A LOW RESOLUTION HYDROGEN-LINE SURVEY OF THE MAGELLANIC SYSTEM

II. INTERPRETATION OF RESULTS

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Summary

A low resolution (2°.2) survey of the neutral hydrogen in the Magellanic Clouds has produced two important additions to our knowledge of the system. (1) A bridge of gas between the Small and Large Cloud has been mapped. (2) The Small Cloud profiles show double peaks over a wide area, suggesting the possibility of two substantially separate masses of gas.

The observations are discussed in terms of the distribution of integrated brightness and the median velocity of the H-line profiles. Contours of integrated brightness are compared with distributions of HII regions and globular clusters. The overall mass of neutral hydrogen in the system is estimated at $10^9 M_\odot$.

The contours of median velocity reveal a rotation curve for the Large Cloud from which a total mass of 7 to $10 \times 10^9 M_\odot$ is estimated for this galaxy.

I. Introduction

In the present paper we discuss the results of a survey carried out in late 1960, of hydrogen-line radiation from the Magellanic Clouds (Hindman *et al.* 1963—paper I). As this survey was conducted with an aerial having a beamwidth of 2°.2, we shall be mainly concerned with the large-scale distribution and motions of the hydrogen. A detailed description of the equipment, observations, and reductions is given in paper I.

This low resolution survey was undertaken with three main objectives:

(1) To gain experience in the use of digital recording and reduction techniques.

(2) To check and extend the original 21-cm observations of the Clouds (Kerr, Hindman, and Robinson 1954). As shown in paper I, the use of the digital system produced an effective improvement in receiver sensitivity through integration of a number of successive profiles and through the use of more sophisticated calibration procedures.

These improvements, together with a better receiver performance, led to an overall sensitivity which was about three times that of the earlier observations. Also, the use of the multichannel receiver enabled the data to be collected more quickly and more reliably.

(3) To round off the low resolution picture of the Clouds.

The present survey gives useful results on the broad distribution of the hydrogen in and between the Clouds, but some of its greatest value lies in providing information

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on which to base the high resolution programs that have now begun. Early observations of the Clouds with the 210 ft telescope at Parkes have indicated the wealth of detail that can be explored with a beamwidth of 14 minutes of arc.

The discussion that follows will mainly be in terms of the integrated brightness and median radial velocity for each "picture-point", as these are the most useful simple quantities to characterize the slightly complex profiles obtained in this survey. The properties of individual peaks will, however, receive attention in the case of the central region of the Small Cloud.

II. General Description of Profiles

The observed line profiles for the whole region of the Clouds were presented in Figures 13 and 14 of paper I, for points approximately a degree apart. Most of these profiles are single peaked and fairly simple in shape. In the main part of the Small Cloud, however, the profiles are double peaked, with an approximately uniform velocity separation between the peaks; this effect will be discussed in Section VI. The other notable systematic effect is a characteristic asymmetry of the profiles over the main body of the Large Cloud, which is apparently related to the internal rotation of the Cloud (Kerr and de Vaucouleurs 1955).

Table 1

HALF-WIDTHS AND OVERALL WIDTHS OF PROFILES

Region	No. of Profiles in Sample	(kilometres per second)			
		Mean Half-width	σ	Mean Overall Width	σ
SMC	130	59	15	115	26
LMC	133	50	18	110	27
M.S. "bridge"	28	65	17	125	29
Local galactic spiral arm	2500	26	12	104	44

Table 1 gives figures for the mean overall width of the profiles between zeros and also the half-width, for the SMC, LMC, and bridge region, and, for comparison, the corresponding figures for the local spiral arm in directions away from the galactic plane (McGee and Murray 1961).

The overall widths do not differ significantly, suggesting that the rather widely dispersed gas which appears to contribute a low intensity widespread component to all galactic profiles has a counterpart in the Magellanic System.

The approximate constancy of the overall width may be related to an escape velocity. If so, the observed value of 110 km/s would correspond to an order-of-magnitude figure for the total mass of the system of 3×10^9 solar masses.

