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PROBLEMS OF GALACTIC STRUCTURE*

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Since the first quantitative investigations of the Galactic System were started by William Herschel, two great developments have taken place in our knowledge of the structure of this system. The first of these may be tied up with the name of J. C. Kapteyn. Consistently pursuing the ideal of revealing the general structure of the entire stellar system, Kapteyn laid the foundations for much of the modern work in this line, thereby initiating essentially all the methods used today. Although Kapteyn succeeded in determining the structure in those parts of the system that are more than about 20° from the Milky Way, obtained important numerical results for the variation of star density with distance from the galactic plane, successfully investigated the peculiar distribution of the B stars, and in the course of this work discovered the first dynamically important phenomena in stellar motions, he did *not* reach the principal aim he had set out for, because of the unexpected strength of interstellar absorption near the galactic plane.

The second great development was initiated by Shapley's investigation of the distribution of the globular clusters. Here the absorption of light was comparatively unimportant, because the clusters have high velocities and a large fraction were well outside the thin galactic layer of absorbing matter. These high velocities insured also that the clusters were well shuffled and therefore distributed symmetrically around the gravitational center of the entire Galactic System. As a consequence, they indicated its true dimensions and the position of its center.

It seems that at present a third phase in the development of galactic research has begun by the successful reception of radiation at radio frequencies. This research is still in its early infancy, comparable perhaps to the stage that Sir William Herschel had reached some hundred and fifty years ago by his star gauges in the visible radiation. What has been reached in the few years since active radio-astronomical research was started can hardly be expected to give more than the faintest glimpse of the changes of insight that the next years are likely to bring about. This circumstance evidently renders risky the task I have set myself here, which is to take stock of what knowledge has been acquired from the visible wave lengths and to compare this with the tentative first observations of the new era.

Let us begin by considering the region for which we have extensive knowledge, namely, the cylindrical region with axis through the sun and perpendicular to the galactic

* Henry Norris Russell Lecture, delivered in Cleveland, Ohio, on December 27, 1951.

plane and with radius of the order of 1 kpc. In this cylinder we shall consider, in the first place, the density distribution in a direction perpendicular to the galactic plane. We are then very little hampered by absorption effects. For ordinary stars the density is found to vary rapidly, as well as smoothly; it falls to less than one-tenth the density near the galactic plane at distances for which fairly reliable data can still be obtained from proper motions and spectra. Let us follow the common practice and denote the distance from the galactic plane by z. For z larger than 300 parsecs the density falls off approximately as the inverse square of z.

The cause of this decrease in density must be the attractive force of the Galactic System, more particularly the z-component of this force. Indeed, when we add up the mass of all the stars we know, as well as the interstellar gas, in a unit volume near the sun, we find that, together with the extra central mass of the Galaxy needed to explain the observed galactic rotation, this yields just about enough attraction to explain the density decrease observed. And this not only near the galactic plane, but likewise up to the largest values of z for which we have any knowledge about the density. Put into other words we may say that the distribution in the z-direction seems approximately to fulfil the conditions of a steady state, and to satisfy Poisson's law. The mass density near the sun needed to satisfy Poisson's equation would be about 80 solar masses per 1000 cubic parsecs;[1] known stars provide for about 50,[2] interstellar gas for 12. These values, which are all rather uncertain, would leave about 20 per cent of the mass unaccounted for. This should be ascribed to the unknown stars fainter than about +15 absolute magnitude.

Different types of stars show great differences in their distribution perpendicular to the galactic plane. As I have just mentioned, there is some evidence that the distribution in this direction corresponds with at least some approximation to a well-mixed, or steady, state. If, as a working hypothesis, we suppose this to be so, the velocity and density distribution are directly related to each other, and knowledge of either suffices to decide about the other.

It appears that all those types of stars that are *common* in our neighborhood show approximately the same distribution in the z-direction, corresponding to an average distance of some 300 psc from the galactic plane. An entirely different picture is shown by the O- and B-type stars, with an average distance of only about 50 psc. A transition is formed by the A and F stars. On the other side the extreme is presented by those variables of the RR Lyrae type that have periods longer than 0.42 day. These have an average peculiar velocity of 64 km/sec in the direction perpendicular to the galactic plane. Average velocities of the same order are found for the globular clusters. Another type of stars that seem to belong in this category are the faint white stars in high galactic latitudes discovered by Humason and Zwicky. This is indicated by the few radial velocities that have recently been measured by Humason[3] and by proper motions measured at Minneapolis and at Leiden. Corresponding average distances from the galactic plane are about 3000 or 4000 psc. There are again various types of stars that are intermediate between this extreme and the ordinary stars. Such transitional stars are generally much more frequent than the objects of extremely high velocity. As examples, we may mention the long-period variables; their average velocity in the z-direction is about 30 km/sec, corresponding to roughly 1000 psc average distance from the plane.

Among the stars of common types, such as ordinary G, K, or M dwarfs, we also find a certain fraction (perhaps 10 per cent among the fainter dwarfs) that distinguish themselves by velocities higher than one would expect in a velocity distribution of exponential

[1] *B.A.N.*, **6**, 284, 1932 (slightly corrected with modern data).

[2] This value is given by Blaauw in *Ned. Tijdschrift v. Natuurkunde*, **17**, 34, 1951; see also Kuiper, *A.J.*, **53**, 194, 1948.

[3] I am indebted to Mr. Humason for permission to quote this unpublished result.

type; these velocities show a highly asymmetrical distribution. The *Z*-velocities of the common-type high-velocity stars are however *not* very high. In the *z*-direction these stars hardly distinguish themselves from the low-velocity dwarfs. In that respect there is a pronounced difference in character between the main-sequence stars of high velocity and the RR Lyrae variables, for instance, a difference that indicates a quite different origin.

Another thing that may be mentioned at this point is that, especially among the types of stars that contain many high velocities, like the long-period variables, there seems to be a *smooth* transition from subtypes with moderate velocities to those with highest velocities, so that it is impossible to draw a satisfactory dividing line between the two. In these cases, at least, it would be an unwarranted oversimplification to try to divide the stars into two groups, corresponding to the two populations introduced by Baade.

We must here digress for a moment to discuss the notion of these two populations.[4] This idea is a most important one, by which Baade not only has considerably clarified our insight into the differences between various types of stellar systems but has likewise inspired quite a number of most interesting new investigations.

When Baade first introduced the idea of populations of types I and II, the meaning of these terms was clearly meant to apply to the general population of a certain category of stellar systems or of a part of a stellar system. Recently a tendency has developed to designate various classes of stars as belonging to populations I or II according to whether they show strong or weak galactic concentration or have low or high velocities. This usage of the terms is liable to lead to confusion, because the objects in the Galactic System present all gradations of concentration to the galactic plane as well as of velocity dispersion. It appears an inadequate simplification to describe the population of the Galactic System as a mixture of two different kinds of populations. If we were to extend the notion of population to cover the complicated phenomena observed, we would have to introduce a considerable number of different populations, or "subsystems" as they were originally named by Lindblad, a term that Kukarkin has later adapted to modern data. It would seem preferable to reserve the terms "population I" and "population II" for characterizing the general type of population of a stellar *system*, and to specify the degree of galactic concentration of a given type of *stars* by other terms.

The differences in population noted so far relate necessarily to such rare stars of great intrinsic brightness as can be observed in other stellar systems. We do not know as yet whether the *common* stars in a globular cluster or elliptical nebula are also different from those in our surroundings. However, there are two kinds of observations that can tell us at least *something* about the more common ingredients that other systems are made of.

