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DISTRIBUTION AND MOTION OF INTERSTELLAR HYDROGEN IN THE GALACTIC SYSTEM WITH PARTICULAR REFERENCE TO THE REGION WITHIN 3 KILOPARSECS OF THE CENTER*

BY G. W. ROUGOOR AND J. H. OORT

LEIDEN OBSERVATORY

Distribution of the Interstellar Gas.—Observations of the 21-cm emission of the hydrogen atoms in the interstellar medium have enabled astronomers to obtain a general survey of the distribution of interstellar gas throughout the Galactic System. The main features of this distribution may be described as follows. The gas is strongly concentrated into a very thin layer. The thickness as given by the distance between the planes where the density has dropped to half the maximum density averages about 220 pc,† which is of the order of $^1/_{100}$ of the disk's diameter. It is only near its center that the disk becomes considerably thinner. Over most of its extent the hydrogen layer is surprisingly flat: within 6 kpc from the center the points of maximum density deviate nowhere more than 75 pc from the mean plane, except in a few small areas. It is only in the thinner, outer regions of the Galactic System that the layer begins to deviate from the plane defined by the principal part of the disk. These deviations have a systematic character, the layer tipping up on one side and down on the opposite side; the greatest deviations from the plane are 600 and 800 pc, and occur at distances of about 13 kpc from the center. This interesting phenomenon was first found by Kerr, Hindman, and Carpenter.[1]

The gas, as is well known, is composed mostly of hydrogen and helium atoms, with a small admixture of heavier elements. Most of the hydrogen is neutral; the ionized part is probably only of the order of 5 per cent.

There must be *some* gas far outside this main disk, connected with the magnetic fields which seem to play an essential part in the "radio corona" surrounding the Galactic System. So far, this gas has not been directly observable. In a very indirect manner it has been estimated that its density may be of the order of 0.01 atom/cm^3 and its temperature 10^6 °K. Both numbers are extremely uncertain.

The distribution of the gas in the disk is very far from uniform. It is concentrated in clouds of widely varying sizes, densities, and forms, which have a tendency to form huge agglomerations and are more or less arranged in long bands winding through large parts of the Galactic System. The general distribution may be seen in Figure 1. Although the evidence obtained from the 21-cm observations is not quite complete enough to obtain a coherent map of these bands, the close analogy between the Galactic System and spiral galaxies of the so-called Sb type, renders it rather probable that the bands of gas in our galaxy form a spiral pattern. The spiral arms are evidently very irregular, with more or less sudden breaks, subsidiary arms, etc.; irregularities quite like those found abundantly in all spiral systems.

The arms in the Galactic System are about 2 kpc apart; a radius vector from the center would cross four or five main arms beyond 3 kpc from the center.

The 21-cm observations have greatly extended our knowledge concerning the rotation of the System. The angular velocity is found to increase strongly towards

