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The New Milky Way

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Summary. Our understanding of the large-scale structure of the Milky Way has undergone considerable revision during the past few years. The Galaxy is larger and much more massive than was previously supposed; the newly discovered mass consists of nonluminous matter which is likely to be the dominant form of matter in the universe. New analyses of the atomic hydrogen gas show that the disk of the Galaxy is about twice as extended as was previously thought. Beyond the sun, the gas is concentrated in large-scale, coherent spiral arms indicative of a regular four-armed spiral pattern. The outer edge of the disk has a remarkable scalloping.

Ten years ago, the study of the overall structure of our Galaxy, the Milky Way, seemed to be past its prime. The basic large-scale features and properties of the Galaxy were thought to have been known for some time, and a theory proposed in the middle 1960's (*1*) showed considerable promise in explaining the dynamics of the rotation of the disk. Subsequently, many of the workers most active in galactic structure research turned their attention elsewhere. There was more to be learned, it seemed, from observations of other galaxies than from observations of our own.

Over the past several years, however, it has become clear that not only have our ideas about the structure of the Milky Way needed some refinement, but the most massive component of our Galaxy had been overlooked. This component has recently been detected gravitationally, but it is not luminous enough to have been recognized by any observer at any wavelength. It may therefore be composed of a currently unknown type of astronomical object. In this article we describe how the large-scale picture of the Milky Way has changed over the past few years (*2*).

The Old Milky Way

The traditional picture of the Galaxy is that it is a thin round disk 30,000 parsecs (pc) in diameter with a thickness a few percent of its extent (*3*). The sun is located at a distance of about 10,000 pc (10 kpc) from the center, and has a roughly circular orbit with a velocity of about 250 km/sec (*4*). The sun thus orbits the center once every 250 million years. The center of the Milky Way cannot be seen with optical telescopes, but contains a powerful source of radio waves, much more energetic than the sun. It was, in fact, the first source detected by any radio telescope, and was discovered in 1932 by Jansky (*5*). Within a few kiloparsecs of the galactic center, the disk of stars fattens into a spheroidal bulge of old stars. Also spheroidally distributed about the center, but to distances as large as 50 kpc, are about 200 globular clusters: spherical clusters of old stars containing as many as a million members. Completing the picture is the interstellar gas, which is closely confined to the plane defined by the disk of stars.

Most of the mass of the Milky Way was thought to be in ordinary stars. Interstellar gas, almost all of which was thought (until the late 1960's) to be neutral atomic hydrogen, comprises roughly 1 to 2 percent of the total mass. The gas resides mainly in the disk and has a thickness of only 250 pc (measured between points with half of the midplane density). The hydrogen was known to have a large-scale warp with a shape like the brim of a fedora.

Observations of other disk galaxies showed that many of them have beautiful spiral structures. It was natural to wonder whether the Milky Way might also have large-scale regular spiral arms. Indeed, within 3 kpc of the sun, three segments of armlike concentrations of luminous young stars were identified (*6*) and were thought to be representative pieces of the overall large-scale spiral structure of the Galaxy. The interstellar dust (which comprises about 1 percent of the mass of interstellar gas) absorbs starlight, however, and it is difficult to see much beyond a few kiloparsecs in the plane of the Milky Way in most directions; the overall spiral structure could not be convincingly deduced from optical observations alone. It was hoped that radio observations of the atomic hydrogen gas, which is pervasive, relatively transparent, and not absorbed by the dust, would show the concentrations which could be seen in the spiral arms of other galaxies.

When the radio observations were completed, however (*7*), it turned out that the results were difficult to interpret (*8*), and the question of whether the Milky Way has large-scale spiral structure could not be answered unambiguously. Although most disk-shaped galaxies exhibit spiral structure of some sort, in many galaxies this structure is quite irregular. The length of a spiral arm segment which can be continuously identified might be quite small, and it has not been clear whether the inability to identify a system of large-scale regular spiral arms in the Milky Way on which all observers could agree results from the limitations of the observing technique or the absence of such arms in the Galaxy.