The first relates to the interstellar gas, which can be observed by its well-known emission lines or by the dark matter that usually accompanies it. In the near future, observations of the emission line of neutral hydrogen at 21-cm wave length may give additional information on the total amount of hydrogen contained in a galaxy. It is well known that systems of population II show little or no interstellar material, while the population I systems appear always to contain a considerable amount.

The second sort of observations that teach us something about the *common* population are the measures of rotation. In many cases these permit some estimate of the total mass contained in the inner part of a stellar system, and sometimes they even give information about the variation of mass density within the system. We can compare these data to the amounts of light and can form, for instance, the ratio of mass to light. We observe a great variety in the values of this ratio in different systems and in different parts of the same system. If both are expressed in the sun as a unit, the ratio is found to be about 2 in the neighborhood of the sun. In other galaxies much higher values have been found. In the Andromeda Nebula, for instance, it varies from 13 at 600 psc from the center to

[4] Cf. Baade, *Pub. Obs. U. Michigan*, **10**, 7, 1951.

about 70 at 5500 psc.[5] The high relative mass density per unit of light in this latter case must indicate either that the amount of interstellar gas must be some hundred times higher than in our surroundings or else that practically all the mass density is due to stars of extremely low intrinsic brightness, which contribute only little to the mass density near the sun.

A similar result is found for the outer parts of the elliptical system NGC 3115, where the ratio runs even up to about 250.[6] In this case the possibility of the high mass density being due to interstellar gas must probably be discarded, so that the mass must be made up practically entirely of very faint dwarfs having a ratio of mass to light of more than 1000:1. Contrary to the light-intensity, which is strongly concentrated toward the center of the nebula, the mass density is found to be practically constant over the larger part of the system. The stars responsible for this mass must therefore form an approximately homogeneous atmosphere, imbedded in which lies the luminous system. In the central part the ratio of mass to light is only about 20. The relative numbers of the giant stars that are probably responsible for most of the light and the very faint dwarfs that must make up the bulk of the mass, therefore, vary considerably over the nebula.

From the scant information that has been obtained on radial velocities of individual stars in globular clusters we infer that in *these* population II systems the ratio of mass to light is near unity; the relative frequency of the type of faint dwarfs that form the bulk of the population of NGC 3115 must therefore be insignificant in globular clusters.

The examples just given indicate that, at least in the relative numbers of different kinds of stars, there must be a great disparity between systems classed in the same population groups according to criteria used so far.

We must now return to the structure of the Galactic System. We have discussed the distribution in the direction perpendicular to the galactic plane. If we leave out for the moment the new radio data, our further *direct* knowledge of the general structure may be summarized in few words. It consists of an estimate of the direction and distance to the center by means of globular clusters and RR Lyrae variables, of the density distribution of globular clusters throughout the system, and, finally, of a determination of the inclination to the galactic plane of the surfaces of equal star density at a z of about 1000 and 1500 psc.

However, some additional knowledge can be derived from stellar *motions*. The information they provide is summarized in Tables 1 and 2. Table 1 gives a confrontation of various *direct* determinations of the galactic longitude of the center with the direction of the center derived from the *motions* on the supposition that the relative systematic motions are perpendicular to the radius vector. It is evident that this condition is fulfilled to a close approximation. Table 2 shows the interrelation of various determinations of the constants of differential galactic rotation. It is to be noted that the determinations listed are largely independent of one another, both in the character of the data used and in the method. They have been combined in a least-squares solution. The results for A and B, as well as for the rotational velocity itself and the distance R to the center, are given in the last lines. In deriving the velocity of rotation, no use has been made of the velocities of globular clusters, because it would seem an unwarranted hypothesis to suppose that the system of clusters has no rotation. On the contrary, the available data seem to indicate a rotation for this system of about 90 km/sec at a distance from the center equal to that of the sun.

Assuming that the rotational velocity of the Galactic System corresponds to the circular velocity, we can at once derive the value of the force K that is exerted by the system on a unit mass near the sun. The quantity that is most accurately determined is K/R; this is equal to $-(A - B)^2$ and is found with a mean error of about 12 per cent.

[5] Wyse and Mayall, *Ap. J.*, **95**, 24, 1942; *Lick Obs. Contr.*, Ser. II, No. 2.

[6] *Ap. J.*, **91**, 302, Table 4, 1940.

From this we can obtain an estimate about the measure in which the density must increase in the parts of the system nearer to the center. If we compute the attraction exerted by a homogeneous ellipsoid with a density equal to the local density in our neighborhood and such a flattening that near the sun its thickness corresponds to the mean thickness of the layer of common stars, we find that this attraction accounts for less than one-fourth of the value of $K:R$ found from the angular rotation. This means that there must be a considerable additional mass in the central part.

At present we cannot say very much about the way in which this mass is distributed, except that it cannot be much concentrated toward the center. This follows in the first place from a consideration of the dynamics of the system of globular clusters. Because we know velocities of globular clusters throughout the Galaxy and because, on account of their high random motions, it is probable that their arrangement in space corresponds to a steady state, they enable us to draw at least rough conclusions regarding the gravitational potential in the Galactic System. If we represent the central mass by a homogeneous ellipsoid, it can be made compatible with the distribution of the clusters only if it extends to at least three-fourths of the distance from the center to the sun. An uncertain indication in the same direction is given by the differential rotation. This gives not only K/R, but likewise dK/dR. Taking into account the value of the local density, we would require, in order to explain the observed value of dK/dR, a homogeneous central ellipsoid extending at least 0.85 of the distance from the center to the sun and having a sensible flattening.

TABLE 1

GALACTIC LONGITUDE OF CENTER OF GALACTIC SYSTEM

	l_c	m.e.
Direct determinations:		
Star counts in intermediate and high latitudes	{324° 335	±5° ±5
Globular clusters (Shapley)	325	±3
Planetary nebulae (Minkowski)	328	±3:
Infrared radiation (Stebbins and Whitford)	326	±2
Radiation at 100 Mc/sec (Bolton and Westfold)	329	±1
Radiation at 200 Mc/sec (Allen and Gum)	325	±1
Average	327	±1
From motions, on supposition that systematic motions are perpendicular to radius vector:		
From differential gal. rotation (various determinations)	325	±1
From the motions of high-velocity objects	323	±4

A tentative working model of the distribution of mass in the Galactic System, fitting all data mentioned, is schematically shown in Figure 1. It consists of a set of superimposed concentric homogeneous ellipsoids. Those extending beyond the sun will be called "outer ellipsoids," while those which do not extend to the sun will be denoted as "central ellipsoids."[7] The model actually used in the calculations in this article contains some ten outer ellipsoids extending beyond the sun, which have been so chosen as to represent the observed distribution for dwarf stars in the z-direction, as well as the observed inclination of the equidensity surfaces between $z = 1000$ and $z = 1500$ psc. The most uncertain feature of the model is the axial ratio of the large central ellipsoid. In Figure 1 this ratio has been taken as 1:5, in rough analogy with the light-distribution in

[7] For details concerning a very similar model cf. *B.A.N.*, **9**, 185, 1941.

the central parts of spirals. As we shall see later on, this appears also to be in agreement with the distribution of "radio stars." The density in this ellipsoid must then be 2.2 times the mass density near the sun, this density being superimposed on that given by the outer ellipsoids. All dynamical observations might, however, be equally well represented by a different axial ratio, as long as the density is adjusted approximately in inverse proportion to the axial ratio assumed. For the purpose for which the model will

TABLE 2

(All errors indicated are estimated mean errors)

