REPORTS ON THE PROGRESS OF ASTRONOMY

THE GALACTIC SYSTEM AS A SPIRAL NEBULA

1. *Introduction.*—The view that the Galaxy might have a spiral structure has been expressed almost since the first discoveries of spiral structure in nebulae. The oldest explicit reference to this seems to be in a paper by Stephen Alexander (1). Both he and Proctor (2), seventeen years later, tried to find support for their spiral theory and to construct to some extent the galactic spiral from the appearance of the Milky Way as inferred mainly from the observations of the Herschels*. In 1900, and more completely again in 1913, Easton (3), apparently quite independently and unaware of these earlier suggestions, made a very careful study of the Milky Way as shown by visual and photographic observations, especially with a view to delineating the course of the possible spiral arms of the Galactic System; he placed the centre of the spiral in the direction of Cygnus.

Later developments have made it clear that this representation can hardly resemble the real structure of the Galaxy, the main cause of its failure and of the failure of all attempts to find spiral-like structure being the strong and uneven absorption near the galactic plane; for there is little doubt that many of the features of the apparent Milky Way structure are determined rather by the distribution of absorbing material than by that of the stars.

The extreme flatness of the Galactic System, as well as the frequency of large groupings of O and B stars, had for a long time been convincing evidence that it belonged to the class of spiral galaxies. It was not until 1951, however, that part of the galactic spiral structure was actually found. This was accomplished by using the luminosity criteria for O and B stars, as developed by Morgan, to determine the location of distant groupings of these stars. The first publication on the subject was an article by Morgan, Sharpless and Osterbrock (4) in which it was shown that regions of ionized hydrogen were arranged in long stretches which undoubtedly outlined parts of spiral arms (Fig. 1.).

It was a curious coincidence that at just about the same time systematic measures of the 21-cm line of neutral hydrogen were beginning to be made, and only two years later a much more comprehensive picture of the galactic spiral structure could be derived from these radio observations (5, 6).

The 21-cm observations brought about a revolution in the study of galactic structure. The scattering of optical radiation by small interstellar particles is so strong that in almost all directions in the galactic plane this radiation is effectively stopped in a few kiloparsecs. Although there are some places where, through accidental windows in the absorbing screens, one can observe a few stars in the galactic disk up to distances of the order of 10 kpc, these windows are so rare and so small that, but for the radio measures, it might have always remained a hopeless task to outline the general pattern of the galactic spiral.

Radiation in the range of radio waves passes without hindrance through the interstellar dust. For wave-lengths longer than a few metres absorption by

* In 1940 Dr Rosseland informed one of us about Alexander's and Proctor's articles. He also mentioned the possibility that Lord Rosse himself may have had the idea that the Galactic System had a spiral structure. So far, however, no direct published reference to this by Lord Rosse has been found.

ionized hydrogen becomes appreciable. With decimetre waves the most distant parts of the Galaxy can be explored. Observations in the decimetre continuum can only give the integrated radiation over the line of sight. The 21-cm line gives discrimination in distance. But although the 21-cm observations give discrimination in distance they cannot by themselves provide actual distances. The distance distribution in a given direction can only be inferred from radial velocities. For this we have to suppose that in each part of the Galactic System the average motion of the gas coincides with the circular velocity at the corresponding distance from the centre. Observations of stellar motions indicate that this condition is probably fulfilled to a fair approximation in the neighbourhood of the Sun. It seems plausible to assume that it holds as well for other parts of the Galactic System. But the possibility of deviations must certainly be kept in mind. The 21-cm observations themselves have given clear evidence of systematic divergence from circular motion in some fairly large regions. Moreover, it is certain that the hypothesis is no longer correct in the nuclear part. Within about 3 kpc from the centre the radio observations show that the large-scale motion of the gas deviates greatly from circular motion. We shall return to this below.

Beside systematic deviations from circular motion there are also the smaller-scale, internal motions. The interstellar gas is largely concentrated in clouds; the clouds have considerable random motions. These must be taken into account when computing the distance distribution of the hydrogen in a given direction from the observed velocity distribution. The difficulty is that the distribution of the random motions is very incompletely known, and that, moreover, it seems to vary from region to region.

2. *Rotation.*—A fundamental thing we must know in order to transform radial velocities into distances is how the circular velocity Θ_c varies with the distance R from the centre; in addition we must know the Sun's distance from the centre. We shall denote the latter by R_0.