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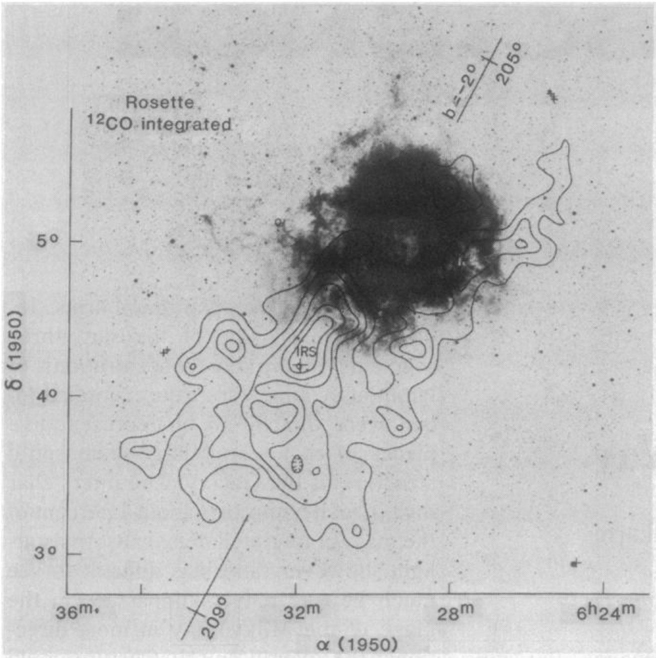


Fig. 1. A typical giant molecular cloud complex in the vicinity of the sun, associated with the Rosette Nebula (*59*). The contours are integrated CO antenna temperature and delineate the extent of the H_2 cloud associated with the nebula, a moderately bright HII region. The map shows a clear interaction between the HII region and the molecular cloud. The extent of the cloud is 100 pc and its mass is about 1.5×10^5 solar masses.

In the middle 1960's, the Lin-Shu (*1, 9*) density wave theory suggested an explanation for the major unsolved problem of spiral galaxies: Why don't the spiral arms wind themselves up and become unrecognizable? Galaxies rotate differentially, the inner portions orbiting the center more frequently than the outer portions. Over the lifetime of a spiral galaxy, there are so many orbits (about 50 in the vicinity of the sun) that any large-scale spiral pattern should be completely obliterated. The Lin-Shu theory suggested that the spiral arms were not material arms, but were manifestations of a wave phenomenon which propagated through the disk of a galaxy. The density wave theory had success in explaining a number of the detailed structural and kinematic features of the Milky Way and other spiral galaxies.

By 1970, the major stellar components of the Milky Way had been known for some time and the atomic (*7*) and ionized (*10*) gas had been surveyed. Although surveys at a number of wavelengths were to be completed later (indeed, some are not yet complete), the outlines of the large-scale distribution of matter in the Galaxy seemed to be known with some confidence, even though many of the details remained obscure.

Interstellar Molecules

In the late 1960's, our understanding of the nature of the interstellar gas in the Milky Way began to change drastically with the discovery of large quantities of molecular gas in addition to atomic gas (*11*). The early molecular observations demonstrated the presence of cold (10 K) gas in large quantities, with densities 10^2 to 10^5 times greater than were previously thought to be common in the interstellar medium [the atomic gas typically has temperatures of 30 to 5000 K (*12*) and an overall mean density of 0.3 atom per cubic centimeter (*7*)]. The discovery of interstellar formaldehyde (*13*) in 1969 indicated that organic molecules were readily manufactured in the interstellar environment. Subsequently, more than 50 molecules have been detected in the interstellar medium.

The most abundant molecule by far is molecular hydrogen. But, because it has no permanent electric dipole moment, it does not emit and absorb photons at the low temperatures typical of most of the molecular gas. Molecular hydrogen has been observed directly only when it absorbs the ultraviolet light from a hot massive background star (*14*), or under unusual high-temperature conditions such as those associated with star formation (*15*).