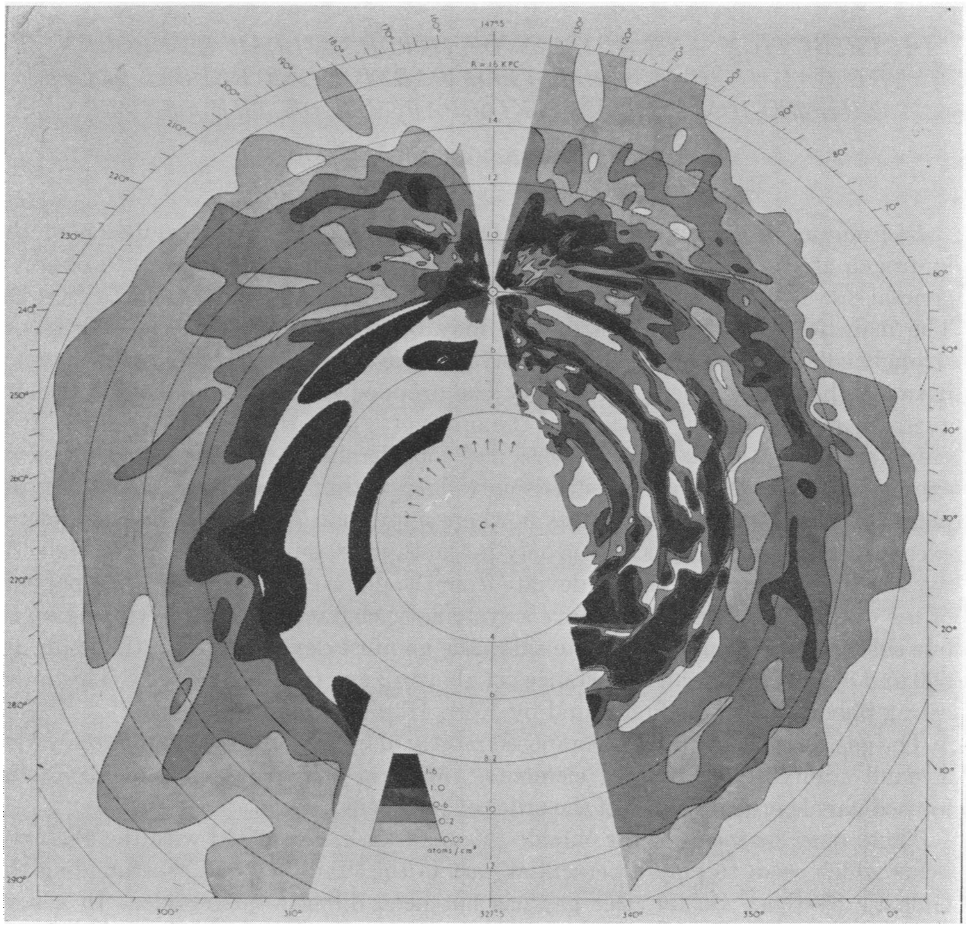

FIG. 1.—Distribution of neutral hydrogen in the galactic plane after observations made in Australia and in the Netherlands (from Oort, Kerr and Westerhout[10]). The center of the Galactic System is at *C*, the position of the sun has been marked by a small circle indicated by *S*. The hydrogen in the central part has not been drawn in. The numbers on the sides indicate galactic longitudes, on the old system. Distances from the center are indicated in kiloparsecs. Blank spaces between 311° and 340° and between 135° and 160° are due to the fact that these parts cannot be "resolved" because of the smallness of differential rotation in these longitude intervals.

the center. At 4 kpc it is about twice that near the sun, which lies at 8.2 kpc from the center. In the absence of some form of gas transport between the arms, the spirals would seem to have to wind up, so as to be practically effaced in a time brief compared to the age of the Galactic System. As we shall see below, the angular velocities in the central region are still considerably higher than at 4 kpc. At 500

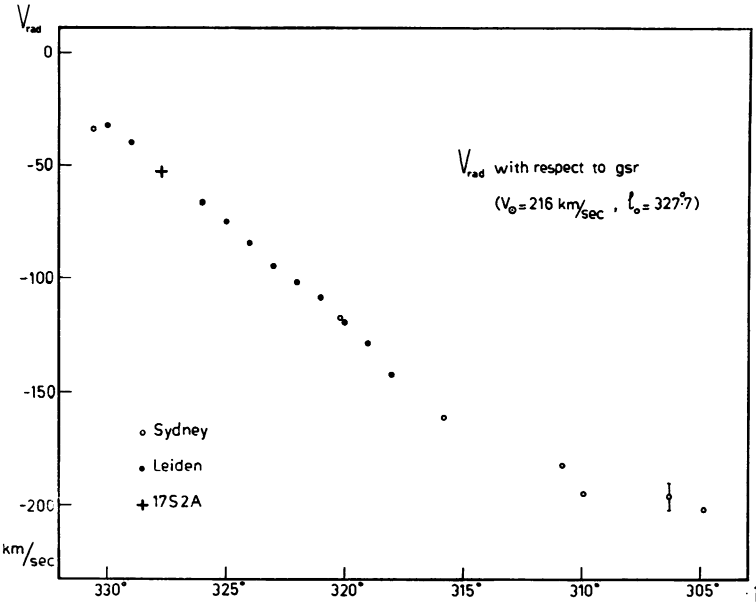

FIG. 2.—Radial velocity of the 3-kpc arm at different longitudes. The longitudes are on the old system. The cross gives the velocity of the absorption line due to the radio source Sagittarius A.

pc from the center they are roughly twenty times that near the sun, at 100 pc even a hundred times (cf. Fig. 8). Here the problem of the permanence of the spiral arms becomes still much more difficult.

Expansional Motions in the Central Part of the Galactic System.—In the region farther than 4 kpc from the center nothing has, so far, been found to indicate large-scale deviations from circular motion. But in the central part, which we shall define roughly as the region within 3 kpc of the center, we observe quite unexpected motions. The 21-cm observations indicate a rather dense arm situated at about 3 kpc from the center and passing between the sun and this center. The arm is very well defined, and more homogeneous in density as well as velocity than any of the outer arms. It takes part in the rotation of the System at a velocity of probably about 200 km/sec. The unexpected feature, which was discovered by van Woerden *et al.*[2] in 1957, is that the entire arm appears to move out radially, away from the center, at a velocity which, at the point where it passes in front of the center, is −53 km/sec. At this point it is seen in absorption against the radio source Sagittarius A, which forms the nucleus of the Galactic System. The emis-

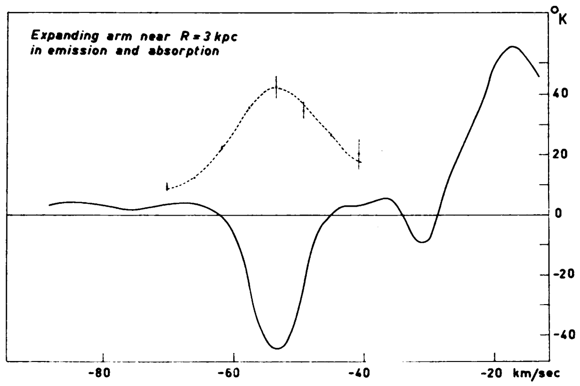

FIG. 3.—Emission and absorption profiles of the 3-kpc arm.

sion velocities measured in various points of the arm, as well as the velocity of the absorption line, are shown in Figure 2. It may be observed that the absorption line fits in very well with the emission lines on either side. The great regularity of the variation of the velocity with longitude may be noted. This regularity is also striking

