SECTION 1

THE GALAXY

1. STRUCTURE OF THE GALAXY

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I. Introduction and Survey of Problems

The title which the organizers of the Symposium have suggested for this introductory report covers an enormous domain. Even if one limits oneself, as I intend to do, to the *large-scale* structure, it is impossible to summarize this adequately in one communication. I intend therefore to confine myself to give, firstly, a list of principal subjects in which advances have been made and of the main problems which these advances have raised, and, secondly, to comment somewhat more extensively on some points which at the moment appear to be especially important.

In the study of the large-scale structure of the Galaxy the information obtained from radio-astronomical observations has surpassed that obtained from optical data. This is due to the fact that in the disk of the Galaxy optical observations are practically restricted to a region with a radius of at most 3 kpc around the Sun, while objects outside the disk are generally so faint that it is extremely difficult to get adequate observations in the more remote parts of the Galactic System. Nevertheless some very interesting information on the large-scale structure has been extracted from optical data. I shall come to this a little later.

The following list summarizes the most relevant domains of research:

21-Cm Line Observations	*Inferences and Problems*
Rotation curve	Used for determining distribution of gas and for finding mass distribution in disk
Thickness of layer	
Flatness and tipping	Intergalactic "wind", or attraction by Magellanic Clouds
Spiral structure	Problem of origin and conservation
Overall density distribution of the gas	Why density maximum near $R=11$ kpc?
Radial motions in central region Asymmetry between $l^{\mathrm{II}}= -10$ to $0°$ and 0 to $+10°$ Amount of gas involved Distribution of gas in central part	Magneto-hydrodynamic effects, or super-explosion
Gas in halo	Where does it come from?
Zeeman splitting	Strength of magnetic field

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Thermal Radiation	
Distribution	Relation with expanding gas in central part?
Nonthermal Radiation	
Distribution in disk Halo	General distribution of magnetic field Extragalactic background
Polarization	
Discrete sources	
Optical Observations	
A, B, R_0, Θ_0	
Spiral arms Vertex deviation	Dynamics and evolution of arms
Mass density near Sun	Density of unobservable stars
Density- and velocity-distribution of old disk objects	
Density- and velocity-distribution of halo objects of varying metal abundance	Length of period in which most of the heavy elements were formed Length of contracting stage of the Galaxy Ratio of regular to irregular motion in primordial gas

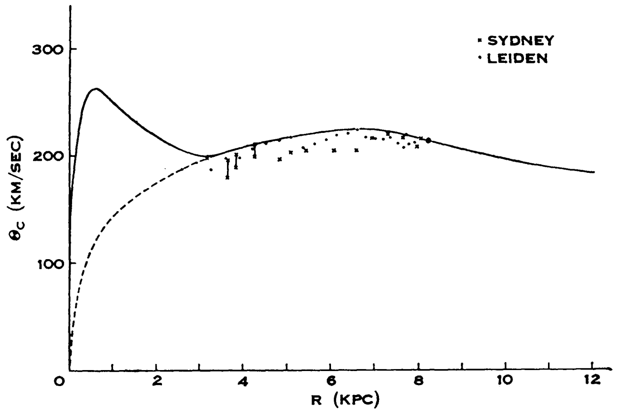

Fig. 1.—The variation of circular velocity with distance from the centre.

Radio Data

II. Rotation Curve

A very provisional rotation curve is shown in Figure 1. I shall not enter upon the difficulties of its determination, except to say that the part between 0·6 and 3 kpc has been interpolated. In this interpolation it was assumed that the mass distributions in the Galactic System and the Andromeda nebula are similar, and that the distribution is also similar to that of the light.

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The curve purports to give the "gravitational" circular velocity. In the region between $R=0\cdot6$ and 3 kpc the actual motion of the gas is quite different. It has large radial components and there are indications that its rotational motion is very much lower than that given by the curve.

In the region between 3 and 8 kpc from the centre the rotation curve found from the southern part of the Milky Way — between 300 and 330° longitude — appears to be about 10 km/sec lower than that in the northern hemisphere. This may be due to a real difference in the transverse velocity of the gas, or it may be due — as Kerr has suggested — to an outward velocity of about 7 km/sec of the gas in the vicinity of the Sun.

From the rotation curve we can derive a rough picture of the mass density in the galactic plane at various distances from the centre. The resulting values are indicated in Table 1 below, together with the run of the gas density, both in units of 10^{-24} g/cm^3; R is in kpc. The mass density increases very strongly towards the centre.