Nevertheless, the presence of H_2 can be inferred from the excitation of other molecules, especially carbon monoxide. Excitation of carbon monoxide to the temperatures at which it is observed in the interstellar medium requires collisions with other particles that have a density of $\sim 10^3 \text{ cm}^{-3}$. It was shown (*11, 16*) that the collisions take place primarily with electrically neutral particles, and these were inferred to be molecular hydrogen (atomic hydrogen would have been detected by means of its 21-cm radio radiation). Subsequently, a few regions have been observed in which both CO and H_2 have been detected directly (*17*). These observations confirm that the H_2 is present in sufficient quantities to collisionally excite CO. Although the abundance of CO is only 10^{-4} times that of H_2, it is the next most abundant of the molecules detected to date in the interstellar medium. It is readily detected with high-frequency millimeter-wave radio telescopes by means of the $J = 1 \rightarrow 0$ rotational transition at a wavelength of 2.6 mm. The CO molecule thus acts as a tracer of the more abundant H_2. Recently, it has been shown that OH, the third most abundant molecule, can also be used as a reliable tracer of the H_2 gas (*18*).

Observations of CO in the vicinity of the sun have shown that the molecules are collected in discrete clouds with well-defined boundaries (*19*); an example is shown in Fig. 1. These clouds are almost entirely molecular, with only small quantities of atomic gas. Some of these clouds (perhaps all of the largest of them) have extended atomic envelopes. In contrast, atomic hydrogen is detected essentially everywhere in the disk of the Galaxy. The molecular gas fills only about 1 percent of the volume of the disk, and the atomic gas appears to fill most of the rest. [An alternative picture of the interstellar medium was proposed recently by McKee and Ostriker (*20*), who argued that the largest fractional volume of the disk is hot ionized hydrogen gas. The validity of their picture, which is supported by a number of observations, does not affect any of the subsequent discussion in this article.]

The largest of the molecular clouds, which are referred to as giant molecular clouds, are remarkable in several respects. First, they are the most massive objects in the Galaxy—typically several hundred thousand solar masses. They contain as much matter as the richest of the globular clusters, but are about 20 times as numerous (*19, 21*). Second, they are the nucleation sites for most of the present-day star formation in the Galaxy (*19, 22*). Essentially all of the stars in the Milky Way known to be young—that is, less than a few million years old—appear to have formed from the dense molecular gas (dense by interstellar standards, but still far more rarefied than the best terrestrial vacuum) that comprises the giant molecular clouds. Third, the total mass of H_2 locked up in the giant molecular clouds approaches the total mass of atomic hydrogen in the Milky Way (*21, 23*). The precise ratio of atomic to molecular gas has been the subject of considerable debate (*24*), but all observers agree that the molecular gas is a substantial fraction of the total. Not only are the giant molecular clouds a new, previously unsuspected component of the Milky Way, they have played an important role in our newly emerging understanding of galactic structure.

Galactic Rotation

The dominant large-scale force on astronomical scales is gravity, and it is the mutual gravitational attraction of massive cosmic bodies that determines their state of motion. The large-scale distribution of matter in the Milky Way can therefore be revealed by the motion of its constituents—for example, by measuring the variation of the rotational velocities of objects in orbit around the galactic center as a function of distance. A plot of the velocity (V) versus distance from the galactic center (R) is called a rotation curve, and it is one of the fundamental astronomical measurements made of our own and other galaxies. Once the rotation curve is measured, the distribution of matter in the Galaxy can be inferred from the equations of motion. The solar system, for example, has a Keplerian rotation curve with $V \propto R^{-1/2}$ because almost all the mass is concentrated in the sun. If the mass in the solar system were more spatially extended, the exponent of R would be greater than $-1/2$; its precise value would depend in detail on the mass distribution. In the outer regions of a galaxy, the rotation curve is expected to approach a Keplerian form because most of the mass can be approximated to be in the central regions.