			Θ_c/R (km/sec psc)
$A=\frac{1}{2}\left(\frac{\Theta_c}{R}-\frac{d\Theta_c}{dR}\right)$	rad. vel. and p.m. $+0.0195 \pm 14$	$\frac{-B}{A-B}=0.26\ldots \pm 6$	0.026 ± 2
$B=-\frac{1}{2}\left(\frac{\Theta_c}{R}+\frac{d\Theta_c}{dR}\right)$	proper m. -0.0069 ± 15		
From ellipsoidal velocity distribution b^2/a^2		$0.24\ldots \pm 3$	
Vel. distr. and dens. gradient long-period variables			0.031 ± 5
Vel. and dens. distr. RR Lyrae vars. in z-direction			0.028 ± 6
Space distr. of glob. cl. and RR Lyrae vars.	$R=8500$ psc ± 1300		0.036 ± 9
Radial velocities local group of nebulae	$\Theta_c=308$ km/sec ± 60		
Vel. distr. and dens. gradient glob. clusters	$\frac{\Theta_c^2}{R}=2.5 \times 10^{-8} \pm 0.4$		

Least-squares solution from all the above data:

$$R = 9400 \pm 1200 \text{ psc*}\,; \quad \Theta_c = 259 \pm 32 \text{ km/sec*}\,; \qquad 0.0275 \pm 17$$

$$A = +0.0206 \pm 14\,; \quad B = -0.0069 \pm 7\,; \quad \frac{d\Theta_c}{dR} = -0.0137 \pm 16\,;$$

$$\text{Period} = 223 \pm 13 \text{ million years}$$

* *Note added in proof.*—A provisional discussion of observations of the 21-cm hydrogen line obtained in recent months seems to point to somewhat lower values of R and Θ_c.

be used, the axial ratio of the inner ellipsoid is immaterial. I am indebted to Mr. Seeger for the calculation of this model and of the corresponding rotational velocities.

We can only vaguely speculate as to the composition of this central mass, in which two-thirds of the entire mass of the Galactic System is contained. The most positive thing we can say about it is that it must be composed of high-velocity stars. This is necessary in order to keep up its extension perpendicular to the galactic plane against the attraction corresponding to its high density. This conclusion holds for whatever axial ratio we assume. In the model drawn, the density of these high-velocity objects would have to be more than twice the total star density near the sun and therefore more than twenty times the density of known high-velocity dwarfs in our surroundings. A density increase of such amount, which would have to take place in the distance interval of between 1 and 2 kpc that separates us from the edge of the inner ellipsoid, appears to be difficult to fit in with direct data about density gradients of high-velocity objects in our neighborhood. It does not seem possible at present to give a solution of this difficulty. Maybe the mass of the central ellipsoid is mainly made up of stars that are considerably fainter than the faintest dwarfs which we know. These would then have to possess a

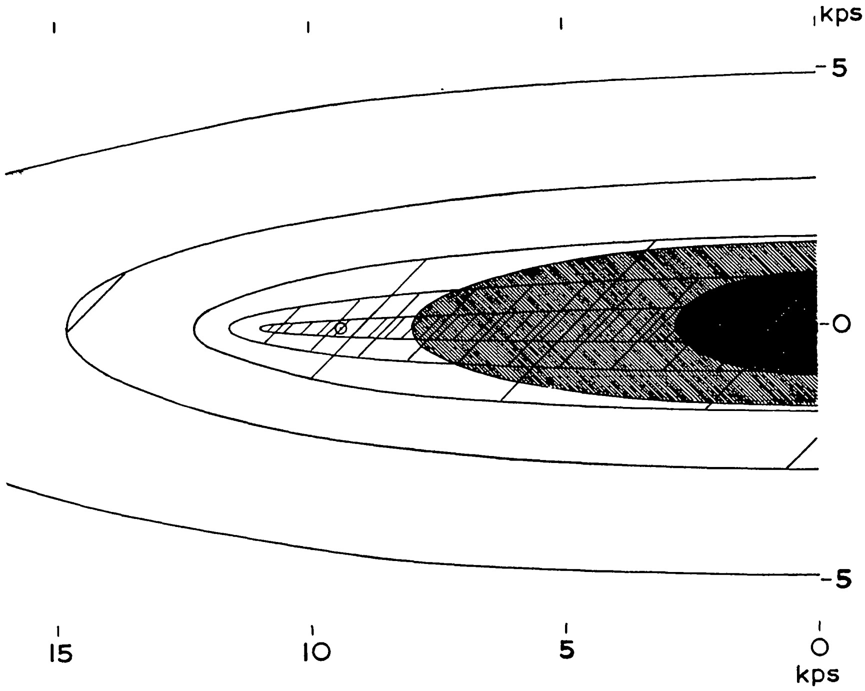

FIG. 1.—Schematic model of Galactic System. The diagram shows a section perpendicular to the galactic plane, through the center and the sun. The position of the sun is indicated by a small circle. The large central ellipsoid has axes of 8 and 1.6 kpc and a density 2.15 (using the density near the sun as a unit); the small central ellipsoid, with axes 2.8 and 1 kpc, has a density 3.13. The axes in kpc and densities of the five outer ellipsoids are as follows·

a	*c*	
11.0	0.3	0.446
11.6	0.9	.104
12.3	1.7	.026
14.8	2.8	.007
20.3	4.9	0.003

The ellipsoids are superimposed upon one another.

velocity distribution such as to give a more or less homogeneous distribution over the whole extent of the central ellipsoid and a steep drop at the outer edge. We are reminded of the phenomena observed in the elliptical nebula NGC 3115, where we were forced to assume that the bulk of the mass was composed of stars that also were extremely faint intrinsically and had a homogeneous space distribution over the whole part of the nebula over which the rotation has been measured.

I should now like to refer briefly to considerations that have more relation to direct observations. In particular, through the observations of Australian scientists a fair picture has in recent years been obtained of the distribution of the surface intensity of radiation at 100[8] and 200 Mc/sec.[9] It can be shown that, with any likely density of interstellar hydrogen, radiation at these wave lengths between 3 and $1\frac{1}{2}$ meters cannot have suffered appreciable absorption. The radio measures are therefore eminently suited to give information on the distribution of the sources of this radiation over the entire Galactic System, and in particular in its inner parts. Part of the radiation comes from the ionized clouds in interstellar space, but it seems probable that at 100 Mc/sec this is only a minor fraction of the total radiation, the bulk probably coming from so-called "point sources." It is now of interest to inquire after the distribution of these radio sources. We find that the distribution over the hemisphere surrounding the center does not resemble the distribution of globular clusters or RR Lyrae variables, lacking their concentration toward the center, and in particular also the nearly spherical symmetry of their distribution around the center, the equidensity lines of radio intensity showing a