TABLE 1
MASS DENSITY IN GALACTIC PLANE

R	Density		R	Density	
	Stars	Gas		Stars	Gas
0·02	80000:	100:	3·0	70	5
0·10	7000	5	8·2	10	2
0·5	400	2			

III. Thickness and General Shape of the Gas Layer

The effective thickness varies from about 50 pc in the disk within 0·5 kpc from the centre to roughly 110 pc in the "3-kpc arm", and 270 pc between $R=3$ and 9 kpc. Between 9 and 12 kpc it appears to increase to about 600 pc. The gas layer is remarkably flat over the denser part of the Galactic System, but, as Kerr has first noted, it bends away from the mean plane beyond about 8 kpc. The bending is in opposite sense in opposite parts of the disk. The deviations run up to about 500 pc at $R=12$ kpc (Fig. 2). Blaauw and Habing in Groningen have shown that at larger distances the deviations increase to still larger values, up to perhaps 4 kpc for R between 15 and 20 kpc; however, the densities in these parts are very low (about 0·03 atoms/cm^3).

There must be an outside mechanism which keeps up these systematic deviations. Kahn and Woltjer (1959) have suggested that they may be caused by what one might call an intergalactic "wind". It has also been suggested that the tipping might be caused by the tidal force of the Magellanic Clouds. However, it is still uncertain whether the effect could be sufficient to explain the derived deviations.

IV. Spiral Structure and General Density Distribution of the Gas

Notwithstanding the great amount of information obtained from 21-cm line profiles, it has not yet been possible to delineate the overall run of the spiral arms

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through the Galaxy with any confidence. This is due, on the one hand, to the large gap in the general direction of the centre (where the radial component of differential rotation is too small to give a proper resolution) and to a similar but smaller gap in the direction of the anticentre. On the other hand it is due to the difficulty of separating nearby and distant arms in the part inside $R=8$ kpc.

We *do* know that the gas is strikingly concentrated in long ridges, which at our distance from the centre are about 2 kpc apart (cf. Fig. 3). We can surmise that in analogy with other spirals the arms form a large-scale pattern over the major part of the system.

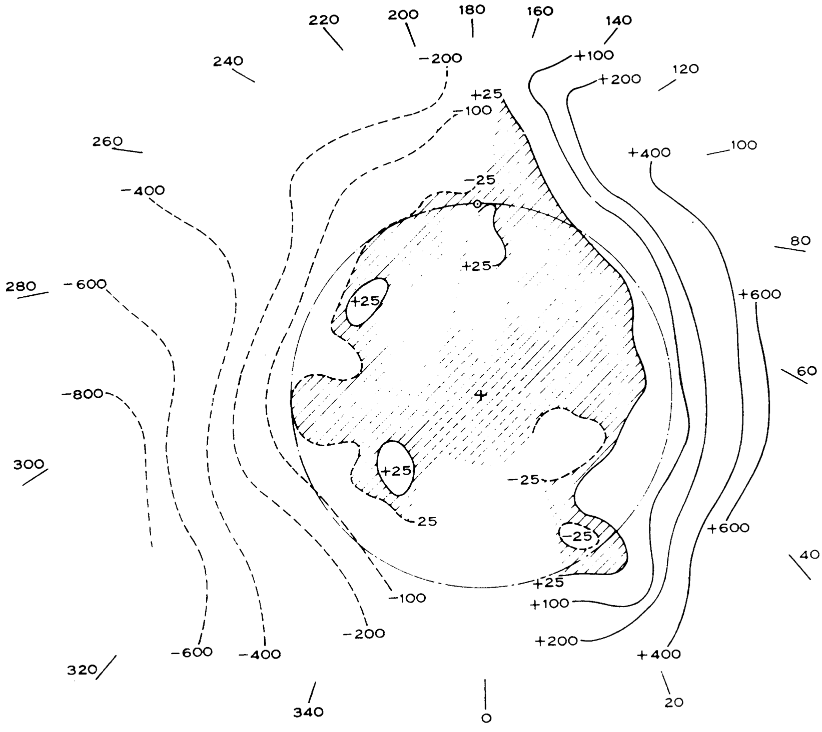

Fig. 2.—Relief map showing the height (z pc) of the position of maximum hydrogen density above the new galactic plane. The distance scale is based on the Leiden velocity model.