In order to measure the rotational properties of the Galaxy as a whole, it is necessary to find a pervasive component whose velocity and distance can be independently measured over a large range of galactocentric distances. Until recently, the most useful component has been the atomic hydrogen gas. Unlike starlight, the 21-cm spectral line of atomic hydrogen is unattenuated by galactic dust and can therefore be observed almost anywhere in the Milky Way. The differential rotation of the galactic disk causes the 21-cm line from gas at different distances from the center to be Doppler-shifted relative to the local gas. Along a line of sight that intersects the solar circle—the circle at the distance of the sun in the plane of the Galaxy centered on the galactic center—the biggest radial velocity comes from the point closest to the galactic center (see Fig. 2). By making observations along all such lines of sight, it is possible to measure the velocity and distance of the hydrogen gas along a particular, well-defined locus of points. This method allows the rotation curve to be measured out to the solar distance, but not beyond (*25*).

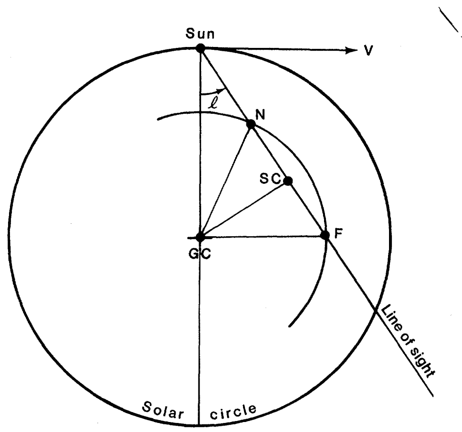


Fig. 2. Schematic diagram of the geometry related to observations of the gas in the plane of the Galaxy as viewed normal to the plane. GC is the galactic center and V is the orbital velocity of the sun, which orbits the center along the solar circle at distance R. The gas in the disk rotates differentially with decreasing angular velocity at increasingly large distances from the center. Along a given line of sight, the differential rotation produces the largest Doppler-shifted emission at SC, the subcentral point. The points N and F are equidistant from the center and therefore have the same angular velocity. Gas at these positions produces emission lines with the same radial velocity (the velocity component along the line of sight). Thus, for positions inside the solar circle, it is not possible to determine whether the emission is coming from point N or point F from measurements of the radial velocity alone. The angle ℓ is galactic longitude; it increases counterclockwise from a direction toward the galactic center (see Figs. 4 and 5).

From a distance of about 4 kpc to the solar distance, V is not strongly dependent on R. There is a local maximum about 8 kpc from the galactic center, and it had been expected that V would continue to decrease at larger distances. Observations of other spiral galaxies showed that the disk light decreases exponentially from the center (*26*). Because the disk light is produced by ordinary stars, and because these stars were thought to be responsible for most of the mass, an exponential disk implied that there would be little mass beyond the solar distance. A mass model of the Galaxy incorporating the most reliable observations available at the time was developed by Schmidt in 1965 (*27*). The model, which became the standard for a number of years, predicted a rotation curve in which V decreased with increasing R beyond the solar circle and approached a Keplerian form 15 to 20 kpc from the center. This expectation of the Schmidt model has turned out to be grossly inconsistent with recent observations.