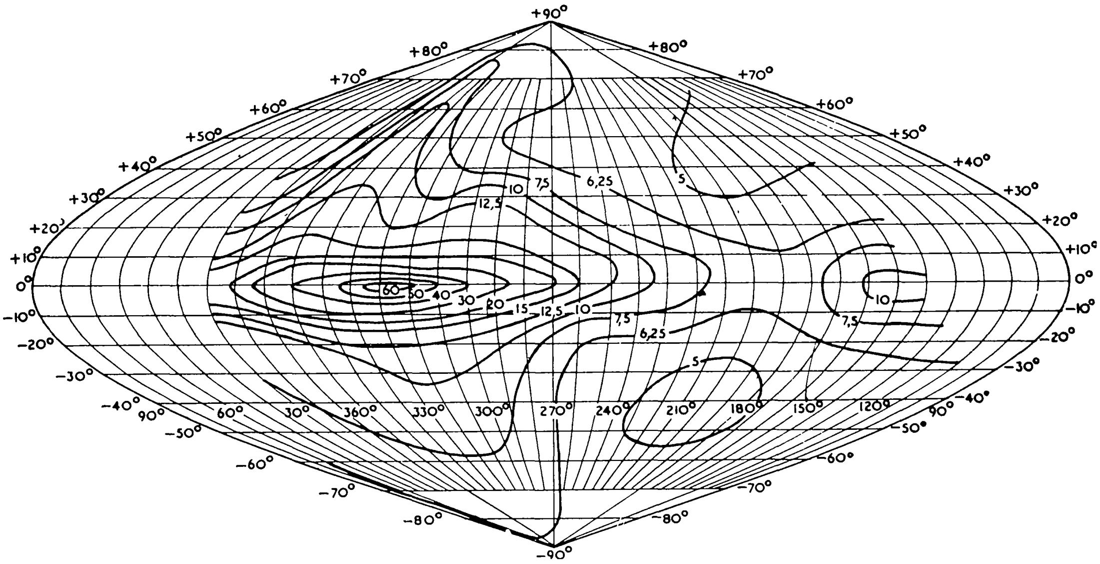

FIG. 2.—Equal-area charts of equivalent black-body temperature at 100 Mc/sec(λ 3 meters). From an article by Bolton and Westfold in *Australian J. Sci. Research*, **19**, 1950 (reproduced from H. C. van de Hulst, *Hemel en Dampkring*, **49**, 1951).

strong flattening. Neither does the distribution of the radio-frequency radiation show any resemblance to the distribution of objects like interstellar clouds or B-type stars that are strongly concentrated in the galactic plane. If, however, we compare its surface intensity distribution with that computed from the model of the mass distribution in the Galactic System, as outlined before, we find almost perfect agreement in all directions where the intensity given by the model is considerable (cf. Figs. 2 and 3). This shows that at least the major part of this radiation comes from sources having a spatial arrangement very similar to that of the mass, the main feature being a homogeneous ellipsoid of axial ratio about $\frac{1}{5}$ and extending almost to the sun. This does not, however, give the whole picture. There are indications that several different types of objects contribute to the radio intensity. This becomes particularly evident when we look at longitudes that are more than about 70° from the center or at regions above 20° latitude. Here the observed radio intensity is very much higher than that given by the model. Unless the difference is due to a large zero-point error that would have to be common to several independent series of observations, the residual intensity of about 600° points either to a large background

[8] Bolton and Westfold, *Australian J. Sci. Res.*, ser. A, **3**, 19, 1950.

[9] C. W. Allen and Gum, *Australian J. Sci. Res.*, ser. A, **3**, 224, 1950.

radiation from the universe or to radiation from a type of radio sources distributed as an extremely large envelope around the Galactic System. The fact that various observers have found a pronounced unevenness of the intensity over the galactic polar cap, with generally greater intensity in longitudes near that of the center, may make the latter interpretation more probable than the first. But more accurate observations, especially in high latitudes, are required before this question can be even tentatively settled.

It is interesting to remark in passing that convincing evidence has recently been found by B. Y. Mills that, besides the ordinary radio-point sources, which, partly, at least,

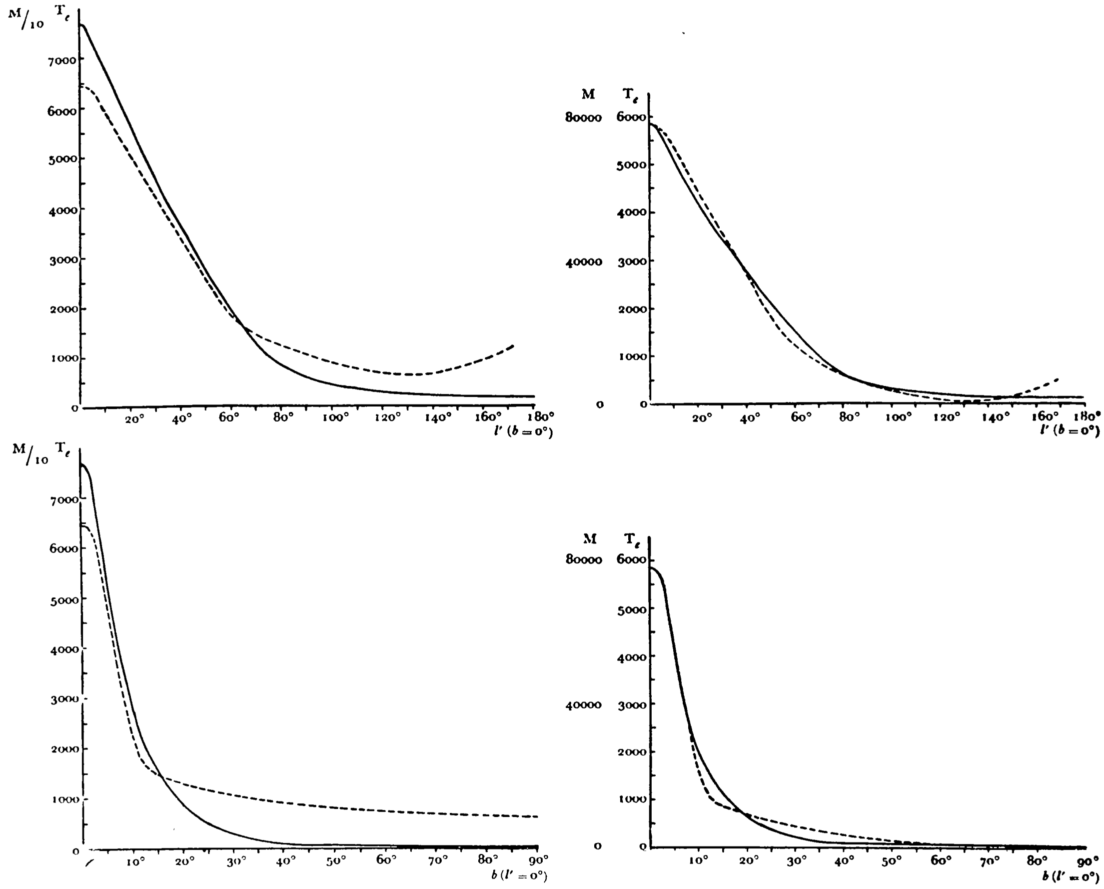

FIG. 3.—Comparison of Bolton and Westfold's measured temperatures (*dotted curves*) with the values computed from the hypothetical model of the Galactic System (*left*). In the comparisons at the right a background temperature of 600° has been subtracted from the observed temperatures. l' denotes the difference in longitude from the center of the galaxy at $l = 327°$.

seem to be near-by objects showing a uniform distribution over the sky, there exists another class of sources, strongly concentrated in the Milky Way and presumably far more distant than the ordinary sources.