Once we know both this distance and the circular velocity near the Sun, the 21-cm observations themselves may be used to derive Θ_c for values of R smaller than R_0. As a simple geometrical consideration shows, the circular velocities are given directly by the cut-off of the line profiles at the side of positive radial velocities for the quadrant between 328° and 58° longitude, and at the side of negative velocities for the quadrant between 238° and 328°, provided the hydrogen is distributed evenly over the disk. Actually, the derivation of Θ_c is complicated by the fact that, because of the spiral structure, the gas is very *un*evenly distributed. A second complication arises from the random motions of the clouds, as well as from *systematic* deviations from circular motion.

The rotational velocity near the Sun and the Sun's distance from the centre may be derived by combining the data just mentioned with the constants A and B of differential galactic rotation. The values of the latter constants, which rest on distances of distant stars, are more uncertain than the velocities derived from the 21-cm measures. This causes an uncertainty of about 10 per cent in the scale of the Galactic System. The distance to the centre can also be determined in a direct manner from the RR Lyrae-type variables concentrated near the centre. In this case the accuracy is limited by the uncertainty in the interstellar absorption and in the absolute magnitude of the variables.

For the regions situated farther from the centre than the Sun the rotational velocities cannot be determined from radio observations. Here we must rely on values computed from the mass densities in these outer parts, the distribution of mass density being inferred from the star density. For $R > R_0 + 2$ kpc the densities become very uncertain and this affects the calculated rotation curve. The resulting systematic uncertainty in the distances may be 10 per cent.

The rotation curve, as derived by M. Schmidt (7) from all available data, is shown in Fig. 2 (full-drawn curve). For the part within $R = 8 \cdot 2$ kpc it is based on 21-cm data discussed by Kwee, Muller and Westerhout (8). These referred to the quadrant from 328° to 58° longitude and are shown as dots. Data for the quadrant at the other side of the centre, measured by Kerr and Hindman, are shown as crosses. Taking into account that in the southern longitudes the

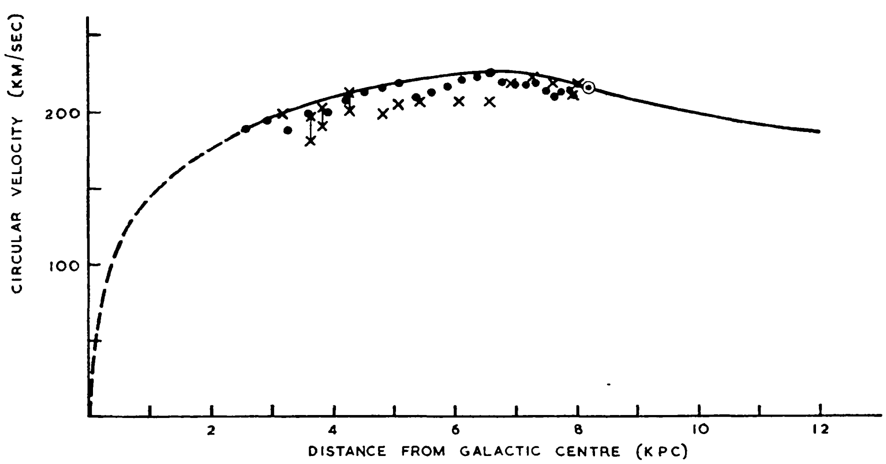

FIG. 2.—*Variation of circular velocity with distance from the galactic centre* (7, 8). *Observational points from the northern* (●) *and southern* (×) *sectors have been included, except in the innermost region, where expansion makes the interpretation more difficult.*

line of sight seems to pass more frequently through inter-arm regions at the point where it comes closest to the centre, which causes the cut-off velocities to be smaller than the rotational velocities, the agreement between the two sides of the Galactic System is satisfactory, at least for $R > 3$ kpc. In the innermost region great irregularities occur, which we shall discuss below.

3. *Hydrogen distribution. Spiral structure.*—From profiles of the 21-cm line observed in various directions one can now derive the density distribution of the neutral hydrogen throughout the Galactic System. It appears that most of it is confined to a flat disk. The distance between the surfaces where the density has dropped to half the value in the central plane is about 220 pc, or only about 1/100th of the disk's diameter in the galactic plane. The arms lie for the most part extremely closely in one plane, which we may call the true galactic plane (this makes an angle of roughly 1°·5 with the standard plane as used in the Lund tables). Within a circle of 8 kpc around the centre the points of maximum density nowhere deviate more than 75 pc from the plane, except in a few small areas. Within 6 kpc from the centre the deviations are all less than 30 pc (cf. Fig. 3), or roughly 1/1000th of the diameter of the disk. The extreme neatness with which the gas has arranged itself into such a disk is the more remarkable when contrasted to the unevenness of the distribution *in* the

plane. For $R > 10$ kpc somewhat greater deviations occur, running up to 600 and 800 pc in the outermost regions of low density. These deviations present a distinctly systematic character, as may be seen from Fig. 3 (cf. also (**9, 16**)).