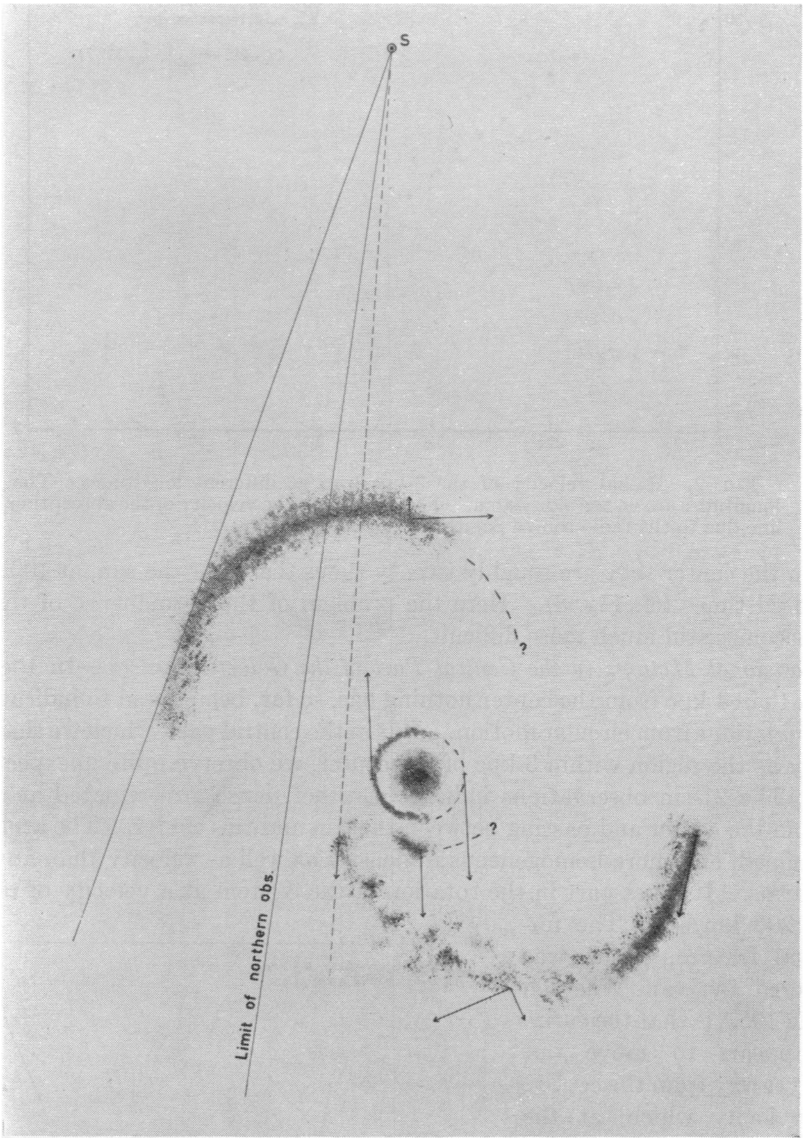

FIG. 4.—Sketch of possible distribution of hydrogen in the central part of the Galactic System. The position of the sun is indicated by S. The arm in the upper part is the "3-kpc arm." The ring and disk in the nuclear region do not seem to be expanding.

in the profiles of the emission and the absorption (Fig. 3). The emission profile is sensibly wider than the absorption profile, the half-widths being 15.8 and 10.6 km/sec, respectively. The cause of this difference is still unknown. The situation of the arm has very tentatively been sketched in Figure 4. The observations made in Sydney have been interpreted to indicate that it becomes tangential to the line of sight near galactic longitude 303° (old system), which would correspond to a distance of roughly $3^1/_2$ kpc from the center. For this reason the arm has been drawn at a radius of about 3 kpc, and will be referred to as the "3-kpc arm." It should be emphasized, however, that the conclusion as to where it becomes tangential is quite uncertain. Its distance at the point where it crosses the center is still more uncertain. It is quite possible that the arm spirals rapidly