We must now return to our model of the Galactic System and discuss the information about such a model that can be obtained from another type of observation in the region of the short radio waves. These are the observations of the emission line of neutral interstellar hydrogen, suggested by van de Hulst in 1944. The first successful observations of this line were made by Ewen and Purcell of Harvard in March of this year, and a little later by C. A. Muller in the Netherlands, as well as by Christiansen and Hindman in

Australia.[10] When observed in the direction of the center or anticenter, the line has a half-width of about 25 km/sec, corresponding to an average random radial velocity of the interstellar clouds of 5 km/sec. From the average galactic latitude at which the intensity falls to half its maximum value in the Milky Way, we deduce that, in the central part of the line, unit optical thickness is reached in a layer of about 1000 parsecs when we observe in the direction of the center or anticenter. It is probably not possible, therefore, to obtain information about the density of the interstellar gas in the central parts of the Galaxy from observations right in the direction of the center. However, if one observes

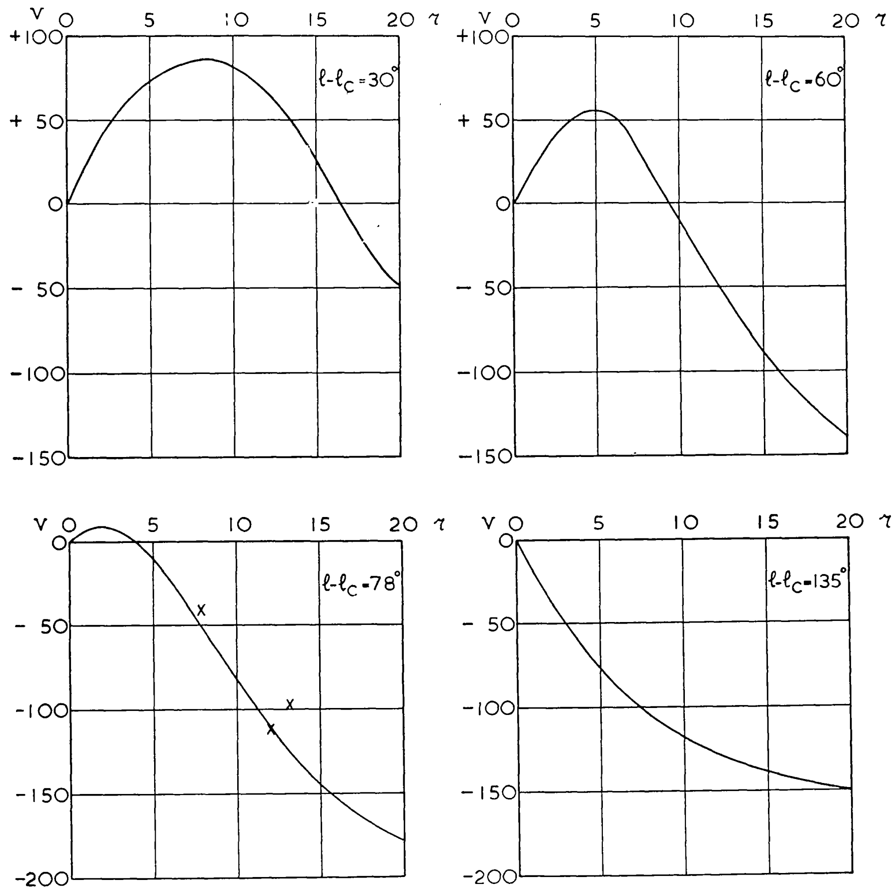

FIG. 4.—Variation of radial velocity with distance from the sun for gas clouds in different galactic longitudes. The curves were computed on the basis of the model of the Galactic System described above.

in longitudes differing more than a few degrees from that of the center, the Doppler effect due to the differential rotation of the Galactic System may change the frequency of the line to such an extent that the radiation from the central region is no longer absorbed by the clouds nearer to the sun. Observations of the intensity of the hydrogen 21-cm line may thus be expected to provide information on the distribution of the interstellar gas in different parts of our Galaxy. And, equally important, they give a means of determining the rotational velocity of the system at various distances from the center. As the velocity of rotation of the interstellar gas will probably practically coincide with the circular velocity, they will therefore provide us with a fairly complete picture of the gravitational force in the galactic plane at various distances from the center up to the

[10] *Nature*, **168**, 356, 1951.

distance of the sun. Such measures are now being made by Mr. Muller at the Kootwijk Transmitting Station in the Netherlands. The accompanying diagrams indicate the way in which the observations are arranged. Figure 4, calculated on the basis of the model sketched previously, shows how, in four different longitudes, the radial velocity relative to the average of the bright stars in the vicinity of the sun varies with distance. The crosses in the graph for $l - l_c = 78°$ indicate the radial velocities of the very distant δ Cephei variables in this direction that were measured by Joy. In the model the circular velocity varies with distance R from the center, as shown in Figure 5. You will note that it increases fairly linearly with R up to a distance of about 8 kpc, and then begins gradu-

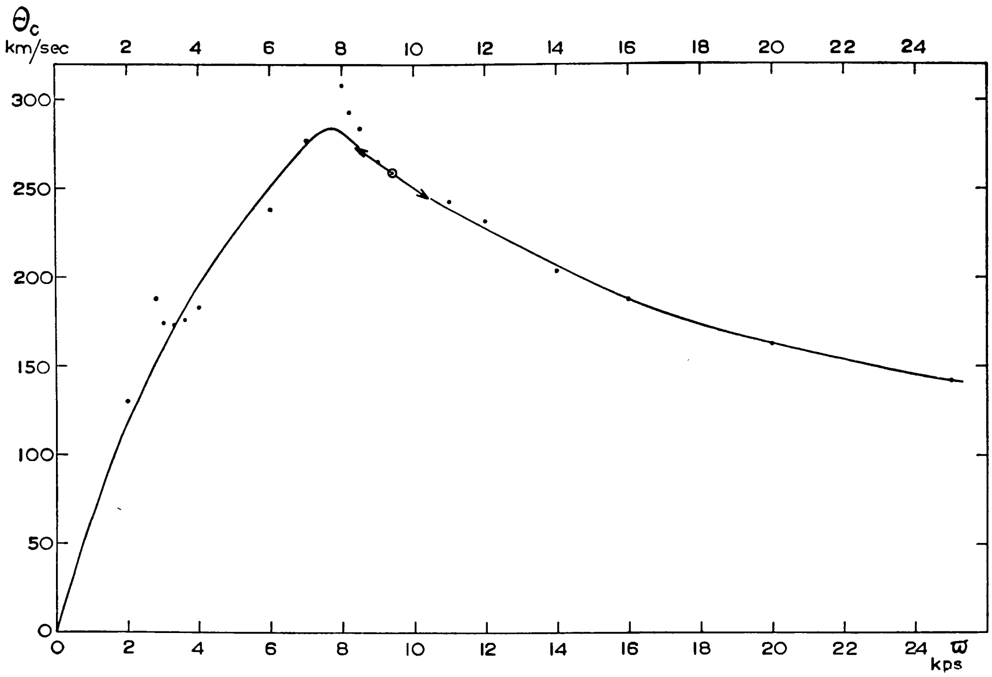

FIG. 5.—Variation of the circular velocity of rotation in the Galactic System with distance from the center. The small circle indicates the position of the sun and the estimated circular velocity in our neighborhood. The arrows indicate the slope of the curve as derived from the observed differential galactic rotation. The dots were computed from the model used; the curve has been drawn so as to smooth out the artificiality of the sharp boundaries of the discrete ellipsoids.

ally to decrease. The inclined arrows on the downward branch indicate the part around the sun's distance where the slope of the curve can be found from the constants of galactic rotation. The derivative there is equal to $-A - B$. It may be noted that the general shape of this curve bears great resemblance to what is observed in spiral nebulae, in which generally over the whole of their brighter parts the velocity of rotation increases in rough proportion to the distance from the center. Only in two cases, viz., the Andromeda Nebula and M33, where rotations have been measured from emission nebulae, the observations extend to regions comparable to the situation of the sun in the Galactic System. It is only in these cases that the declining part of the rotation curve has also been observed.[11] Figure 6 gives a schematic picture of the contours of the 21-cm line that would correspond with the radial-velocity curves of Figure 4 if the hydrogen forms a

[11] A comparison of the rotation of M31, M33, and the Galaxy has recently been made by N. U. Mayall, *Pub. Michigan U. Obs.*, **10**, 19, 1951.

homogeneous disk of 120 psc thickness* and extending to $R = 15$ kpc, and if it is observed with a 7.5-meter paraboloid like that actually used, having a beam width to half-power of 2°8. The unit of intensity is that corresponding to black-body radiation at the temperature of the neutral interstellar hydrogen. Abscissae are radial velocities in km/sec.

