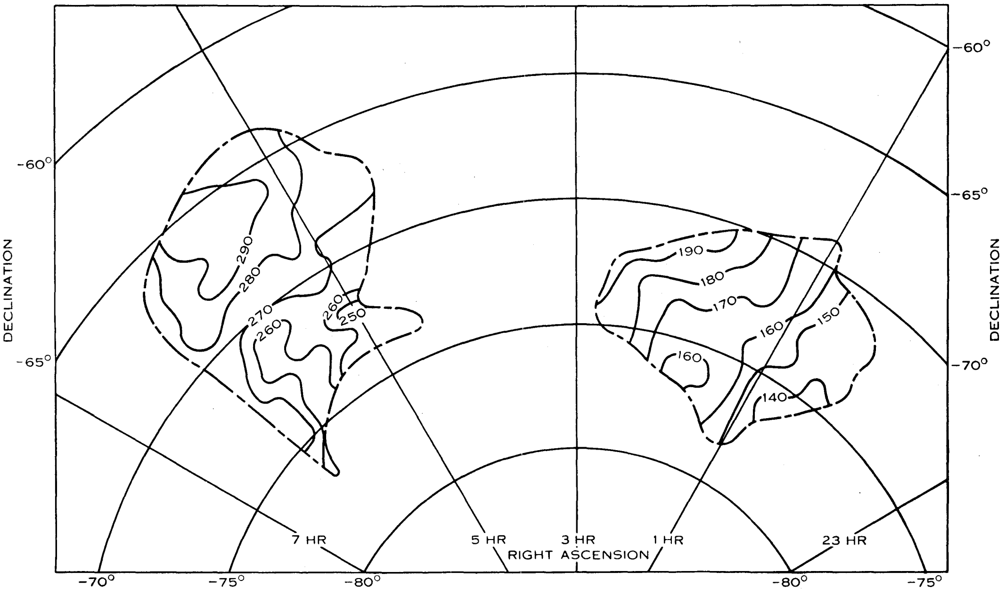


Fig. 3.—Contours of observed mean radial velocity, in kilometres per second.

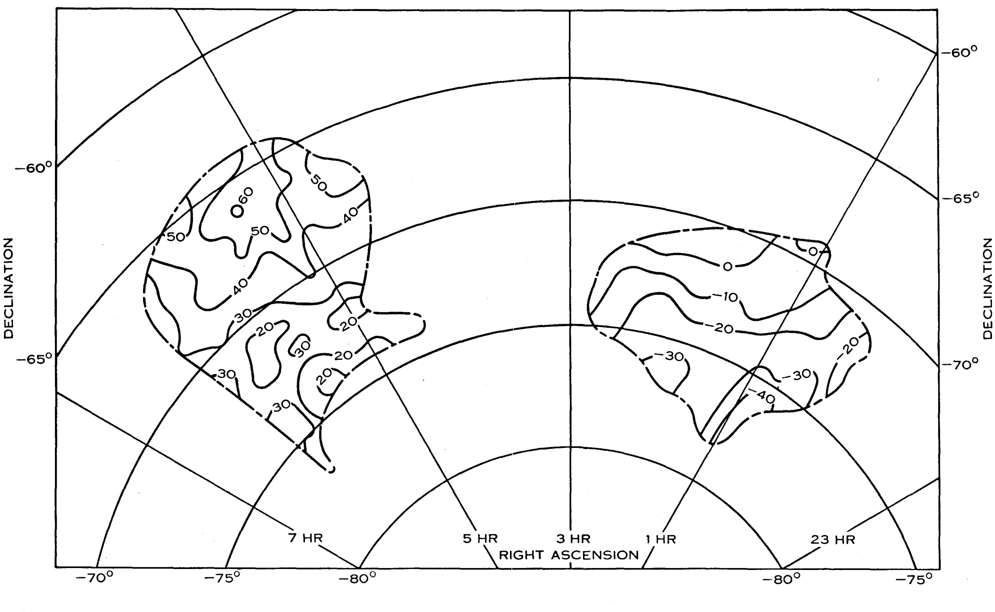


Fig. 4.—Contours of residual mean radial velocity, after removal of galactic rotation and solar motion.

values obtained are +280 and +160 km/s for the Large and Small Cloud respectively, relative to the Sun, and +37 and −16 km/s after removal of the Sun's motions.

A detailed discussion of the velocity data in Plate 2, Figure 4, will be given in a subsequent paper.

VII. Conclusions

The 21 cm line has been received from large areas extending well beyond the easily visible regions of each Cloud, and the hydrogen of the Clouds is much less concentrated towards the nucleus than are the brightest stars.