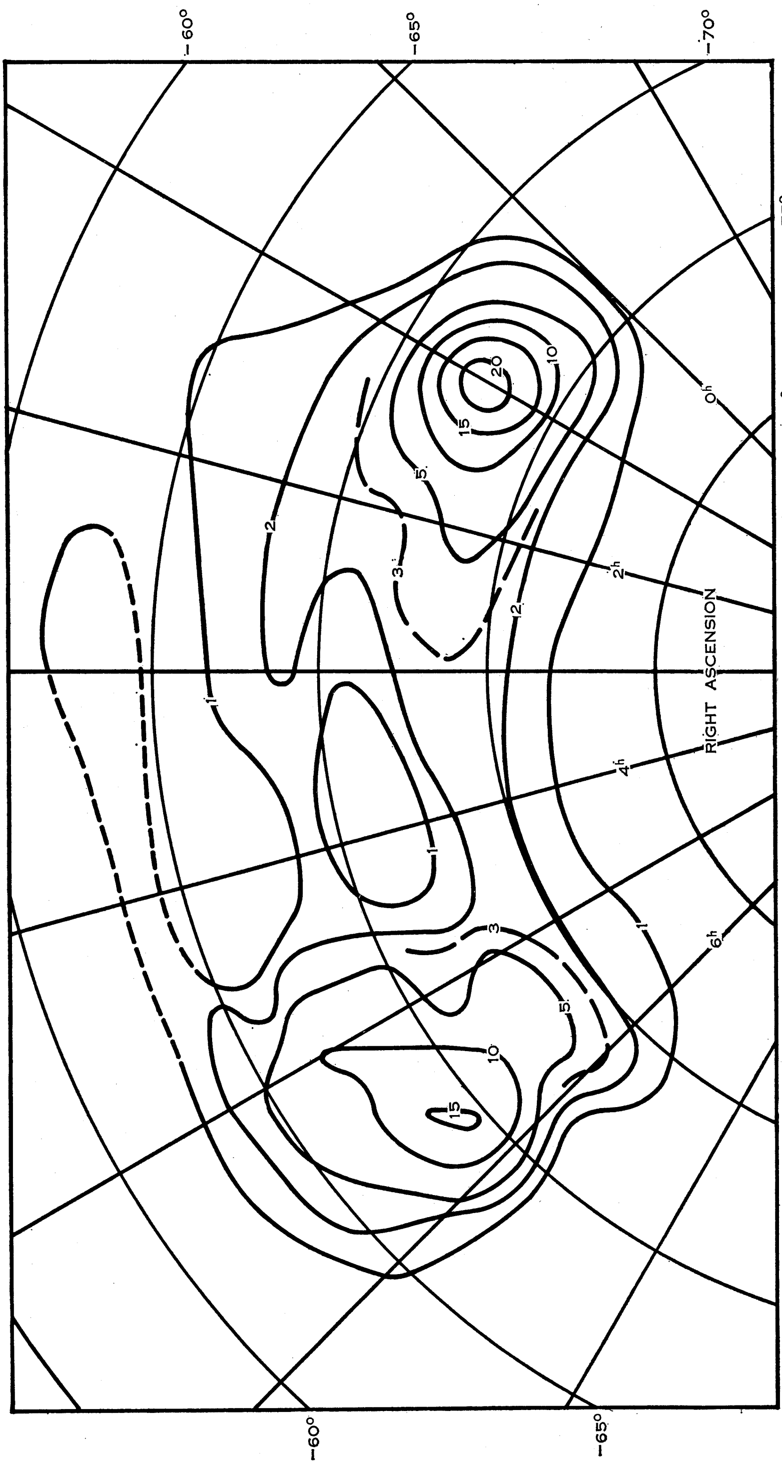

Fig. 1.—Contours of integrated brightness of neutral hydrogen in the Magellanic System. Contour unit = 2×10^{-16}W m^{-2} sr^{-1}.

In comparing the half-widths in the Magellanic System and the Galaxy the great differences in the volume of gas included in the aerial beam in the two cases should be borne in mind.

III. Integrated Brightness Distribution

The integrated brightness (the area under the line profile) observed at a given point is a measure of the total quantity of hydrogen along the line of sight. Provided the gas is optically thin, and therefore the line is not saturated, the number of hydrogen atoms, N, in a column extending from the observer to infinity is related to the integrated brightness, $B_{\text{int.}}$, by the relation:

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

where N is expressed in atoms per cm^2, and $B_{\text{int.}}$ in W m^{-2} sterad^{-1} (Kerr, Hindman, and Robinson 1954).

The distribution of integrated brightness over the area of the Magellanic Clouds, according to this survey, is shown in Figure 1, which is reprinted from Figure 11 of paper I. Because the integration has been limited to the Magellanic range of velocities, there is no contribution from foreground hydrogen in the Galaxy, and all features of the pattern can be attributed to the region of the Clouds.