The hydrogen distribution in the plane of the disk is shown in Fig. 4. The densities are indicated by contour lines and different types of shading. The picture is based partly on results derived in Leiden (from 340° to 220° longitude) and partly on measures made in Sydney (from 220° to 316°). There was a large region of overlap, inside which the observations agreed very well. The radio telescopes used were a 7·5-m Würzburg and a 11-m meridian telescope, respectively. The beam width to half power was $1^\circ\!\cdot\!8 \times 2^\circ\!\cdot\!8$ for the Dutch telescope and $1^\circ\!\cdot\!5$ for the Australian one.

It should be emphasized that the distribution obtained depends considerably on the resolving power and on the particular assumption made regarding to velocity dispersion, temperature of the gas, circularity of the average motion, etc. We believe that the diagram gives the general pattern fairly well, but the densities must be considered very uncertain, in some cases by a factor of two or more. The relatively wide beams efface the detail structure of the interstellar medium and are suitable for observing the large-scale features with which the present report is concerned. The zone between latitudes -10° and $+10^\circ$ was practically completely covered from 318° to 125° longitude; in the remaining longitudes the observations were spaced at somewhat larger intervals, so that roughly half of the surface between -10° and $+10^\circ$ may have been covered.

The distribution of the hydrogen evidently shows great irregularities. Nevertheless, several arms can be followed over considerable lengths. The Sun appears to be situated near the inner edge of an arm which stretches out in the direction of Cygnus and can be followed more or less continuously down to about 340° longitude. The continuation of the arm in longitudes past that of the anticentre is not so well defined; it probably passes through the big Orion association. Because of this the entire arm has been called the Orion arm. In the longitudes from 65° to 130° there is a conspicuous arm at a distance of about 10·5 kpc from the centre. This has been called the Perseus arm, after the large association around h and χ Persei which is situated close to it. The broad, almost circular structure between $R = 9$ and 12 kpc, extending from 65° down to 340°, may be a continuation of this arm. On the southern side there is no counterpart to this prominent outer arm. The pattern ends in a more straggly style. Inside $R = 8$ we meet between $R = 6$ and 7 the "Sagittarius arm", which appears to move in towards the centre when we follow it in clockwise direction. At longitudes between 200° and 310° the structures may be slightly less continuous. For this reason and because of the great gap between 315° and 340°, where, except at small R, the differential rotation is too small to separate the various arms, it is not yet possible to follow the arms all around the centre.

The outer boundary of the disk appears to be about 15 kpc from the centre, but the average density diminishes very gradually, and it is quite possible that more distant bits will be discovered. Fig. 5, based on the sector between 340° and 220° longitude, indicates how the overall average of the gas density varies with distance from the centre. There is a distinct maximum around $R = 7$ kpc. It may be noted that a similar maximum, around $R = 11$ kpc, occurs in the Andromeda nebula, but there it is much sharper. The distribution in the Andromeda nebula is shown by a dotted line in Fig. 5. The thickness of the