It has been known for some time that, in order to be dynamically stable, clusters of galaxies generally require more mass than can be accounted for in terms of their luminous mass (*28*). In the middle 1970's, evidence began to accumulate that spiral galaxies in general, and the Milky Way in particular, contain large quantities of undetected matter. Ostriker and Peebles (*29*) argued that the disks of spiral galaxies like our own should be unstable to the formation of bar-shaped structures, but could be stabilized if they possess massive, spheroidal halos. In a recent, more general analysis, Vandervoort (*30*) takes issue with the detailed results of Ostriker and Peebles, but does not dispute their fun-

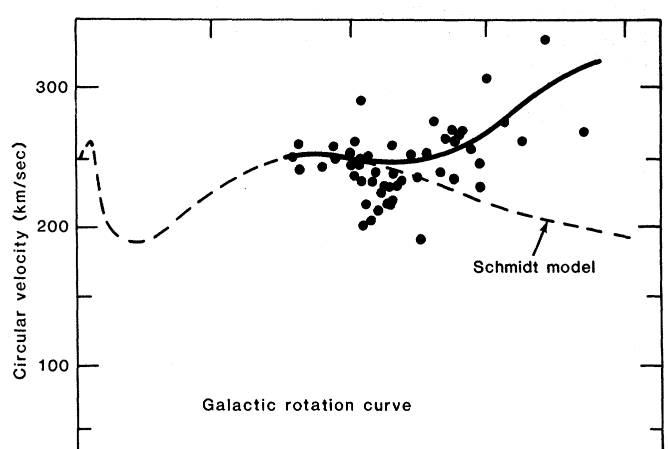


Fig. 3. Rotation curve of the Milky Way (*42*). The filled circles represent data and the solid line a fourth-order least-squares fit to the data. The dashed line is the rotation curve from the Schmidt mass model (*27*). The Schmidt model fits the rotation curve from the atomic hydrogen data inside the solar circle well, but does not fit the data beyond 12 kpc from the center.

damental qualitative conclusions. Analyses of various observational results lent support to the conjecture that galaxies have massive halos. Among these have been the comparison of the rotational velocities and light distribution of some spiral galaxies, the statistical analysis of the radial velocities of binary galaxies, and the analysis of the tidal radii of nearby dwarf spheroidal galaxies (*31*, *32*). A computer simulation of the Magellanic stream, a tidally generated flow resulting from the passage of the Magellanic Clouds, also pointed to a large mass for the Milky Way (*33*).

Perhaps the most convincing evidence that spiral galaxies contain large quantities of nonluminous matter came from the measurement of the rotation curves of a large number of spiral galaxies. Rubin *et al.* (*34*), from optical measurements of the Hα line, and Bosma (*35*), from radio measurements of the 21-cm hydrogen line, showed that nearly all of the spiral galaxies they observed have rotation curves that are approximately flat (that is, V independent of R) as far as they can be measured. Thus, the outer regions of spiral galaxies do not have Keplerian rotation curves, presumably because of the presence of large quantities of nonluminous material. By 1978, although a direct measurement was still lacking, many workers had begun to suspect that the rotation curve of the Milky Way is also flat. A dynamical analysis of the distant globular clusters and dwarf spheroidal galaxies (*36*) gave results consistent with a flat rotation curve, as did a kinematic analysis of distant atomic hydrogen gas (*37*).

The New Rotation Curve

The first direct measurements of the rotation curve to large galactocentric distances beyond the sun (*38*, *39*) resulted from the recognition that there are many very young star clusters in the outer parts of the Milky Way which show evidence of interaction with their placental molecular clouds. Because young clusters contain the brightest, most massive stars in the Milky Way, they can often be identified to large distances from the sun. Beyond the solar circle, the obscuration due to dust is significantly lower than in the inner parts (*40*). By comparing the brightness and color distribution of the stars in the outer clusters to those in nearby clusters, whose distances are independently known, one can obtain distances to the more outlying clusters to an accuracy of about 25 percent. An important survey by Moffat *et al.* (*40*) obtained distances to 40 of the most distant young clusters.