Table 2

Mass of hydrogen, from $B_{\text{int.}}$ contours

	(solar masses)
Large Cloud, main body (inside 3 contour)	$3 \cdot 2 \times 10^8$
Small Cloud, main body (inside 3 contour)	$2 \cdot 8 \times 10^8$
Whole composite object	10^9

As in the earlier observations, the main bodies of the Clouds stand out clearly, but the increase in sensitivity has made it possible to show that the two Clouds are joined by a bridge of gas, and they are in fact contained within a common envelope. The present low resolution observations cannot show whether this gaseous envelope is actually continuous, either in its projected form or in its distribution in depth, but it is clear that the two Clouds and the surrounding gas must be regarded as a single composite object, which we will designate "The Magellanic System". This conclusion is strengthened by the way in which the gas density tails off slowly from each Cloud toward the other, but drops away sharply on the outer edge of each Cloud. The edges are in fact sufficiently steep that they cannot be properly resolved by the present aerial.

If we take the distance of the Clouds as 46 kpc the projected dimensions of the composite object are 25 by 10 kpc. This size should be compared with the usual figures for the "diameters" of the Large and Small Clouds of 9·7 and 6·5 kpc respectively.

Integration over the contour pattern of Figure 1 leads to values for the total mass of hydrogen, as set out in Table 2.

These figures agree well with those obtained in the 1954 survey.

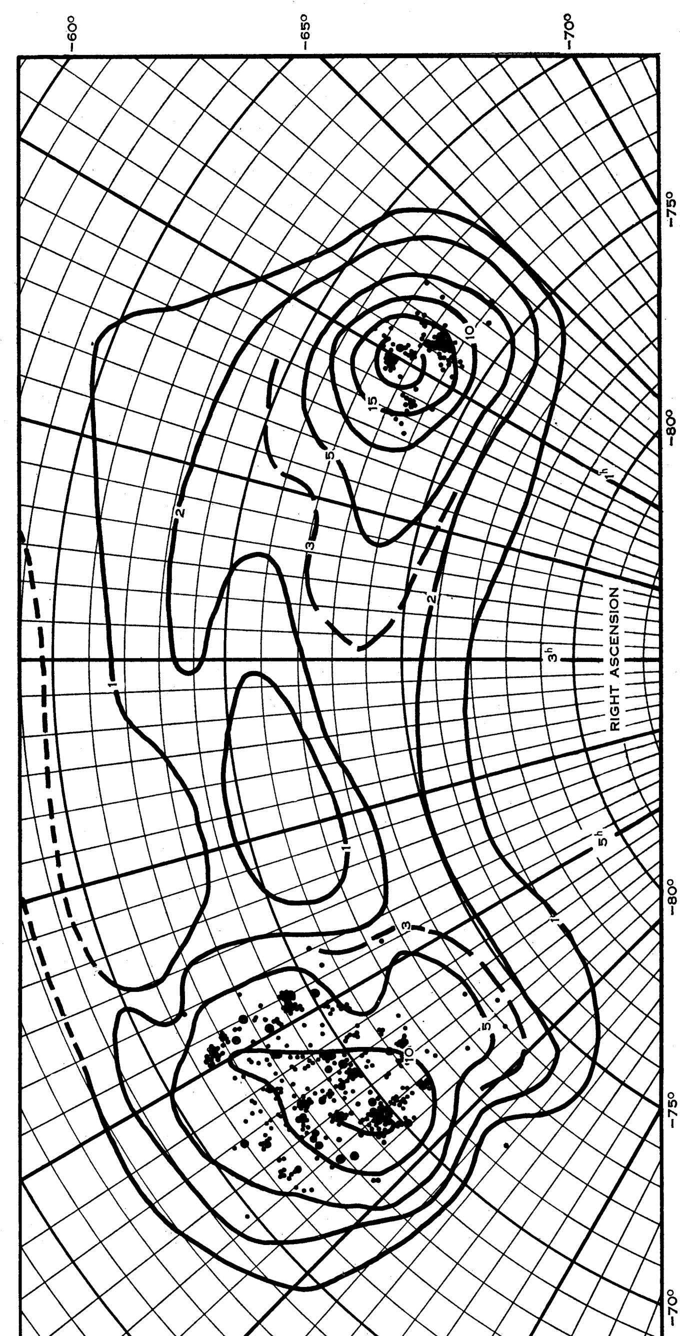

Fig. 2.—Distribution of HII regions (Henize 1956) compared with the neutral hydrogen distribution of the Magellanic System.