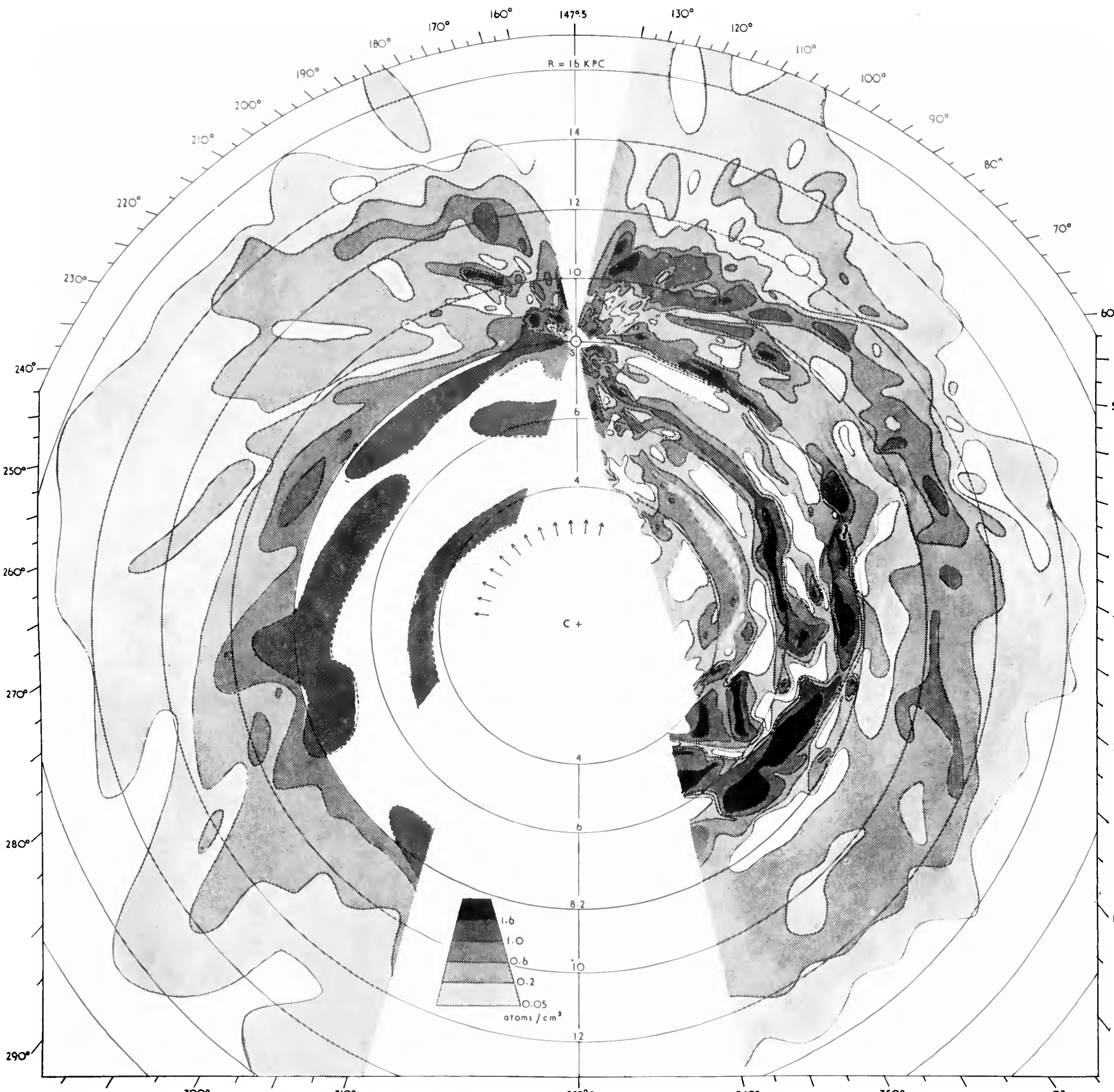

FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

The Galactic System as a Spiral Nebula layer is unknown in this case; the densities have been computed on the hypothesis that it is the same as in the Galactic System.

Because of the imperfections in the observed hydrogen distribution it is still somewhat difficult to assign to the Galactic System an accurate classification among the classes of spirals. Judging from the number of continuous arms cut by a radius vector and from their spacing, it is similar to the Andromeda nebula and M 81, possibly slightly " later ". It would therefore be of class Sb.

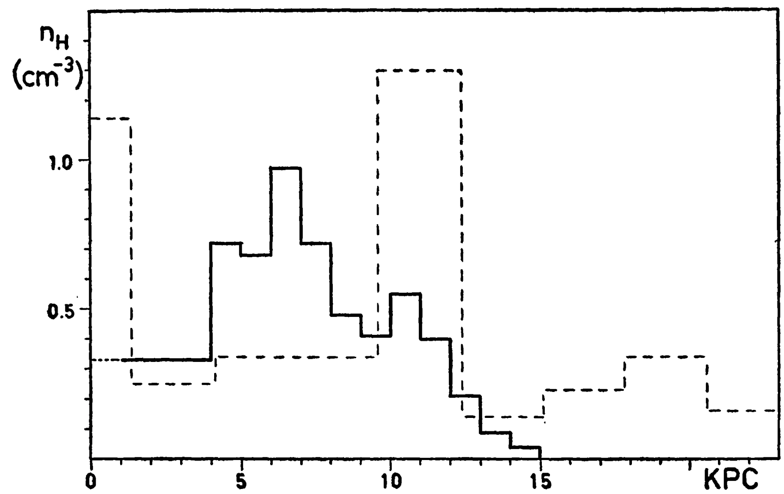

FIG. 5.—*Variation of average density in the galactic plane with distance from the centre* (6), *and comparison with the Andromeda nebula* (**17**) (*dotted line*).

It is certainly much more compact than typical Sc galaxies like M 101 and M 33, while it does not show the closely wound arms of early Sb nebulae like NGC 4594. Moreover, it clearly has a considerable central bulge of stars, but nothing comparable to that in NGC 4594. An additional indication of its place in the sequence of spiral galaxies may be obtained through a comparison of the fraction of the total mass which exists in the form of interstellar gas. For our Galaxy this is 2 per cent, for the Andromeda nebula it is 0·8 per cent, while in M 33 4 per cent of the mass is interstellar hydrogen. In elliptical galaxies, on the other hand, the interstellar component seems to be quite small. These considerations would make the Galactic System just a little " later " type than M 31.