Let us consider the curves for $l - l_c = 30°$ as an example. The radial velocity has a rather flat maximum of +86 km/sec, at a distance of 8.2 kpc. It is symmetrical about this point, becoming zero again at 16.5 kpc, where the line of sight intersects the circle with radius equal to the sun's distance from the center. At still larger distances it becomes negative. This run is depicted in the theoretical line contour of Figure 6. At distances beyond 2.5 kpc the acceptance cone of the 7.5-meter paraboloid will no longer be completely filled by the radiation from the thin layer of interstellar gas; this is why the curve already begins to fall off at $V = +60$ km/sec. It is planned to construct an instrument

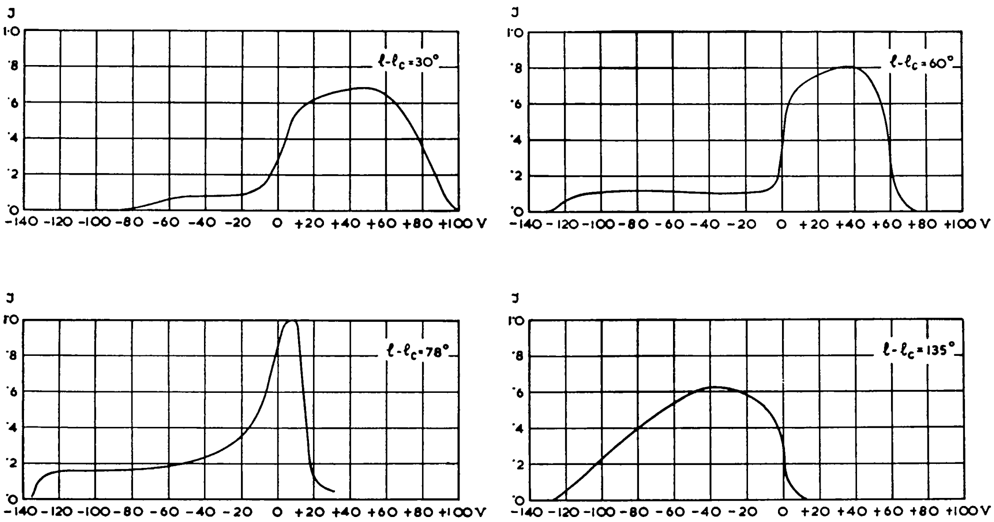

FIG. 6.—Line contours for observations of the 21-cm line, computed on the basis of uniform distribution of hydrogen.

with a 3.2 times larger aperture. With that instrument the measured intensity would become unity from about +65 to +86 km/sec and show a steep drop beginning at the maximum radial velocity of +86 km/sec. This would evidently allow an accurate determination of the rotational velocity at half the sun's distance from the center.

The toe shown by the line contour for negative velocities corresponds to matter situated at the other side of the system at distances from the center larger than that of the sun.

A rather provisional measure of the downward slope of the line contour just considered has been made at Kootwijk in June, 1951. This indicated an effective width of the emission line of about 70 km/sec, in good enough agreement with the predicted width of about 80 km/sec. That the matter observed at frequencies corresponding to the right-hand edge of the line contour is indeed at a large distance is shown by Figure 7. The three upper graphs illustrate the distribution of the line intensity in galactic latitude when the meas-

* *Note added to proof*.—This is the approximate equivalent thickness of the layer of B stars. There is evidence, however, indicating that the equivalent thickness of the *gas* layer is considerably higher. Van Rhijn (*Gron. Pub.*, No. 50, pp. 10 and 11) estimates it to be 240 psc. A similar thickness has been found for the layer of solid particles. It is probable, therefore, that the abscissae in Fig. 6 should be considerably increased for the larger distances.

urements are made at frequencies corresponding to the frequency of the undisplaced hydrogen line. They show the interstellar gas within roughly 1000 psc. of the sun. The tracings were made in right ascension, the vertical lines are 20 minutes of time apart. The spots at which the tracings intersected the galactic circle, and the corresponding galactic longitudes, are indicated by arrows. The galactic co-ordinates of the beginning and end of each tracing are also shown. The observations were made differentially, the receiver being switched 30 times per second between two frequencies, one of which is in the line and one outside, 110 kc/sec away. The bottom curve gives a similar tracing made at frequency 250 kc/sec below the normal frequency of the line, thus correspond-

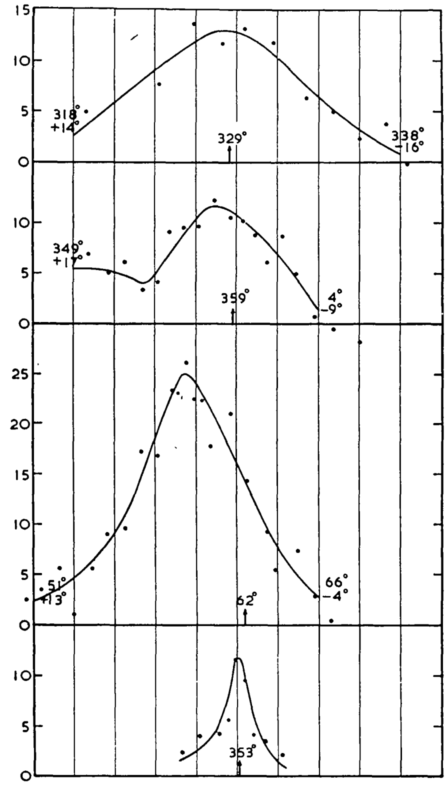

FIG. 7.—Distribution of intensity of hydrogen emission at 21 cm. The three upper curves were obtained at the normal frequency of the emission line, and refer presumably to interstellar matter within 1 kpc. The lower curve supposedly refers to matter at distances of the order of 9 kpc.

ing to a radial velocity of +55 km/sec. It is evident that this tracing is much narrower than the first three, indicating that the radiation comes from matter at a much greater distance. Its width is indeed no larger than would correspond to the beam width of the instrument.

The predicted line contours are, of course, meant only to give a schematic picture. It is likely that the actual curves will show important differences from those in Figure 6. If the gas in the Galactic System is concentrated in spiral arms, the observations of the line contours will probably indicate this.[12]

So far we have considered only the smoothed-out, over-all structure of the Galactic System. It is of evident interest also to investigate another aspect of its structure,

[12] NOTE ADDED MAY, 1952.—The first measures made by Mr. C. A. Muller with a greatly improved receiver indeed show big humps in the line contours, probably due to important concentrations of hydrogen at distances up to 8 kpc.

namely, the spiral-like formations that, judging from the analogy in other respects between the Galactic System and the later-type spiral nebulae, our stellar system presumably contains.

As has been pointed out particularly by Hubble and Baade, interstellar matter as well as the closely related early-type stars are of particular significance for the spiral structure. It even seems probable that, directly or indirectly, the interstellar gas is the determining factor for the origin of this structure. At one time I thought that the dynamics of spirals might perhaps be explained as the consequence of instability caused by the rapid contraction of interstellar gas in the equatorial plane. It may be, however, that the spiral forms are due to turbulence-like effects on interstellar matter, a hypothesis especially advocated by von Weizsäcker.