Inspection of the $B_{\text{int.}}$ contour pattern shows that the main "bridge" between the two Clouds is connected with the short extension which Shapley (1940) discovered

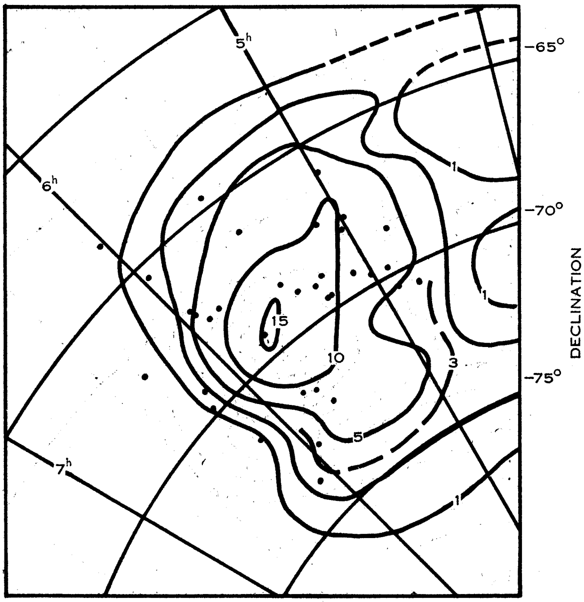

Fig. 3.—Distribution of old populous clusters (Hodge 1960) compared with the neutral hydrogen distribution in the LMC.

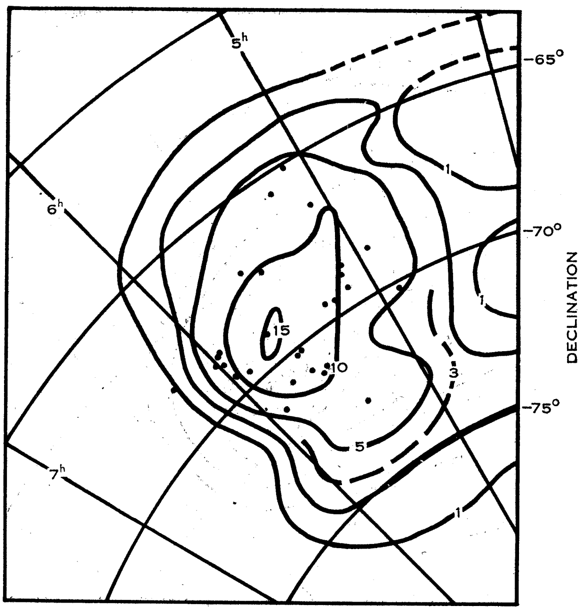

Fig. 4.—Distribution of young populous clusters (Hodge 1961) compared with the neutral hydrogen distribution in the LMC.

in the star counts on the following side of the Small Cloud, and which was traced to a greater distance in the direction of the Large Cloud in the earlier 21 cm survey. The neutral hydrogen bridge is not in the same position as a closed feature in the $3\frac{1}{2}$ m contour pattern presented by Mills (1955). The latter feature may well be due to the

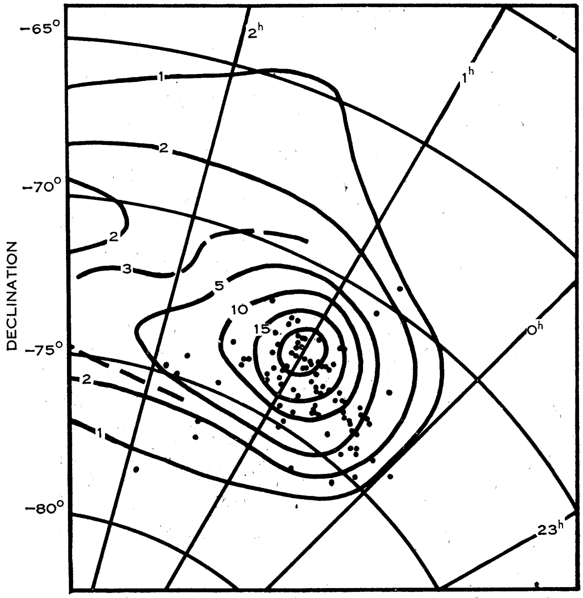

Fig. 5.—Distribution of clusters (Lindsay 1958) compared with the neutral hydrogen distribution in the SMC.