4. *Expansion in nuclear region.*—In Fig. 4 one conspicuous arm has been drawn in a tentative manner, viz. the arm indicated by small arrows at about $R=3$ kpc. It can be followed from about 303° to 331° longitude. Its distance has been inferred from the fact that it appears to become tangential to the line of sight around 303°. If observed with a sufficiently narrow band and beam it stands out as a well-defined and rather sharp maximum in the line profiles. In Fig. 6 the velocities of this maximum are plotted against longitude. The run is extremely regular. The arm can be seen in absorption against the strong source Sagittarius A, which is presumably situated at the galactic centre* (**18**). The absorption-line velocity has been indicated by a cross in Fig. 6; it agrees perfectly with the emission velocities in the surrounding points. It shows that the arm passes between the centre and us, and that, in addition to rotation, the

* This may be a concentration of ionized gas of about 200 000 solar masses, of the same nature as the concentrated masses of gas which are so frequently observed at the centres of elliptical galaxies; generally the latter masses are somewhat higher.

gas of the arm has a velocity of 53 km/sec away from the centre. We shall therefore refer to it as the " 3-kpc expanding arm ". It is certainly not the only feature of this kind. From the line profiles in directions differing less than about 15° from 327°·7 one can see that in the part within 2 or 3 kpc from the centre large systematic deviations from circular motion must be the rule rather than the exception. Deviations up to 200 km/sec have been found. They are not of the nature of random motions, but represent mass motions of extended concentrations of matter. In the case discussed above we are clearly dealing with an *arm*. It is still unknown whether the other moving features are likewise

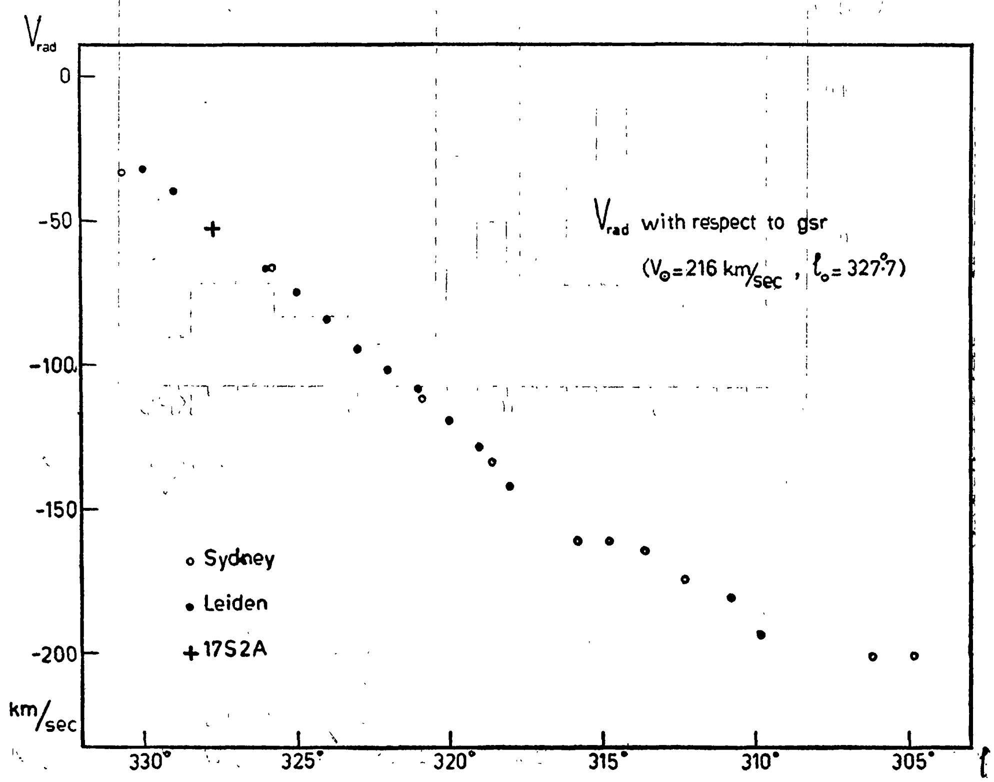

FIG. 6.—*Variation with longitude of the radial velocity of the " 3-kpc expanding arm ". The observed values were corrected for the motion of the Sun around the galactic centre. The Leiden points were measured with the Dwingeloo 25-m telescope. (Courtesy of Mr G. W. Rougoor.) The Sydney points were measured with the Sydney 11-m meridian telescope. Further details concerning the expanding arm are given in* (10).

arranged in arms or whether they are just loose bits. It is plausible to assume that, as in the 3-kpc expanding arm, the gas in these other " arms " is streaming away from the centre. Indeed, recent absorption measures in Sgr A by Rougoor show that the gas clouds for which the radial velocity (corrected for solar motion) exceeds 30 km/sec *all* move away from the centre. He has been able to verify this for radial motions between about 30 and 140 km/sec. It is worth remarking that these expanding velocities must be almost exactly in the galactic plane, as practically all of these features lie within 100 pc of the true galactic plane.