The distribution shown in Figure 3 is based on surveys made in Australia and the Netherlands with aerial beams of 1°.5 to 2°. New observations with narrower beams, such as are now being made at Parkes and as have been made during the last five years at Dwingeloo, are likely to produce a rather better insight into the true structure. At Dwingeloo and Leiden, Rougoor has just completed a detailed study of the region between -8 and $+22°$ longitude; the region between 22 and 42° longitude has been investigated by W. Shane. This latter investigation covers the belt between -8 and $+8°$ latitude; it was chosen because it is just outside the region where large expansional motions had been found. There are signs of some "expanding" features at the edges of the main galactic belt at 22° longitude.

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If we suppose that the arms observed in the 21-cm radiation are part of a more or less continuous spiral pattern, we are faced with the problem of how such a pattern can be maintained in the presence of the relatively fast differential rotation observed in the system. We either have to assume that the gas flows along the spiral arms — and presumably in an inward direction — or that the spiral arms are continually accreting gas in such a way that this compensates the stretching caused by the differential rotation. A model showing this latter effect will be discussed by Lindblad. In either case we must assume that a large-scale circulation of gas takes place through the system (cf. Oort 1962).

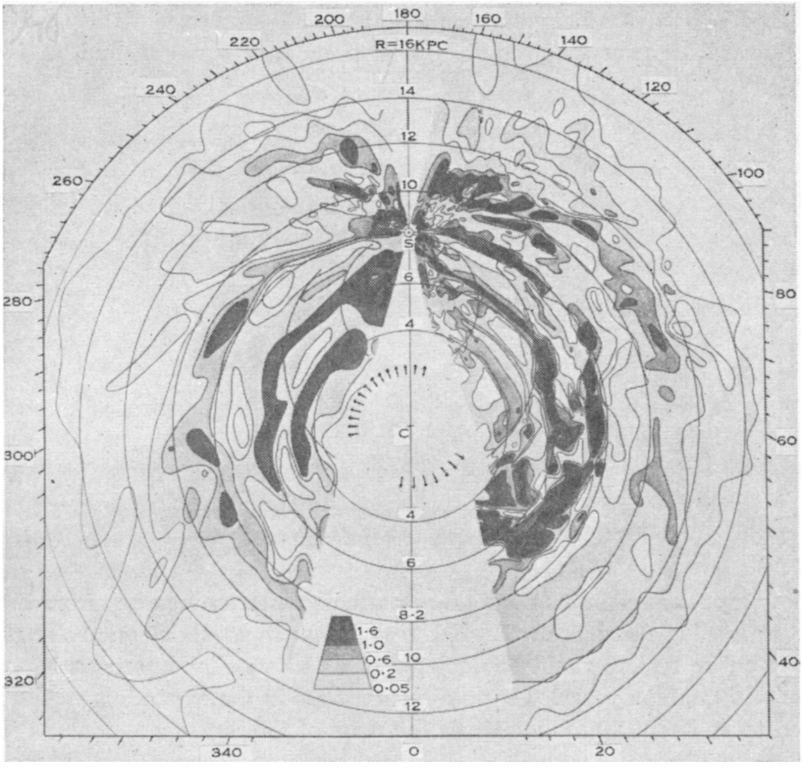

Fig. 3.—Distribution of hydrogen in the galactic plane.

Attempts to find evidence for a systematic radial motion of the gas in the main part of the disk have so far given negative or inconclusive results (cf. an extensive investigation by Braes (1963) from scans perpendicular to the Milky Way at longitudes within 5° from the centre).

The overall density of hydrogen in the plane shows a maximum around 11 kpc and a sharp drop beyond that distance. The reason why the gas density is less in the inner regions than in this outer ring, a phenomenon that is still much more pronounced in the Andromeda nebula and in various other galaxies, is still unknown.

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V. The Central Region

For a discussion of the phenomena in this region I refer to this volume, paper 42, as well as to an article by Rougoor and Oort (1960). The main features observed are collected in a rather schematic way in the sketch (Fig. 4). This shows a disk of about 600 pc radius around the centre, rotating with an angular velocity which at the outer edge is about 20 times that near the Sun and must be at least 10 times higher still in the innermost parts. The so-called 3-kpc arm, between the centre and the Sun, has at the point where it is seen in the direction of the centre a radial motion of 53 km/sec away from the centre. On the other side of the centre there is a somewhat less outstanding arm which appears also to move away from the centre. At $l^{\rm II}=0°$ the radial component is about 130 km/sec, but this must increase rapidly toward negative longitudes. The arm ends, or turns around, at $l^{\rm II}=-5°$.