The most precise evidence concerning the relation of interstellar matter to spiral arms has been produced by Baade, who showed how closely emission nebulae as well as dark matter in the Andromeda Nebula are confined to spiral arms, which, in this case, appear to have a width of not more than 200 psc.

But also in the Galactic System the study of the distribution and motions of interstellar matter has made rapid progress. I need only refer to the subject of a former Russell lecture, in which Adams outlined the results of his observations of the multiple interstellar lines. These observations furnish the most systematic information on interstellar clouds. In a recent discussion Blaauw has considered the effects of the blending that must have been quite general for clouds with velocities less than about 10 km/sec. He concludes that the average peculiar velocity of the clouds in one co-ordinate is around 5 km/sec, and that a line of sight of 1 kpc length cuts, on the average, between 8 and 12 independent clouds.

A great deal of information may be expected from observations of the 21-cm line. From the few preliminary observations already made it has been possible to obtain a first rough estimate of the temperature as well as of the average density of neutral hydrogen in a region of about 1 kpc radius around the sun. As I have already indicated, observations in the direction of the center or anticenter of the system can inform us about the mean velocity of the clouds, as well as about the average absorption coefficient in the central part of the emission line. The mean random velocity in the line of sight is found to be about 5 km/sec, in good agreement with the value from the interstellar absorption lines. The absorption coefficient is observed to be roughly 1/kpc. The third observation we can make concerns the intensity in the central part of the line. It is clear that in combination with the known transition probability and with the fact that the two hyperfine-structure levels between which the transition takes place are almost equally populated, the measured intensity determines the number of neutral hydrogen atoms in the column of 1 kpc that is observed. We thus find that there is, on the average, about one H atom/cm^3. The same measurement of surface intensity also defines the black-body temperature corresponding to this transition. Ewen and Purcell found a value of 35°, but more recent measures in Australia and the Netherlands indicate that the temperature is rather higher, near 100°. This is an interesting datum, because it must be equal to the ordinary gas-kinetic temperature of the neutral hydrogen clouds. The value found gives a beautiful confirmation of the temperature that has been deduced by Spitzer and Savedoff in a theoretical way, from a consideration of the ionization and excitation processes in HI regions. They find about 50°, with an uncertainty that is considerably larger than the difference from 100° found from the 21-cm line.

This much about what the first rather tentative observations have indicated. Further observations may be expected to give considerably more. I have already mentioned the data on galactic rotation and on the general distribution of the interstellar gas. It is probable that with better equipment the complex structure of the 21-cm line can also be unraveled and that a great amount of information on motions and distribution of individual clouds will be obtained.

So far we have mainly discussed the *H* I regions. For *H* II regions important data have been obtained by the observation of the Balmer emission, started by Struve and widely extended by Strömgren and W. W. Morgan. From the systematic study of the emission regions, together with the comprehensive survey of O and B supergiants undertaken by Morgan and Nassau and by Luis Münch, Morgan has very recently been able to show that these objects are arranged in two long stretches that should most probably be identified with parts of spiral arms. It seems that thus for the first time success has been attained in revealing some of the spiral structure of our own stellar system.[13] This is evidently a step of the very greatest importance, and one that is likely to lead to a clarification of several unsolved problems, not only about galactic structure but likewise about the origin of spiral structure in general. The arms indicated by Morgan's investigation show striking resemblance with the arms defined by emission objects in the Andromeda Nebula. From the first evidence produced it seems that the galactic spiral rotates like a winding spring, with the convex side of the arms preceding.

The ionized regions also emit continuous radiation at radio frequencies, which should have a well-measurable intensity if observations are made near the Milky Way and with instruments of sufficient resolving power. In the surveys made so far, all with low resolving power, it is not possible to discern how much of the measured intensity is due to continuous radiation from ionized interstellar clouds and how much comes from the distant point-sources. The interstellar radiation is likely to be relatively more important at lower wave lengths.

For wave lengths less than a few meters the absorption coefficient of the gas is so small that we can probably neglect the absorption, even for paths of the order of the diameter of the Galactic System. This circumstance should render it possible to get a survey of the density distribution of ionized hydrogen through the entire system as soon as sufficiently large antennas have been built, if a way can be found to separate the interstellar radiation from that of other sources.

At the meter wave lengths the radiation between 50° and 120° longitude appears to be between two and three times larger than that in the corresponding region, between 170° and 240° longitude, on the other side of the center. Bolton and Westfold have attributed this, and particularly some more detailed features in Cygnus, to a spiral arm. It is noteworthy that Morgan's outline of the run of the spiral arms in our vicinity shows that the region between 170° and 240° longitude falls entirely in the open region between two arms. It is not yet clear whether the excess radiation comes from interstellar gas or from point-sources. This very interesting feature certainly deserves accurate further investigation.

The irregularity in the distribution of early-type stars and δ Cephei variables is well known. It is found in its extreme form in the Wolf-Rayet stars, as shown in Figure 8, taken from Miss Payne's book on *Stars of High Luminosity*. They are nearly all contained in two clusterings, in Cygnus and Carina, and in a more scattered group in the direction of the center. The Carina region is also exceptionally rich in faint O and B stars and in faint δ Cephei variables.

These features may partly be considered as local aggregates, though of very large size, and partly as revealing some of the large-scale structure of the Galactic System.

Ambarzumian puts the concentrations of Wolf-Rayet stars in the same general class as the groupings of early-type stars in general. These loose groups, stellar associations, aggregates, or relationships, as they have alternatively been called, are of particular interest. They have been known for a long time, ever since spectral classes have been determined, and several have been extensively investigated. It had also been realized that, because of their looseness, these clouds of early-type stars must be torn up by the effects

[13] A brief account of Dr. Morgan's investigation is given in *Sky and Telescope*, **11**, 134, 1952; see also *A.J.*, **57**, 3, 1952 (abstr.).

of differential galactic rotation in a period of the order of one revolution of the Galaxy and that therefore they must be comparatively young. During the last few years considerable work on the problems presented by the B-star clouds has been done by Ambarzumian and his co-workers at the Erevan Observatory, who have made a systematic search for and study of these "associations."[14] In particular, Ambarzumian has stressed their significance for the cosmogony of the massive stars. The most important new concept that, I believe, has first been suggested by Ambarzumian is that the associations are expanding. And this not only because of galactic rotation but also as an essential property of their own. This has proved to be a fertile idea, which seems, in a somewhat unexpected manner, to give an insight into the origin and the meaning of these groups.

In a still unpublished investigation on a group of B stars surrounding ζ Persei,[15] Blaauw has succeeded in proving such an expansion by direct observation. This loose clustering, measuring about 40 × 20 psc, is situated between 12° and 20° southern galactic latitude, at a distance of roughtly 300 psc. The reality of the relationship between the stars can hardly be doubted. However, in 1944, when he first discovered the group, Blaauw was already struck by the fact that the proper motions of the members showed rather unexpected divergences. Recently he has determined independent new

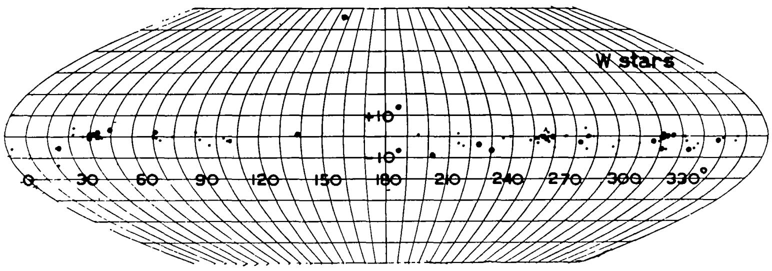

FIG. 8.—Distribution of Wolf-Rayet stars (from a tabulation in *The Stars of High Luminosity* by Cecilia H. Payne).

proper motions, in the same way as H. R. Morgan has determined the proper motions of his N30 system. These new proper motions confirm the divergences found previously and prove that the group is expanding at a rate of $0''.0028 \pm 0''.0004$ m.e. per year and per degree distance from its center. This surprisingly rapid expansion, which averages about 12 km/sec, corresponds to an age of only 1.3 million years (with a mean error of about 14 per cent). The actual motions are illustrated in the accompanying diagram (Fig. 9). Low though this age may seem, it is entirely compatible with the age that may be ascribed on theoretical grounds to the most luminous members of the group, like the O star ξ Persie.