Clearly, estimates of the circular velocity in the nuclear parts are rendered very doubtful by the existence of these large deviations from circular motions, in particular because they appear to have the character of systematic velocities away from the centre. For this reason the rotation curve of Fig. 2 is quite uncertain in the part within $R=3$.

It is possible that outward motions of smaller amount occur also at larger distances from the centre. In principle this could be investigated by special 21-cm line observations. At the time of writing these had not yet been made.

The gas motions in the central part may be strongly influenced by large-scale magnetic fields (cf. Section 5). It is unknown to what extent magnetic forces affect the motions beyond 3 kpc. But it is well to keep in mind the possibility that these may have caused appreciable errors in the gravitational forces and the mass distribution computed from the observed rotation up to about $R=5$ kpc. However, there is good reason to believe that at distances R comparable to that of the Sun such effects are practically negligible. For, in the general vicinity of the Sun, the average motion of stars that are old enough to have become practically independent of the gas from which they originated, is nearly the same as the motion of the gas. There may be a difference of about 5 km/sec between the solar motion with respect to A stars and that with respect to the gas and the very young stars, but such an amount is of no consequence in comparison with the total velocity of rotation.

5. *Evolution of spiral structure.*—What new information can the observations of the spiral structure of the Galactic System give us which could not be obtained from external galaxies, and what hope do they hold out for getting an insight into the processes causing spiral structure and maintaining it after it has originated ? The information may be classed in three categories:

(*a*) The gaseous nature of spiral structure.

(*b*) Relation with the distribution of *stars*.

(*c*) The field of force.

We shall briefly consider each of these subjects.

(*a*) Although convincing evidence that interstellar gas is concentrated in the spiral arms had been obtained previously, in particular in Baade's surveys of emission nebulae in M 31 and M 81, the 21-cm observations of our own galaxy furnish for the first time quantitative data on the concentration of gas in the arms. Although the evidence requires further substantiation, it is already clear that in many inter-arm regions the density is small compared to that in the arms.

A datum of extreme importance for the understanding of the phenomenon of spiral structure is the amount of random motion in the interstellar medium. On this point very little information can be gathered from other galaxies. For our own galaxy the large new radio telescopes will presumably enable us to collect a considerable amount of data on random velocities.

The astounding flatness of the System, which has been commented upon above, is of importance in connection with the internal motions in the medium. Not only does it provide a measure for the average random motion of the interstellar clouds, but it also indicates that there must have been a very large amount of exchange of momentum from the innermost to the outermost parts of the disk.

A fundamental question in the problem of spiral structure is whether this is essentially a phenomenon of *gas* dynamics (possibly connected with magnetic fields) or whether the stars themselves make the major contribution to the density of the arms, so that the problem would be one of *stellar* dynamics. The latter possibility has been worked out in considerable detail by Lindblad (11). Some phenomena in external galaxies give strong indications that the spiral formation is intimately related to their content of interstellar gas, and that the presence of enough gas is an essential condition for the existence of spiral structure (12). But it would evidently be very important to know whether in the Galactic System the arms consist mainly of gas or of stars.

(*b*) It is clear that stars which have recently been formed from the gas must be situated in the gaseous arms. The connection between young stars and the general distribution of the gas is demonstrated in the surveys of OB associations (13) and δ Cephei variables (14). Surveys of such supergiants, fragmentary though they are because of interstellar absorption, are extremely valuable for the investigation of the spiral structure. They can bridge gaps in regions where the differential rotation is too small to resolve the 21-cm radiation and, because the stellar distances are known, they can give information on systematic deviations of spiral arms from circular motion.

It may be estimated that stars will in general stay within the spiral arms in which they were born for several hundred million years, but that after about five hundred million years they may show appreciable differences from the distribution of the gas if the latter is supposed to be kept in its spiral pattern by other forces in addition to that of gravitation. So far, no sufficient evidence for a decisive comparison between the distribution of older stars and gas has been obtained.