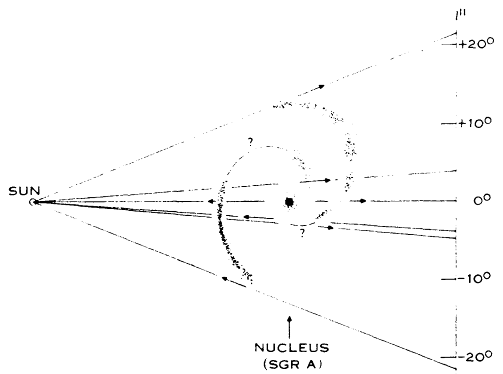

Fig. 4.—Sketch of expanding arms and rotating disk in the central region.

As a very rough estimate the total amount of gas streaming away from the centre in these expanding features in the disk may be given as about one solar mass per year. The entire region would be depleted of its interstellar hydrogen in a time of the order of 40 million years. The total mass of gas in the expanding region may be estimated to be about 20 million times the mass of the Sun.

VI. Gas in the Halo

The first indications of the occurrence of gas clouds in the galactic halo were given by Münch and Zirin (1961) from observations of interstellar Ca^+ lines. Various attempts have been made in Dwingeloo to observe high-velocity gas in high galactic latitudes. Recently these observations have become successful in showing the existence of some high-velocity clouds of neutral hydrogen and possibly also of some gas with a large spread in velocity. The latest observations were made with a parametric amplifier constructed by C. A. Muller. As only a small part of the reductions had been finished before I left Leiden, I cannot yet give any statistics of the halo gas. The amount of high-velocity gas in the halo might be as much as one-tenth of the total mass of hydrogen in the disk.

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VII. Thermal and Nonthermal Radiation

For the thermal radiation I refer to the communication by Mathewson, Healey, and Rome (1962). A remarkable feature found by Westerhout from northern observations and confirmed by Mathewson, Healey, and Rome on both sides of the centre, is the strong concentration around $R=3\cdot5$ kpc, and the sharp drop beyond $3\cdot5$. Mathewson, Healey, and Rome indicate also other concentrations inside this "ring". A noteworthy observation is that there appears to be no strong correlation between the distribution of ionized and neutral hydrogen.

The most essential problems connected with the nonthermal radiation are, firstly, whether or not this radiation is distinctly correlated with the hydrogen arms, and, secondly, what is the nature of the radio corona around the Galactic System. There can be no doubt, in my opinion, concerning the *existence* of an extended corona of small flattening and little concentration towards the centre.

It may be expected that the extension to other frequencies of observations of the polarization of the radio-frequency radiation such as have recently been made at 400 Mc/s will ultimately throw some light on these problems.

Optical Data

VIII. The parameters A, B, R_0, and Θ_0

In recent years evidence has been produced that the constant A is probably somewhat lower than the standard value of $19\cdot5$ used up to the present in 21-cm line reductions. The best evidence comes from new distances and radial velocities of galactic clusters and cepheids. Dr. Schmidt has given a general survey of all the evidence, which leads him to propose the following values:

$A =$ 15 (from galactic clusters and from cepheids)

$B = -10$ (compromise between direct determination, determination from ellipsoidal velocity distribution, and from probable value of the mass density gradient near the Sun)

$R_0 =$ 10 (from RR Lyrae variables and from value of AR_0; this latter was found to be between 140 and 150)

$\Theta_0 =$ 250 (from the above values of A, B, and R_0)

IX. Spiral Arms

If we have sufficiently accurate individual distances of young stars or young clusters, their distribution can be used to trace the spiral arms in a manner which is to some extent independent of the 21-cm studies. And, what is particularly important: we can hope in this way to connect up some of the arms through the longitudes near the centre and anticentre.

As the stars become older they will move away from the arms in which they were formed. This would happen even if the bulk of the gas moved with the gravitational circular velocity, because the stars are born with certain random

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velocities. For a random velocity of 10 km/sec the radial dimensions of the epicycle are 1·0 kpc if the original motion was in the θ-direction, and 0·6 kpc if it was in the radial direction. In the first case the centre of the epicycle will be shifted outward or inward from the position where the stars were born by an amount of 0·5 kpc. The true random motions may well be somewhat higher still. Kraft and Schmidt in their recent exhaustive discussion on cepheid velocities obtain 11 km/sec for the mean residual in radial velocity, corresponding to ± 15 km/sec for the total velocity in the galactic plane.