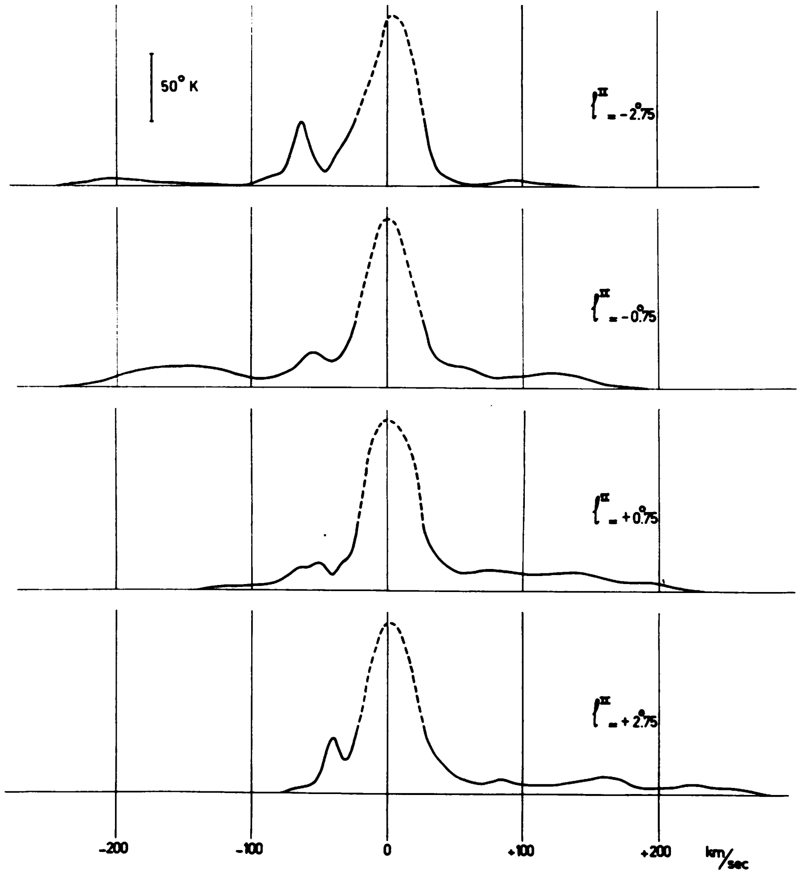

FIG. 5.—Some sample line profiles. The longitudes are on the new system, counted from the direction of the center as zeropoint. The principal maximum, which is almost entirely due to hydrogen outside the central region, and which has not been measured in the present program, is indicated by a dotted curve.

inward, and that at this point it is rather closer to the center than has been drawn in Figure 4. The part shown in the picture is the only part we can observe. The arm is likely to continue on both sides beyond this stretch, but it becomes indistinguishable because its velocity coincides with that of other spiral arms much closer to, or much farther from the sun.

The "expanding arm" is clearly shown in Figure 6, which gives the intensity of the hydrogen radiation, expressed in the usual temperature scale,‡ as a function of radial velocity and galactic longitude. The principal maximum has been left out. This contains almost entirely matter closer to the sun, or gas beyond the central region. A few samples of the line profiles that were used to construct this diagram are shown in Figure 5. The "3-kpc arm" is shown in Figure 5 in the secondary maxima and in Figure 6 by the narrow ridge of high temperature to the left of the broad central maximum which has been left blank. The interruption of the ridge near the longitude of the center and the depression of the feature in the profiles

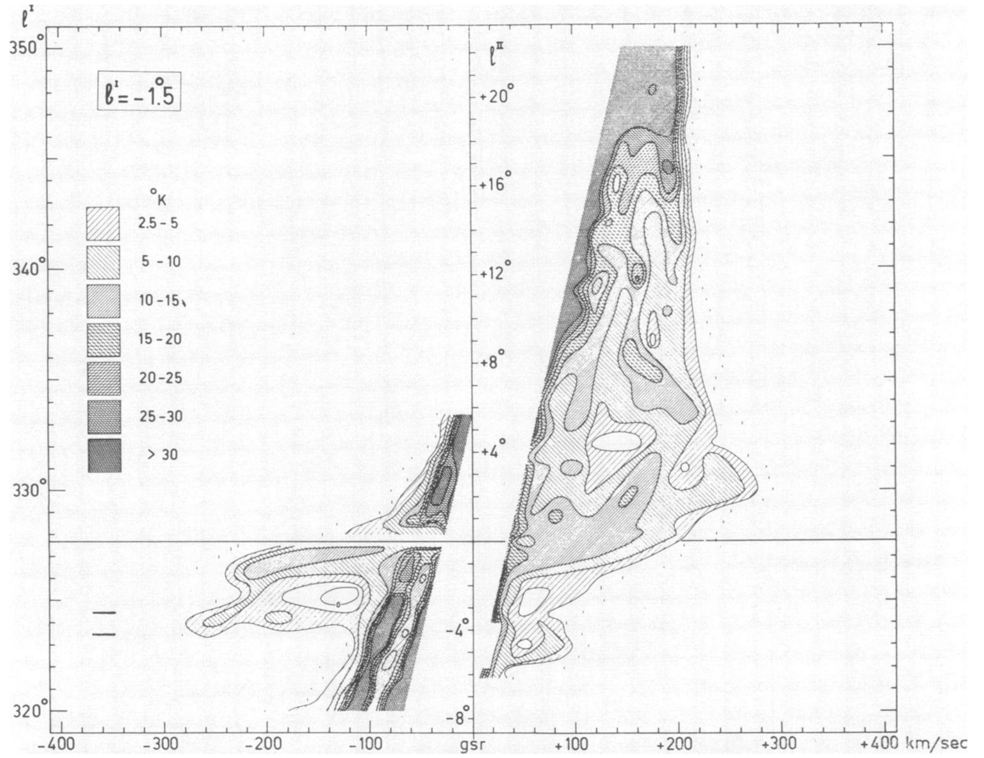

FIG. 6.—Contours of brightness temperature‡ in the 21-cm emission line in the central region of the Galactic System. The contours are for a plane at −1°.5 latitude (old system); this is the plane of maximum hydrogen density. The radial velocities shown are values which have been corrected for the motion of the sun with respect to the galactic center. At the negative velocities the curves have been interrupted over an interval of about 0°.5 around the center, because, on the scale of this graph, the steep absorption profiles occurring in this interval could not be drawn adequately.

for $l^{II} = \pm 0.°75$§ are only apparent, and due to the absorption phenomenon described above.