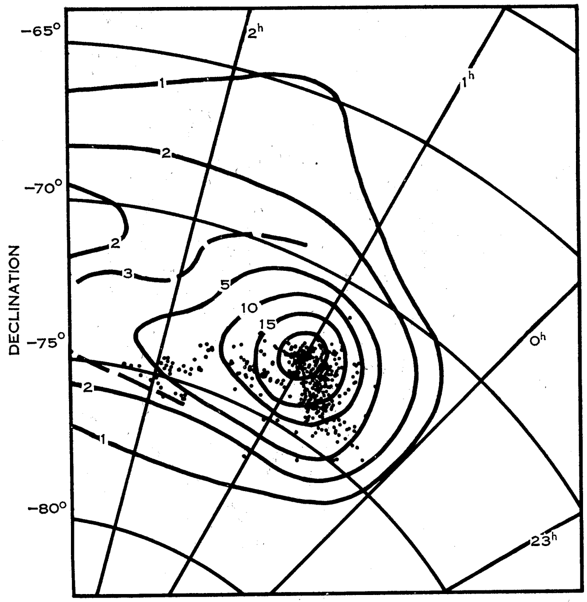

Fig. 6.—Distribution of emission line objects (Lindsay 1961) compared with the neutral hydrogen distribution in the SMC.

galactic foreground, which cannot be distinguished from the Clouds in the case of continuum observations.

The present observations have shown no sign of a link between the Clouds and the Galaxy, as suggested by de Vaucouleurs (1954) and others. 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.

The low resolution contours show only a small amount of detail, and it does not appear fruitful to attempt any comparisons with other distributions, as far as fine structure is concerned. It is interesting, however, to compare the present results with the *broad* distributions of other stellar and interstellar constituents of the Clouds. A series of such comparisons is presented in Figures 2–6, for HII regions (Henize 1956) the two types of globular clusters (described by Hodge 1960, 1961, as young and old populous clusters), SMC Clusters (Lindsay 1958) and emission-line objects (Lindsay 1961).

There is seen to be a general agreement between the main hydrogen nuclei and the distributions of various Population I constituents. However, this may merely indicate that all the objects concerned tend to concentrate in the main bodies of the Clouds.

IV. Median Radial Velocities

Contours of median radial velocity, corrected to the Sun, were presented in Figure 12 of paper I. In a discussion of internal and systemic motions of the Clouds it is desirable to correct also for the motion of the Sun in our Galaxy. This correction, however, is rather uncertain.

We have adopted a figure of 216 km/s for the Sun's rotational velocity about the galactic centre, largely because this value has been used in all hydrogen-line reductions to date. Several authors have argued for a higher value in the reduction of extragalactic (optical) velocities, possibly as high as 300 km/s (de Vaucouleurs 1961), but in fact we do not know what would be the most appropriate value for correcting observations of the Magellanic Clouds, as the peculiar velocities of the Clouds-Galaxy system are comparable with the uncertainty in the galactic rotation velocity. It therefore seemed better to base our choice on consistency with previous practice.

In addition to the galactic rotation term, a correction has also been made for the Sun's peculiar velocity relative to the local standard of rest, adopting the "standard" solar motion of 20 km/s in a direction 18^h00^m, $+30°.0$ (1900), together with an outward motion of 7 km/s in a direction away from the galactic centre (Kerr 1962). The case for a local "expansion" of this order of magnitude in the Sun's neighbourhood appears to be fairly strong, quite apart from the controversial question of whether or not a more general expansion of the gas in the Galaxy is occurring. (In any case, this particular correction has only a very minor effect under the present circumstances.) The galactic rotation correction is by far the most important one; a change in this correction would directly affect the systemic velocities, but it would have only a second-order effect on the internal motions in the Clouds (see Kerr and de Vaucouleurs 1955).

This two-stage reduction of the velocities—first to the Sun, and then to a frame of reference which is fixed with respect to the galactic centre—seems to us to be the best way to treat extragalactic velocities. It is unfortunate that some authors, e.g. van de Hulst, Raimond and van Woerden (1957), Volders (1959), have chosen to reduce extragalactic velocities to the local centre of rest in the Galaxy. This has undoubtedly been done because convenient tables exist for this particular reduction, but the local centre of rest has little significance for extragalactic observations.

The contours of median radial velocity, corrected to the stationary galactic frame of reference, are shown in Figure 7. The main features of the distribution are:

(1) a rotational pattern in the Large Cloud,

(2) a general gradient across the whole composite object,

(3) a possible, but much less definite, rotation effect in the Small Cloud.

The rotational motions and the conclusions to be drawn from them will be discussed in Section V. The continuity of the general gradient across the whole object supports the view that the bridge is a proper link between the Clouds, and not just an accidental overlapping of two separate extensions of the Clouds.