The most straightforward interpretation of these observations is that the members of this group were formed about thirteen hundred thousand years ago as a consequence of a dense conglomeration of interstellar clouds with "turbulent" motions of the order of 5 km/sec. These velocities now show up roughly as an expansion of the group, which has already grown very considerably since its birth. Even today the whole region is full of dark as well as luminous interstellar matter, as is well shown on a picture of this region in Barnard's *Atlas of the Milky Way*. An especially interesting feature is the small and rather compact cluster of faint stars south of *o* Persei. The Russian investigators have drawn attention to the frequent occurrence of such open clusters as a sort of nuclei in the large associations. Another well-known example is the Trapezium cluster in Orion. I believe this is the first direct evidence of the birth of stars from interstellar clouds. A re-

[14] *Abh. Berlin Akad., Kl. f. Math. u. allg. Naturw.*, No. 2, 1950; and *A.J.U.S.S.R.*, **26**, 3 and 329, 1949.

[15] Now appearing in print in *B.A.N.*, Vol. **11**, No. 433, 1952.

markable thing is the extremely short time in which these stars must have contracted from interstellar clouds into actual stars. The available time is only barely long enough for a cloud with a radius of the order of 1 psc to contract under its own gravitation.

It is likely that the ζ Persei aggregate is rather exceptional in the rapidity of its expansion. At least it is certain that in the other B-star clouds for which data are available the expansions are considerably less rapid. By far the longest-and best-known association of B stars is the large Scorpio-Centaurus cloud. The most complete investigation has again been made by Blaauw.[16] It is the only B-star group for which the space distribution can be determined. It is considerably larger than the ζ Persei group and has a strikingly oblong shape, with a long axis of about 290 psc, the other axes being about 100 and 70 psc, respectively. It is tempting to suppose that this aggregate has also formed from a

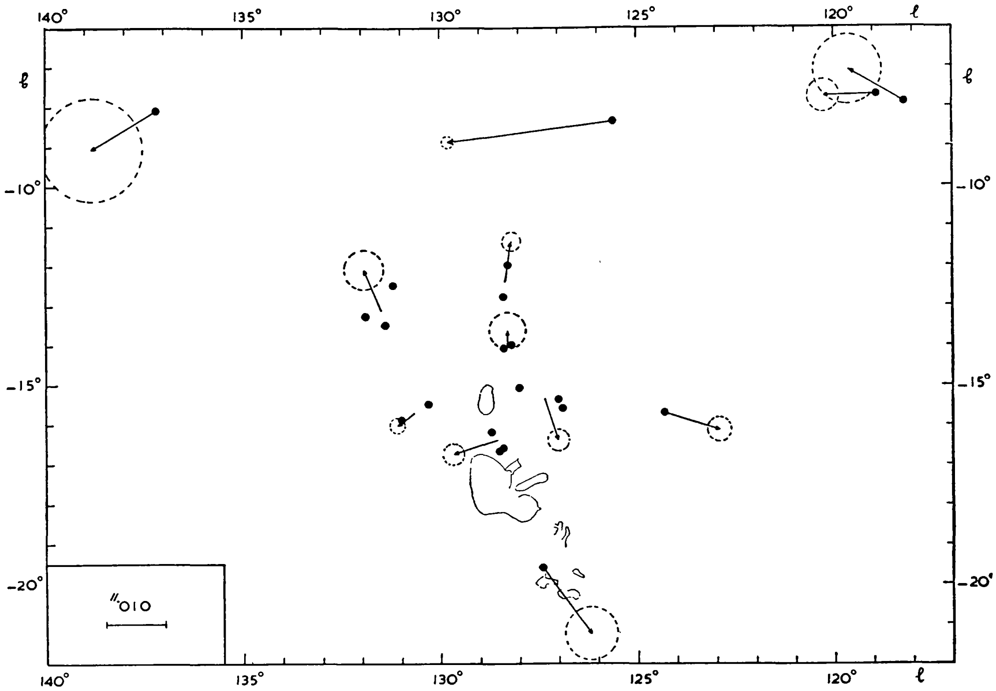

FIG. 9.—Proper motions of stars in Blaauw's ζ Persei group. The stars are plotted in galactic co-ordinates. The arrows show the relative proper motions; some of them refer to the mean of two or three stars that are close together. The radii of the dotted circles indicate the probable errors of the motions. The four stars in the upper part of the diagram have no relation to the group (cf. Blaauw, *B.A.N.*, No. 433).

much smaller conglomeration of interstellar clouds, the stars having dispersed as a consequence of motions in this conglomeration. The motions of the stars are not yet known with sufficient accuracy to determine the amount of expansion, but they suffice to show that it is much smaller than in the case of the ζ Persei group, probably not much larger than 1 km/sec. The Scorpio-Centaurus cloud does not contain very bright supergiants; the ages of the brightest stars might be estimated to be of the order of 50 or 100 million years. Blaauw has noted that both the strong elongation of the group and its orientation in space can be understood as the natural consequence of expansion combined with the differential rotation of the Galactic System. In fact, if an expansional velocity of 1 km/sec is assumed, the cloud would in 60 million years have got the dimensions, the amount of elongation, as well as the orientation in space, that are observed today.[17]

[16] *Pub. Kapteyn Lab. Groningen*, No. 52, 1946.

[17] A. Blaauw, *op. cit.*, p. 414.

As Blaauw has remarked, clouds like this are frequently observed in later-type spirals, where parts of broken-up arms are sometimes considerably inclined to the tangential direction. It is clear that, if this is the correct interpretation of these features, the spirals must rotate again like winding springs.

It is, of course, impossible in the compass of this lecture to give a survey of all the problems concerning galactic structure, not even when limiting the discussion to the more general features. My choice of topics has naturally been influenced by the things with which I have recently been in contact. But also I have primarily selected problems that have reached the stage where at least *some* general insight and understanding appear to have been attained.

I regret particularly that, because of this choice, there is no opportunity to discuss the entire domain of research dealing with the distribution in the galactic plane of the more common stars. Especially by such investigations as have been carried out at Harvard and at the Warner and Swasey Observatory here in Cleveland, evidence of the fairly large-scale unevenness in the distribution of these stars has been rapidly accumulating. But it has not yet been possible to draw a coherent picture of the observed variations in star density and in mixture of spectral types, or to discover the relation that should exist between the density variations and that other striking deviation from a smooth state that has long been known, namely, the difference of about 20° between the vertex of the star-streaming of the brighter stars and the longitude of the galactic center.

It appears probable, however, that, with the accumulation of more, and especially more accurate, data, the near future will bring a solution of these problems, as well as of the intriguing problem of the relation between the distribution of the common stars and the galactic spiral arms.