(*c*) In no other galaxy are the velocities of rotation and the gravitational field known with an accuracy comparable to that obtained in the Galactic System. Though the arms cannot yet be followed around the whole system, it is fairly clear from the parts over which they can be followed that the arms are trailing. If we suppose that like other regular Sb spirals the Galactic System has two main arms, the spacing between the large arms gives an indication of their average inclination. The observed differential rotation gives us then at once the time scale in which the present spiral structure would radically change its appearance. This scale is found to be between 100 and 200 million years. This is so short compared to the age of our galaxy that we are forced to conclude that the arms must either smooth out rapidly and then be replaced by completely new ones, or that there is some mechanism that keeps up the existing arms, notwithstanding the stretching effect of the differential rotation. A possible mechanism is that of gas transport between neighbouring arms. Rough estimates indicate that this would work in the right direction and might be of the right order. But such a mechanism, though it might preserve the arms once they are formed, would give no clue to the way in which the spiral structure could have originated, nor how the expanding arms in the nuclear region come into existence. The latter problem is acute, because, considering the speed with which they move out, these expanding features must be formed at relatively short intervals.

Though it is still entirely obscure how magnetic fields could produce these phenomena, it is tempting to think that there is some connection between large-scale interstellar magnetic fields and spiral arms. Three phenomena point in this direction. The first is that interstellar polarization of light indicates the presence of magnetic fields which, at least in some cases, seem to have their average direction along arms. The second is concerned with the continuous radio-frequency radiation. Part of this is strongly concentrated to the galactic plane. Its intensity distribution in the plane appears to be clearly connected

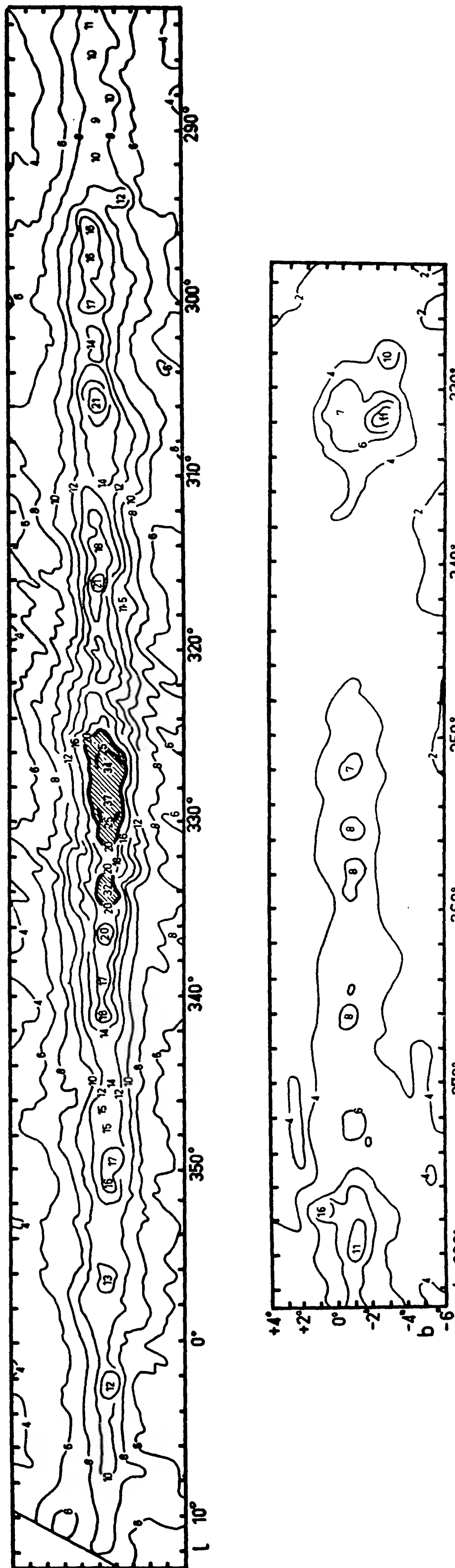

FIG. 7.—*Distribution of brightness temperature near the galactic plane at* $3\frac{1}{2}$ *m wave-length* (15). *The unit is* 1000 °K. (*By courtesy of Dr B. Y. Mills.*)

with the spiral structure. This is well brought out by Fig. 7, which gives the continuous radiation at 3·5 m wave-length observed by Mills, Hill and Slee (**15**). Practically all of the radiation at this wave-length, even at low latitudes, must be of non-thermal origin. This was shown by a comparison with a survey at 22 cm wave-length by Westerhout (**18**). This non-thermal component may be largely "synchrotron" radiation from high-energy electrons moving in interstellar magnetic fields. If this is correct, Fig. 7 indicates that the interstellar fields may be strongly concentrated in the arms.