From a further inspection of Figure 6 and of similar diagrams for latitudes −0°.5, −1°.0, and −2°.0, we see that the 3-kpc arm is not the only case of matter streaming away from the center. If one observes precisely at the longitude of the center, one finds quite considerable intensities between velocities of +50 and +200 km/sec. Between +100 and +200 km/sec there is no appreciable absorption of the radiation of Sagittarius A. This means that the bulk of this gas must lie behind the center and must therefore move away from it with velocities of the order mentioned.

If we now consider the lower longitudes, we see that there is a certain amount of hydrogen moving with radial velocities above +30 km/sec, up to a limit varying from about +100 to +120 km/sec. The rotation of the system is such that matter observed in longitudes lower than that of the center should approach us if it were moving in circular orbits, and thus have negative velocities. As it is practically certain that in this case we are dealing with matter which is not only close to the center in angular measure, but is actually in the region within about 3 kpc of the center, the rotational components projected on the line of sight are likely to be quite high. In order to obtain the high positive line-of-sight velocities observed for the gas concentration between −1.°5 and −5.°5 longitude§ this gas must presumably have radial components of at least 200 km/sec directed away from the center.

Although we cannot prove this from the observations, it appears probable that also the hydrogen with high positive velocities in longitudes *larger* than that of the center has a considerable velocity component directed away from the center.

The Distribution of the Gas within 3.5 kpc of the Center.—In view of the evident, enormous deviations from circular motion occurring within 20° of the center, it is impossible to use the observed Doppler shifts to locate the hydrogen in space. We *can* say with some confidence that all the high-velocity gas observed in these longitudes pertains to the central region. Furthermore, it is possible to conclude that some parts are virtually devoid of gas. In other cases we have made an attempt to locate some of the matter by assuming that it is partly arranged along a spiral, which may even be connected near the outer edge of the "central region" with a reasonably well-defined spiral arm.

It is clear that any sketch of the distribution of matter in the central part, such as shown in Figure 4, must be extremely uncertain and, at best, schematic. This holds in particular for the matter drawn behind the center. It is not at all certain that the various detached agglomerations of gas which we observe at high positive velocities are arranged in a spiral arm, nor whether they connect up with the strong arm drawn in the lower right corner. This latter itself, as well as the 3-kpc arm in the upper left, appear to be well defined. It is likely that some of the matter with high positive velocities between 4° and 22° longitude lies in the space between the arm beyond the center and the 3-kpc arm. We have not drawn it because there is no indication *where* to put it.

On the other hand it is practically certain that the space below the 3-kpc arm, between the dotted line at $l^{II} = -6°$ and the line marked "limit of northern obs." at $l^{II} = -10°$, is virtually empty.

Although it appears plausible to assume that all the large deviations from rotational motion are directed away from the center, as in the 3-kpc arm, even this is not certain. From the emission velocities themselves we cannot distinguish between radial motions towards or away from the center. For the present, however, we shall assume as a working hypothesis that the motions are all outward.

A remarkable feature of the central region is the great difference in appearance between the side of positive velocities and that of negative velocities. If we abstract from the wing of high negative velocities between 0° and −4° longitude which, as we shall see below, is an entirely different feature pertaining to a region closer to the center than we are now discussing, we find that all the gas on the side of negative velocities is concentrated in a well-ordered and continuous structure, the 3-kpc arm. But the gas clouds having *positive* velocities show hardly any order at all. There is apparently a fairly important asymmetry in this central region. Yet, the total amounts of gas appear to be approximately the same in the two halves.

It should be pointed out that, notwithstanding their sometimes very large deviations from circular motions, all features observed in the central region lie very close to the average galactic plane. There are no indications of considerable motions perpendicular to this plane.

Disk and Ring Structure in the Nuclear Part—The Variation of Circular Velocity with Distance from the Center.—A radical change in the distribution and motion of the interstellar gas seems to occur at $R = 600$ pc. The character of this change is displayed most clearly at the side of the negative velocities. Perhaps the most striking feature in Figure 6 is the wing towards high negative velocities beginning at longitude $-4°$ and extending to the longitude of the center. The fact that no

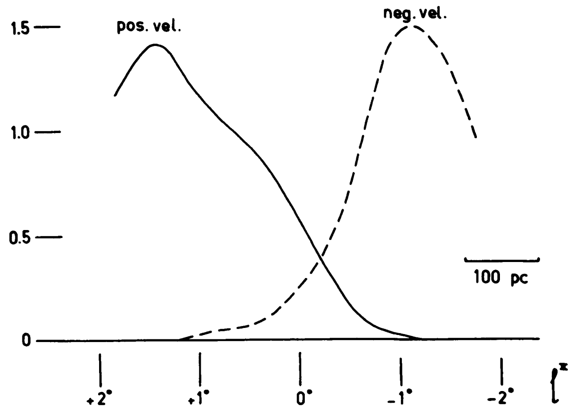

FIG. 7.—Numbers of hydrogen atoms per cm² with radial velocities between 150 and 210 km/sec (after correction for the motion of the sun relative to the galactic center). The numbers refer to latitude zero on the new system; abscissae are longitudes in the same system. Ordinates are in units of 10^{21} atoms.

such high negative velocities are found in any other part of the longitude interval investigated|| and the exact co-incidence of the upper longitude limit with the direction of the center, suggest strongly that the wing is due to matter situated close to the center.