Despite the very different quantities of dust in the two Clouds, each system contains about the same total amount of gas. Thus the ratio of gas to dust is very different in the two Clouds.

If the Clouds are taken to be optically thin for this radiation, the neutral hydrogen content is found to be 6×10^8 and 4×10^8 solar masses for the Large and Small Cloud respectively.

The results have illustrated the great power of 21 cm line studies. As well as giving the total quantity of gas and its distribution, the method can very quickly supply information about radial velocities within the Clouds in more detail than was available from previous optical studies.

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IX. References

Baade, W. (1950).—*Publ. Obs. Univ. Mich.* **10** : 7-17.
Camm, G. L. (1952).—*Mon. Not. R. Astr. Soc.* **112** : 155-76.
Christiansen, W. N., and Hindman, J. V. (1952).—*Aust. J. Sci. Res.* A **5** : 437-55.
Dicke, R. H. (1946).—*Rev. Sci. Instrum.* **17** : 268-75.
Ewen, H. I., and Purcell, E. M. (1951).—*Nature* **168** : 356.
Feast, M. W. (1953).—*Mon. Not. Astr. Soc. S. Afr.* **12** : 63-4.
Gascoigne, S. C. B., and Kron, G. E. (1953).—*Publ. Astr. Soc. Pacif.* **65** : 32-6.
Gum, C. S., and de Vaucouleurs, G. (1953).—*Observatory* **73** : 152-5.
Henize, K. G., and Miller, F. D. (1950).—*Publ. Obs. Univ. Mich.* **10** : 75-8.
van Herk, G. (1930).—*B.A.N.* **6** : 61-4.
Hertzsprung, E. (1920).—*Mon. Not. R. Astr. Soc.* **80** : 782-4.
Holmberg, E. (1952).—Medd. Lunds Astr. Obs. Series 1, No. 180.
van de Hulst, H. C. (1945).—*Ned. Tijdschr. Natuurk.* **11** : 201.
van de Hulst, H. C. (1953).—*Observatory* **73** : 129-39.
Kerr, F. J., and Hindman, J. V. (1953).—*Astr. J.* **58** : 218-9.
McCuskey, S. W. (1935).—Circ. Harv. Astr. Obs. No. 401.
Nail, Virginia McK., Whitney, C. A., and Wade, C. M. (1953).—*Proc. Nat. Acad. Sci., Wash.* **39** : 1168-76.
Oort, J. H. (1940).—*Astrophys. J.* **91** : 273-306.
Oort, J. H. (1952).—*Astrophys. J.* **116** : 233-50.
Russell, H. C. (1890).—*Mon. Not. R. Astr. Soc.* **51** : 39-43, 96-7.

SHAPLEY, H. (1931).—Bull. Harv. Astr. Obs. No. 881, pp. 1-4.
SHAPLEY, H. (1940).—Bull. Harv. Astr. Obs. No. 914, pp. 8-9.
SHAPLEY, H. (1950).—*Publ. Obs. Univ. Mich.* **10**: 79-84.
SHAPLEY, H. (1951).—*Proc. Nat. Acad. Sci., Wash.*, **37**: 133-45.
SHAPLEY, H. (1953).—*Proc. Nat. Acad. Sci., Wash.* **39**: 349-57.
SHAPLEY, H., and MOHR, JENKA (1932).—Bull. Harv. Astr. Obs. No. 889, pp. 13-15.
SHAPLEY, H., and NAIL, VIRGINIA McK. (1954).—*Proc. Nat. Acad. Sci., Wash.* **40**: 1-5.
SHAPLEY, H., and WILSON, HARVIA H. (1925).—Circ. Harv. Astr. Obs. No. 276.
THACKERAY, A. D., and WESSELINK, A. J. (1953).—*Nature* **171**: 693.
DE VAUCOULEURS, G. (1953).—*Mon. Not. R. Astr. Soc.* **113**: 134-61.
DE VAUCOULEURS, G. (1954).—*Observatory* **74**: 23-31.
WILD, J. P. (1952).—*Astrophys. J.* **115**: 206-21.
WILSON, R. E. (1917).—*Publ. Lick Obs.* **13**: 187-90.
WILSON, R. E. (1944).—*Publ. Astr. Soc. Pacif.* **56**: 102-6.
WYSE, A. B., and MAYALL, N. U. (1942).—*Astrophys. J.* **95**: 24-47.
ZWICKY, F. (1953).—*Phys. Today* **6**: 7-11.