Until recently, the only optical velocities available for the Clouds were those for 18 emission nebulae observed by R. E. Wilson (1917). The list has recently been extended with the publication of 61 stellar velocities by Feast, Thackeray, and Wesselink (1961) and a few additional nebular velocities by de Vaucouleurs (1960). Systematic comparisons between radio and optical velocities can now be made on a more worth-while basis. Differences between the two sets of velocities might arise from systematic errors in either or both velocity systems, but they might also be due to the optical and radio sources having different space distributions or velocity patterns.

A comparison has therefore been made between the radio median radial velocities and all available optical velocities. In order to weight the two types of observation in roughly similar ways, the optical velocities were averaged out for regions one square degree in area, centred on the nominal positions of the radio profiles. The difference δV between the mean optical velocity and the median radio velocity was formed for each such region. Apart from giving a more equal distribution of the observations over the region, it was hoped that this method would average out as far as possible any real differences between the optical and radio rotation patterns or other motions.

The mean value of δV (optical minus radio) was $+2$ and $+3$ km/s for the Large and Small Clouds respectively. In his discussion of possible systematic errors in the present system of optical red-shift velocities, Holmberg (1961) has pointed out that the optical velocities are greater than the corresponding radio velocities for some northern galaxies. The present results show a difference in the same sense, but it is too small to be significant. The Harvard group has recently shown that there is no significant difference between radio and optical velocities over a group of 29 other galaxies detected at 21 cm (Dieter *et al.* 1962).