When we now look at the postive velocities, we notice that for these there is a very similar feature at longitudes beyond that of the center. Here, however, it is superimposed upon an extremely irregular background of high-velocity matter making up the very irregular arms shown in the picture. That there is something real superimposed on this background is indicated by the curves in Figure 7 which were obtained from special measurements of high accuracy made at each quarter of a degree from $-2°$ to $+2°$ longitude. These show that the number of atoms of very high positive velocity drops steeply near the longitude of the center, in very much the same way as the high negative velocities. Also, the total numbers of atoms in the velocity range considered is almost exactly the same for positive and negative velocities.

The most plausible interpretation of these new features is that they are due to a disk of hydrogen extending to about 600 pc from the center and rotating at high velocity. A more detailed analysis of the line profiles for the negative velocities—which are uncontaminated by foreground or background radiation—indicates that there is a ring of matter with rather sharp inner and outer boundaries at radii R of about 500 and 590 pc. The density in the ring is 1 atom per cm^3. There appears to be a practically empty space within the ring, the density only becoming appreciable again at R = 300 or 350 pc. It then rises gradually to about 3 atoms per cm^3 at R = 100 pc. Still further inside the density must increase very strongly. The distribution is shown schematically in Figure 4. In the innermost region the interpretation of the observations becomes complicated because of the absorption phenomena caused by the radio source Sagittarius A. Drake in Green Bank[3] has recently shown that the nucleus of this radio source contains two very dense patches about 15 pc from the galactic center. If one assumes that these are regions of ionized hydrogen, the masses would be of the order of 50 000 solar masses. Smeared out over a sphere of 20 pc radius this would correspond with a density of about hundred protons per cm^3. It has been suggested by Woltjer that the ionization in the emission regions would be caused by the ultraviolet radiation of the population II stars rather than by O-type supergiants, which could hardly be sufficiently frequent to furnish a lasting source of energy. The population II stars may be sufficiently dense in the central region to explain this radiation.

If a radio telescope with a beamwidth of 0.°56, like the one used for the present study, is pointed towards the center, the inner parts of the rotating disk are seen in absorption against the wings of Sagittarius A. The absorption has been measured up to velocities of a little over 100 km/sec. It is present at negative as well as at positive velocities. Some sample curves are shown in Figure 9.

There is no sign of any expansional motion in this "nuclear" disk and ring, neither in the emission observed at negative velocities nor in the absorption profiles. There appears to be only rotation. The rotational velocities are quite high. In the ring, at 550 pc, it is about 265 km/sec. Rough estimates from the observed line profiles give velocities of 220 km/sec at R = 260 pc, 190 km/sec at R = 140 pc and about 180 km/sec at R = 70 pc. Assuming, tentatively, that the motions in the ring and disk are governed mainly by gravitation and that these values give the circular velocities, we can derive the concentration of mass density in the nuclear region of the Galactic System. It is well known that in most galaxies which contain a fairly strong population II there is a strong increase in light-density right up to the center. In the Galactic System, where the entire central region is hidden by very opaque dark material, this cannot be observed. But it can be seen quite well in the Andromeda nebula, a galaxy bearing probably a fairly strong resemblance to our own galaxy. In this nebula the increase of light continues to a distance of only a few parsecs from the center. Baade states that the nucleus has diameters of 2.″5 × 1.″5, corresponding with 7 × 4 pc. It is interesting to compare the rotational velocities observed in the Galactic System with those found for the inner part of the Andromeda nebula, on the assumption that the distribution of light is the same as that of the mass, and that the mass-to-light ratio is 20.[4] The space distribution of the light up to about 100″, or 300 pc, was derived from plates taken for this purpose in 1932 with the 69-inch Perkins reflector in Delaware, Ohio. For the region up to about 3 kpc use was made of photometric measures by Fricke[5] and by Redman and Shirley.[6] A rough computation being sufficient for our present purpose, the measures along the major axis and the least obscured, southeastern, half of the minor axis were averaged, and the region considered was treated as if it had spherical symmetry.