With such random motions the stars will disperse so much beyond the edges of an "arm" that the arm structure will no longer be recognizable after a time corresponding to a quarter to half a revolution in the epicycle, i.e. after 50 to 100 million years.

If we want to trace the spiral arms we must therefore in general confine ourselves to objects of about 50 million years or younger; i.e. to main-sequence stars of type B3 and earlier and cepheids with periods longer than about 10 days.

Especially interesting might be the information which the distribution of stars or star clusters of various ages could give on the *systematic* shift with respect to the gas arms. If the motion of the gas differs systematically from the gravitational circular velocity the stars will become shifted *systematically* from the arms. Suppose, for instance, that the gas rotates more slowly than a star moving in a circular orbit. Then the stars will have a tendency to move to smaller R; the centres of their epicycles will on the average lie inside the places where they were formed. Similar systematic deviations in the opposite sense will occur if the arms are continually displaced inward through accretion. In principle, therefore, observations of stars may in the future yield information on the mechanism by which the spiral arms are maintained. Some interesting, though still rudimentary, evidence of this sort has been obtained in a recent study by Kraft and Schmidt on the distribution of cepheids of different ages (cf. this volume, paper 16). There are evidently important differences. But it has not yet proved possible to interpret them satisfactorily. The concentration of older cepheids inside R_0 might indicate that the gas had indeed a lower velocity than the gravitational circular velocity. Somewhat similar phenomena for galactic clusters of different ages will be shown by Becker (paper 3). The *velocity* distribution of stars will likewise be influenced by their formation in spiral arms. It is not unlikely that the well-known deviation of the vertex of star streaming may be explained in this way. A rough numerical attempt for this has recently been made by Andrew Young at Harvard.

X. *Mass Density near the Sun and Distribution of Mass Density in* z*-Direction*

This has been derived from a comparison of the motions and the density distribution in the direction perpendicular to the galactic plane. The resulting density is $10{\cdot}5 \times 10^{-24}$ g/cm^3, or $8{\cdot}8 \times 10^{-24}$ g/cm^3, depending upon whether the unobservable stars are distributed like K III giants, or like a halo population. In the first case the unobservable stars would contribute 1·1 times the density of known stars, in the second case 0·7 times this density. From the same data one can derive the distribution of the total mass density in the z-direction.

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XI. Density- and Velocity-Distribution of Old Disk Stars

The best evidence available is probably that derived from planetary nebulae. Their average z is 340 pc. They show a very strong concentration towards the centre. They cannot, however, be observed in the nucleus itself. We see mainly the extension of the nucleus from 200 to 800 pc south of the true galactic plane. The density in the nucleus must be at least 1000 times that near the Sun.

XII. Density- and Velocity-Distribution of Halo Objects of Varying Metal Abundance

Again, available knowledge is very imperfect. The best general information appears still to be that provided by globular clusters. The density between 1 and 3 kpc from the galactic centre is about 40 times that between 5 and 9 kpc, while the density drops by a further factor of about 10 in the shell between 9 and 13 kpc. The axial ratio of the surfaces of equal density may be about $\frac{1}{2}$, and possibly somewhat smaller in the central part.

A most interesting phenomenon is that in the halo we find side by side clusters with extremely low abundance of metals, like M92, and clusters like M3, where this abundance is only moderately different from that which we find at present in the interstellar gas. The globular clusters which are concentrated near the centre show an almost "normal" metal abundance. This indicates that the formation of the heavy elements must have occurred practically entirely in the very early stage of the evolution of the Galactic System, and well before the gas had collapsed into a centrally concentrated disk. The total density of the halo Population II is unknown. It must, however, be larger than that given by the known subdwarfs, which yield already an appreciable part of the total mass of the Galaxy. The further investigation of the exact relation between metal abundance and z-velocities for subdwarfs is certainly of essential significance for our insight into the early evolution of the Galactic System. A report on this will probably be given by Eggen. It is hoped that a much better insight into the density distribution of various sorts of halo stars will become available through Plaut's and Kinman's extensive surveys of faint RR Lyrae variables in selected regions of the sky.

The only additional knowledge that we have at present is a determination of the density gradient of halo stars at distances between 1 and 2 kpc from the galactic plane. Near the Sun $\delta \log \nu/\delta R$ is about $-0 \cdot 15$, corresponding to a variation of the density proportional to $R^{-3 \cdot 5}$.

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