The third phenomenon relevant in this connection is the radio corona of the Galactic System. We shall not deal with this in the present report, except to mention that its existence around the Galactic System as well as around the Andromeda nebula gives considerable support to the idea that magnetic fields are an essential factor in the large-scale structure of spiral nebulae. It should also be pointed out that the corona is likely to be the reservoir replenishing the central region with the gas needed to keep up the fast stream moving out of it into the larger disk.

It is clear that as yet we have made little or no progress towards an understanding of the origin of spiral structure. But the recent investigations on this structure in the Galactic System indicate at least some new roads for future research into this problem.

J. H. OORT.
F. T. KERR.
G. WESTERHOUT.

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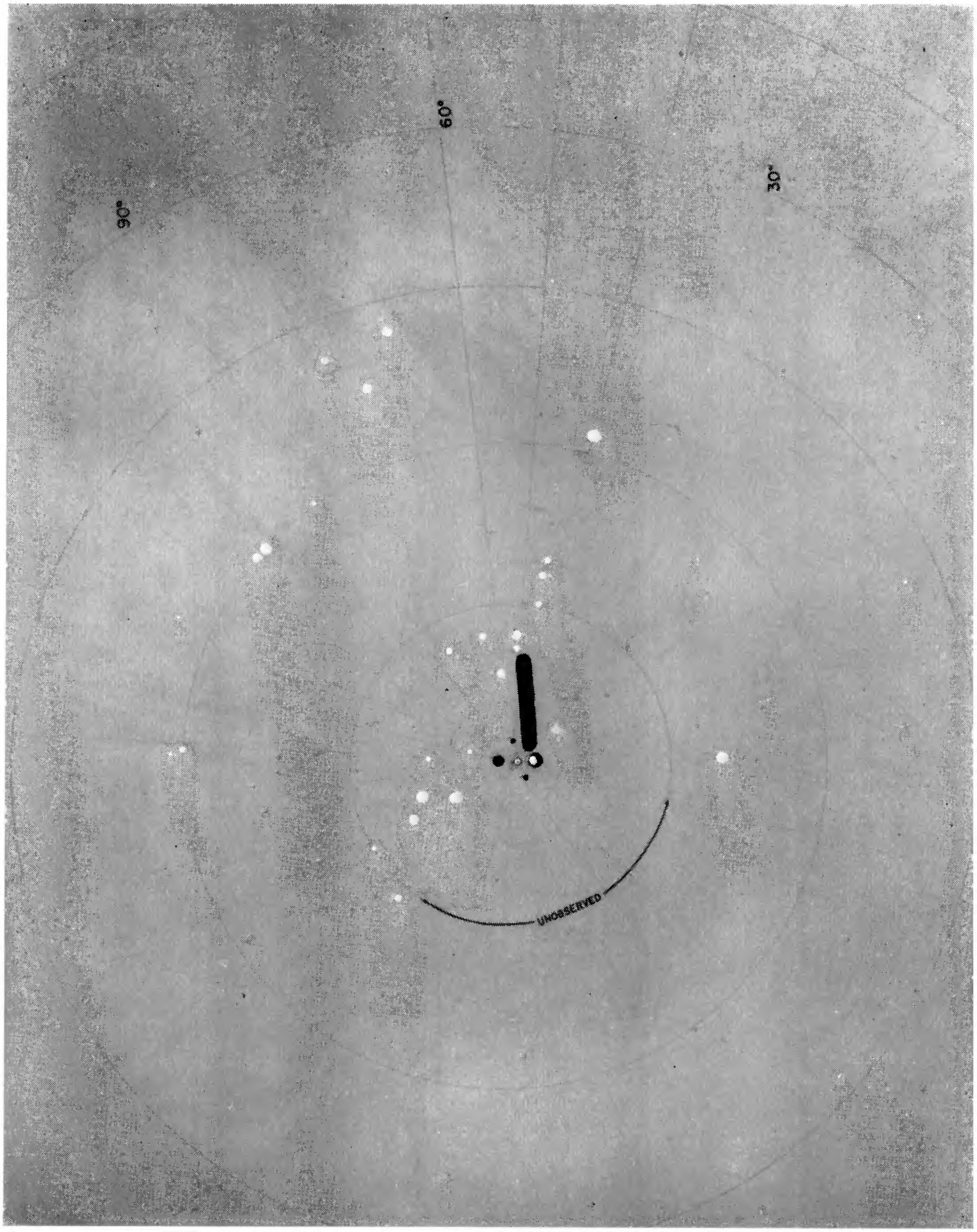
FIG. 1.—*Distribution of emission regions* (4). *The numbers indicate galactic longitudes.*

(By courtesy of Dr W. W. Morgan.)

The Galactic System as a Spiral Nebula



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