The agreement between the circular motions thus computed for the Andromeda

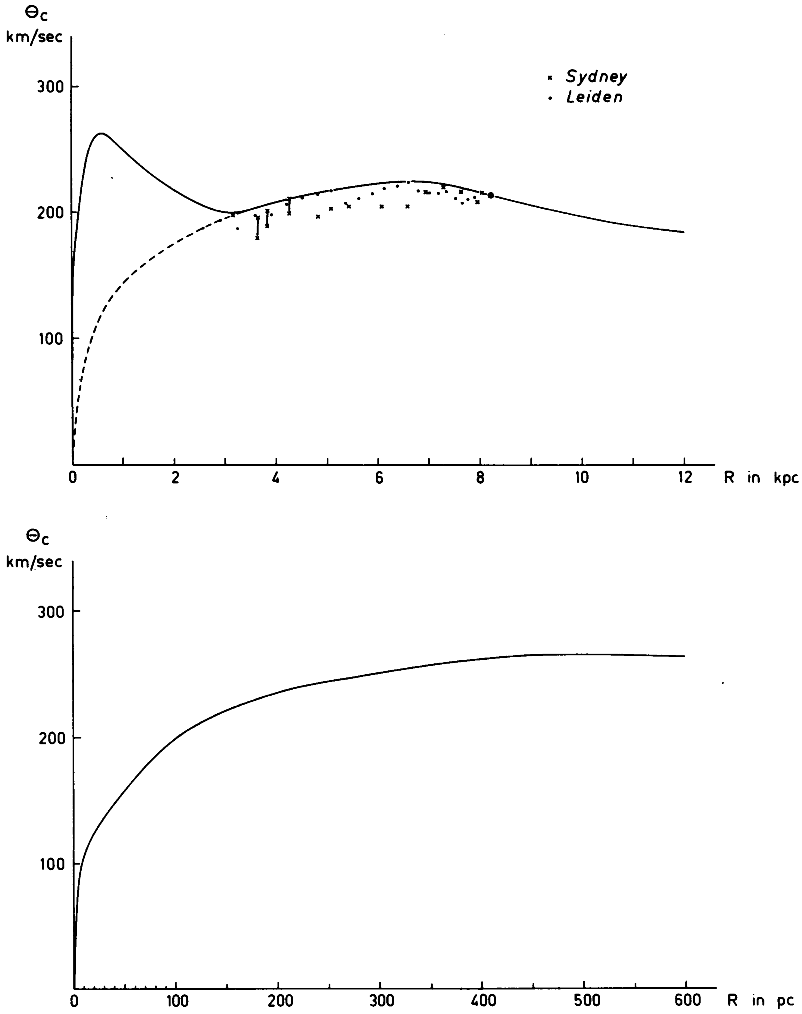

FIG. 8.—The variation of circular velocity with distance from the center.

nebula and the rotational velocities measured in the central disk and ring and between 3 and 4 kpc in the Galactic System appeared to be quite good, except that a reduction factor of 0.79 had to be applied to the Andromeda nebula results. This reduction factor may change slightly for distances greater than 600 pc from the center. The rough Andromeda-nebula data have been used to extend to observed parts of the rotation curve for the Galactic System into the region within R = 100 pc, where it could not be directly measured, and over the interval from 600 to about

3,000 pc, where the unexplained expansional motions prevent any direct estimates of the circular velocities. The resulting circular velocities are shown graphically in Figure 8. It should be stressed that this is only a provisional result, which will be subject to revision after the final reductions have been made. The part beyond $R = 3$ kpc is based on earlier 21-cm data obtained in Kootwijk (Netherlands) and in Sydney. The following table summarizes some of the pertinent data derived from this curve and from the preceding discussion. They are compared with results at 3 and 8.2 kpc derived from other data. The mass density is seen to rise to 1,000 times that near the sun around $R = 90$ pc. At $R = 10$ pc it runs up to roughly 24,000 times this density. The density is almost entirely due to *stars:* within 500 pc of the center the interstellar hydrogen contributes only about $^1/_{400}$ to the total mass. The periods of revolution at the various distances considered are shown in the last column.

R (parsecs)	Mass within R (10^9 suns)	Density: stars (10^{-23} g/cm³)	Density: gas (at/cm³)	Density: gas (10^{-23} g/cm³)	T (10^6 years)
10	0.03	24000	1000:	100:	0.5
20	0.07	7800	100:	10:	1.0
100	0.92	710	3	0.5	3.1
500	8.3	42	1	0.2	12
3000	16	6.9	0.4	0.1	96
8200	60	1.0	1	0.2	230

A few data may be added concerning the distribution in the direction perpendicular to the galactic plane, which we shall call the z direction. In the 3-kpc arm the distance between the two planes where the density drops to half its maximum value is 1.°5, or 120 pc, which is about half the thickness of the layer in the general region between 5 and 10 kpc from the center. Roughly the same linear thickness is found for the aggregate of the matter with high positive velocities.

In the nuclear disk the half-density thickness decreases to about 80 pc. The derivative $\delta K_z/\delta z$, where K_z is the z component of the gravitational force, becomes so large when we come very close to the center, that within $R = 50$ pc the internal velocities must become of the order of 100 km/sec in one co-ordinate to explain the observed thickness.

Replenishment of Gas in the Central Disk and Possible Cause of the Outward Flow.— We are still far from an understanding of the behavior of the gas in the central region. We consider, first, the problem of the replenishment of the gas streaming outward through the thin galactic layer. A very rough estimate gives that per year a mass of hydrogen equal to between one and two solar masses moves outward through a cylinder of 2.5 kpc radius. At this rate the central disk would be depleted of its hydrogen in a time of the order of 10^7, or, at most, 10^8 years. This is so short compared to the age of the Galactic System that we have to conclude that the gas must be replenished in some way. Unless we assume that it is produced from matter in some entirely unknown state, such as has been proposed by Ambartsumian, there are only two possible sources: the stars in this region and the galactic corona. If one computes, on the basis of current theories of stellar evolution, the amount of gas that could be expelled by the population II stars in the central region, one arrives at a figure which is about 50 times too low. We must therefore probably consider the galactic corona as the source of replenishment. Rough estimates indicate that, with a plausible coronal density, just about enough gas may condense into the