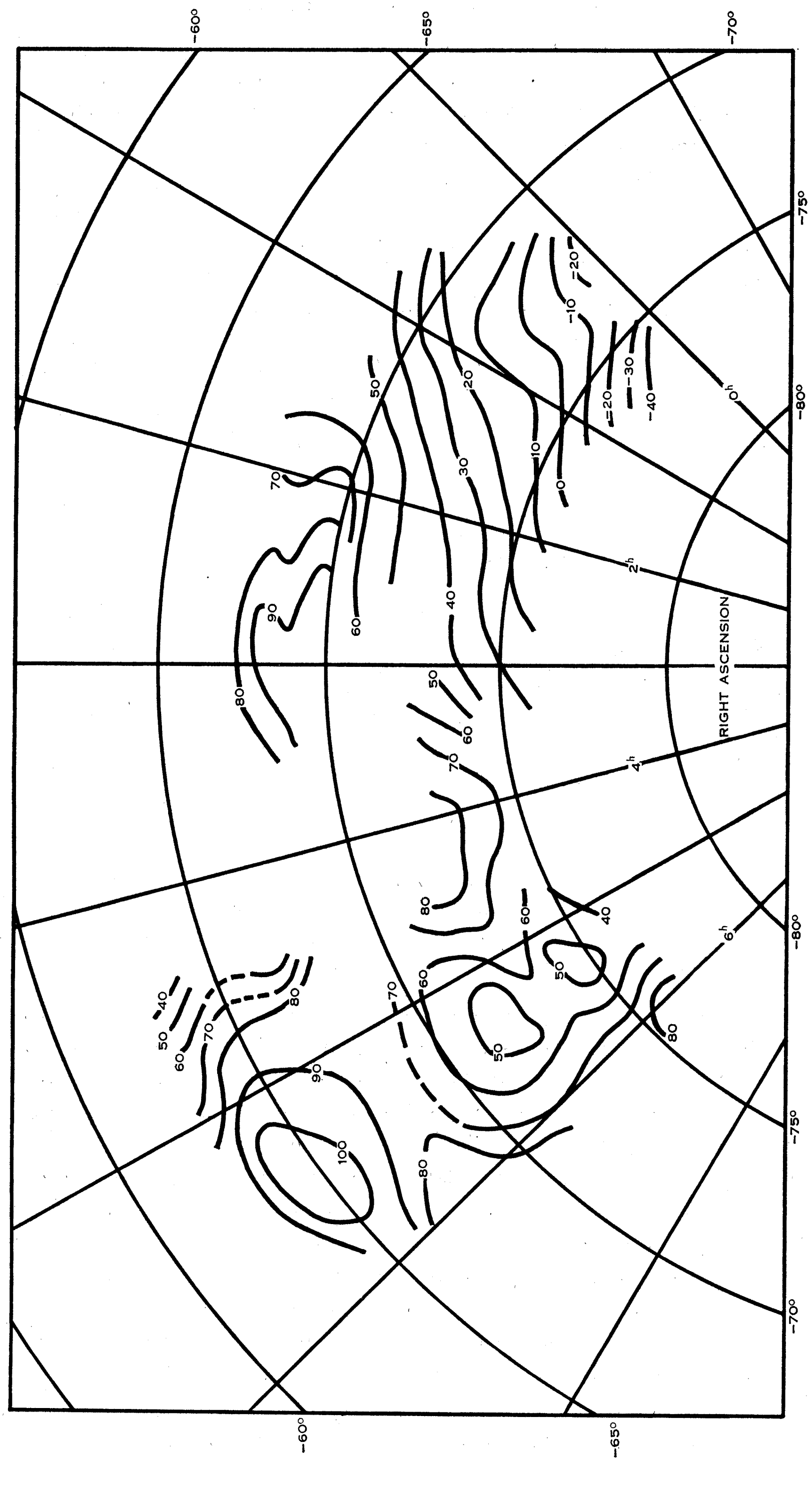

Fig. 7.—Contours of median radial velocity of neutral hydrogen profiles in the Magellanic System, referred to the galactic centre. Contour interval 10 km/s.

V. Rotation of the Large Cloud

The velocity contours for the Large Cloud show a clear rotational pattern, and rotational parameters have been derived using methods which were similar to those applied to the 1954 results by Kerr and de Vaucouleurs (1955). The following results were obtained from the radio data alone:

Rotational centre, derived from the symmetry of the pattern	05^h25^m, $-68°$ (1960)
Position angle of major axis (line of maximum gradient of velocity)	5°
Inclination (the angle from the plane of the sky), derived from the ellipticity of the $B_{int.}$ contours	35°
Systemic velocity	+77 km/s.

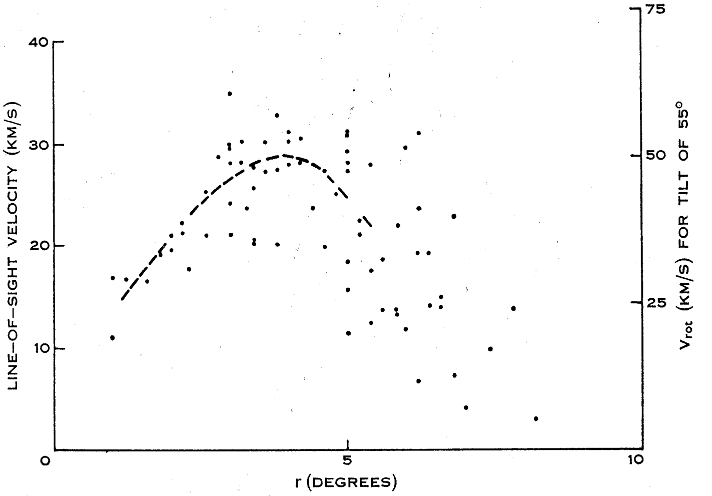

Fig. 8.—Rotation curve for the LMC derived from median velocities of the neutral hydrogen profiles. Centre of rotation: R.A. 0525, Dec. $-68°$ (1960). Position angle of major axis: 5°—185°.

The mean rotation curve obtained with this set of parameters is shown in Figure 8, which also includes the 74 individual points. Both sides of the rotation curve have been plotted together, on the assumption that it is symmetrical about the adopted centre of rotation. The left-hand scale gives the line-of-sight component of the rotation velocity, and the right-hand scale the actual rotation velocity in the assumed equatorial plane of the Large Cloud, after correcting for an inclination of 35°.

The maximum velocity of the line-of-sight rotation curve, 29 km/s, is greater than the figure of 17·5 km/s which was derived by Kerr and de Vaucouleurs (1955) from the earlier observations. This difference is believed to be due to the better definition of the present profiles. It now appears that the earlier profiles must have been smoothed to a greater extent than was realized, during the process of constructing them from a series of observations at discrete frequencies.

We will not undertake a detailed derivation of the mass of the Large Cloud from the new rotational information. The principles have been discussed at length by Kerr and de Vaucouleurs (1956) and by de Vaucouleurs (1960), and we can arrive at an approximate figure by a suitable adjustment. The main difficulties in a mass derivation are associated with uncertainties in:

(i) the disposition of the gas relative to the "equatorial plane" of the system,
(ii) the degree of irregularity and asymmetry which is present.
(iii) the inclination of the "equatorial plane" to the line of sight.

The high resolution observations which are now under way on the 210ft telescope should contribute greatly to the understanding of these factors.