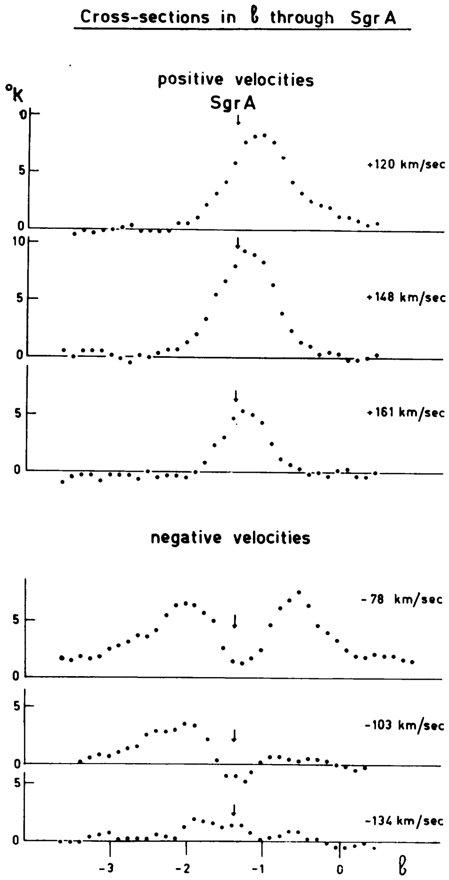

FIG. 9.—Sample distributions in latitude at the longitude of the galactic center. The absorption shown in the lower half is due to absorption of the radiation from the wings of the radio source Sagittarius A in the outer parts of the beam of the telescope. The absorption presumably takes place in the nuclear disk, mainly at distances between 10 and 50 pc from the center. It extends from about −75 to −120 km/sec; the absorptions found at lower negative velocities, down to −40 km/sec, are due to the 3-kpc arm. At *positive* velocities absorption due to the nuclear disk has likewise been observed, but here the measurements are more difficult and the results more uncertain. At higher positive velocities the line appears in emission, as shown in the upper part of the diagram. It shows matter behind the center, moving away from it at high velocities.

cool disk to make up for the loss by the matter streaming away in the plane of the disk.

Work on the theoretical side of the problems discussed is only in its very beginning. The cause of the spiral phenomenon in general is still unknown and it is also unknown how the spiral pattern is maintained against the effects of differential rotation. Almost the only thing we *can* understand is why the galactic layer is as thin as it is found to be. In addition, an interesting theory has been developed by Kahn and Woltjer[7] to account for the systematic bending of the outer edges of the layer as a consequence of the motion of the Galactic System relative to an intergalactic medium.

No theory has yet been developed to explain the systematic outward motions in the central region. Nor has it been possible to understand the existence of the spiral-like features which may be seen in the corresponding region of the Andromeda nebula, and which probably exist likewise in the central region of the Galactic System. With the large differential circular velocities and the short times of revolution in the central parts of these galaxies such features would rapidly be effaced if they were governed by gravitational forces only. The only likely other force which could influence these structures and motions would seem to be a hydromagnetic force. But it is still unknown in what manner it would push the gas outward and contribute to the observed structures.

As regards the small nuclear disk, it has been suggested by Woltjer that the magnetic fields in this disk, which are responsible for the extended non-thermal component of Sagittarius A, would have circular symmetry and form a closed unit.

The observations on the spiral structure outside the central region were partly made at Kootwijk in the Netherlands, using a 7 $^1/_2$-meter giant Würzburg,[8] and partly in Sydney, with a 11-meter meridian radio telescope.[9] A general account may be found in an article by Oort, Kerr, and Westerhout;[10] a more detailed survey article has recently been published by Elwert.[11] The observations on the central region were almost entirely made with the 25-meter radiotelescope of the radio astronomy observatory at Dwingeloo, an institution financed by the Netherlands Organization for Pure Research (Z.W.O.). The instrument has a beamwidth of 0.°56 at 21 cm. The great majority of the measures were made with a bandwidth of 20 kc/s. The total observing time was about 2,400 hours. That we could reach the accuracy required at the low intensities involved was entirely due to the efforts of Professor C. A. Muller, who designed the receiver and continually improved its stability.

* One of four papers presented in a symposium on radio astronomy at the Autumn Meeting of the National Academy of Sciences at the University of Indiana, November 17, 1959. Another paper from the symposium, by R. Minkowski, appears on pages 13-19. The remaining papers will be published as they are received.

† parsec (pc) = 3.26 light-years or 3.08×10^{18} cm.

‡ This temperature, the so-called "brightness temperature," gives the temperature of a black body which at the frequency concerned would give the observed surface intensity of radiation.

§ The longitudes are counted in the new system of galactic co-ordinates, from the longitude of the center as zeropoint; they have been indicated by the symbol l^{II}. For the sake of convenience we have used negative numbers to indicate longitudes below 360°.

‖ These observations extend in a somewhat less complete form beyond the plot shown in Figure 6; the above statement probably applies to the entire interval from −10° to +20° longitude.

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*INTERNATIONAL COOPERATIVE EFFORTS DIRECTED TOWARD OPTICAL IDENTIFICATION OF RADIO SOURCES**

BY R. MINKOWSKI

MOUNT WILSON AND PALOMAR OBSERVATORIES, CARNEGIE INSTITUTION OF WASHINGTON, CALIFORNIA INSTITUTE OF TECHNOLOGY

Radio positions of high accuracy permit us to consider as significant the presence of a faint optical object within the area given by the errors of the source position. But, positions of radio sources are not accurate enough to point uniquely to an optical object with which the source is to be identified. Supplementary evidence