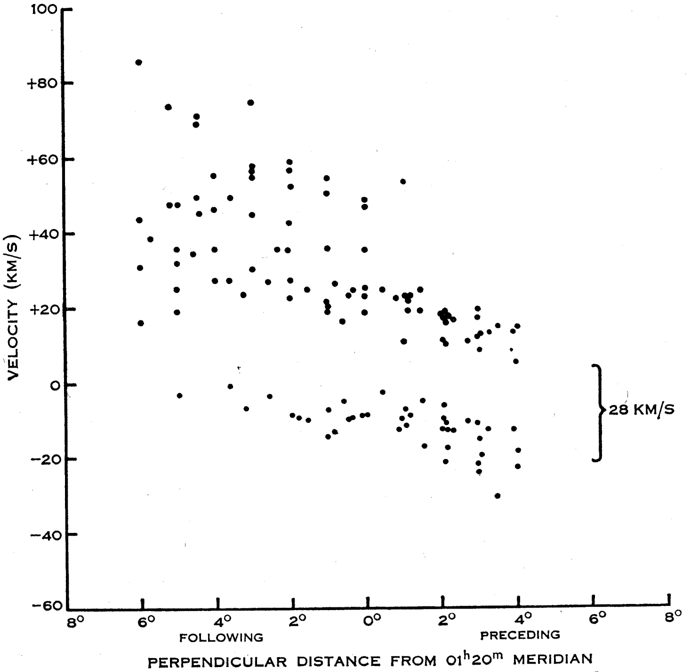

Fig. 9.—Velocities of the main peaks of the neutral hydrogen profiles in the SMC showing systematic separation into two groups.

On present evidence, a reasonable figure for the mass of the Large Cloud is in the range $7–10 \times 10^9$ solar masses.

VI. The Small Cloud

There is a gradient of median velocity across the Small Cloud of about 10 km s^{-1} deg^{-1}, in position angle 315°. This gradient may be wholly or partly associated with a rotation of the Cloud, but there is no clear "turnover" of the type associated with a rotation curve, and it is not possible to separate a rotation component from the other motions that are probably present.

The most interesting feature of the Small Cloud results is the appearance of double peaks in the profiles over a substantial area, with an approximately constant velocity difference of 25–30 km/s between the two peaks. The systematic nature of the effect is shown in Figure 9, which presents the velocities of the peaks as a function of the perpendicular distance from the 01^h20^m meridian of right ascension. In effect, the diagram shows the velocity pattern in a direction near the maximum velocity gradient.

The points fall into two well-defined groups, suggesting the existence of two separate entities of an extensive character. With such a large and systematic velocity difference between them, it seems reasonable to conclude that the two entities are also at different distances from us.

The observed effect could arise from the two sides of an expanding ring, or from gas falling in from both sides towards an equatorial plane. Alternatively, the two entities could be two loosely connected bodies in the large complex system which comprises the Clouds. More detailed observations are needed to decide between these and other possibilities.

Optical observations to date have not given any indication that the Small Cloud is split into two bodies, but if the two had similar populations it might be difficult to distinguish between two entities which lie one behind the other. It is desirable to search more particularly for optical signs of a splitting.

VII. The Overall System

We now have a picture of a composite Magellanic System in which the Large and Small Cloud are linked by a bridge of gas and are enclosed in a common envelope. There is also a possibility that the Small Cloud may be split. The outer edges of the composite body appear to be quite sharp.

This System provides a unique opportunity for studying the internal motions in a multiple-concentration galactic complex. In addition to the rotation of the Large and possibly the Small Cloud, we may expect to find a binary motion between the two Clouds (i.e. a rotation of the whole System), and other large-scale internal motions. The observations, however, include a contribution from the (imprecisely-known) rotation of our own Galaxy, and from a probable translational motion. It is difficult to distinguish a binary motion from these two components, as all three have rather similar variations across the System. Higher resolution observations should help in sorting out the various contributions to the observed velocities.

The gas is presumably extended in depth, but we do not know how far. By analogy with the large area covered by the gas in projection in the sky, we can infer that the gas is spread over a considerable depth also.

For a satisfactory picture of the three-dimensional layout of the System, we must know the relative distances of the two Clouds and the direction in which each main body is tilted to the line of sight. Optical work so far has suggested that the two Clouds are about equidistant from us. On the tilt question, de Vaucouleurs (1955*a*, 1955*b*) has attempted to determine which side of each Cloud is closer, from a study of Cepheids. In the large Cloud, he found an indication that the nearer part of the minor axis is the north-following side, but the uncertainty is high. It is noteworthy that if the Large Cloud were tilted in the opposite direction to that suggested by de Vaucouleurs, its rotational axis would be approximately parallel to that of the Galaxy, but of course this may be entirely fortuitous.

We may hope that optical work will produce more evidence on tilt and relative distances in the near future. Also, radio-optical correlations and observations of 21-cm absorption in radio sources should help in building up a three-dimensional picture.

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