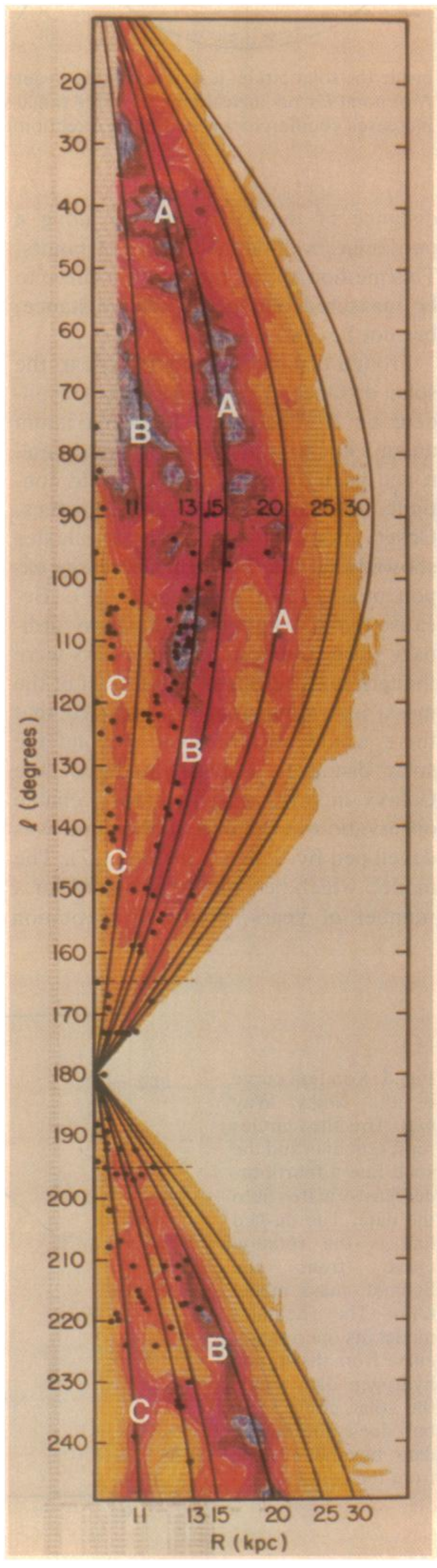


Fig. 4. Surface density of atomic hydrogen beyond the solar distance, showing the large-scale ordered spiral structure. The ordinate is galactic longitude (see Fig. 2), and the solid lines are lines of constant distance from the center of the Galaxy. The contours are in units of 0.5 solar mass per square parsec. Features *A*, *B*, and *C* are discussed in the text. The black dots represent the positions of star-forming molecular clouds, which are seen to be well correlated with the arms defined by the atomic hydrogen.

The brightest cluster members often ionize the hydrogen gas in their vicinity, producing bright, fluorescent nebulae known as HII regions. These regions have been shown by many workers to interact with their placental giant molecular clouds, thus providing clear evidence for the association of the clusters with the molecular gas. A recent survey showed that about 75 percent of all HII regions have associated molecular clouds (*41*). Most of the mass of the star cluster/HII region/molecular cloud complex resides in the molecules. The molecules are observed by radio heterodyne techniques, which can provide velocities accurate to a fraction of a kilometer per second, an order of magnitude improvement over any other method. Therefore, measurement of the velocities from CO observations provides accurate radial velocities of the center of mass of a complex, whose distance can be determined from the optical observations of the young cluster. These quantities are converted to galactocentric distance and orbital velocity (assuming circular rotation), and thus a rotation curve is determined.

The rotation curve to 18 kpc from the galactic center is shown in Fig. 3 (*42*). Although the detailed shape of the curve depends somewhat on the exact value of the galactocentric distance and orbital velocity of the sun, the curve deviates markedly from the expectation of the Schmidt mass model, shown as a dashed curve in Fig. 3. The implication is that there is much more mass in the outer region of the Milky Way than was thought to exist in stars. Or, to put it another way, the dark matter that was predicted on theoretical grounds, and was found to be common in other spiral galaxies, has been detected gravitationally in the Milky Way.

Recently, a dynamical analysis of the globular cluster system (*43*) has shown that the Milky Way rotation curve is likely to be flat to a distance of more than 50 kpc from the galactic center.

Thus the dark matter, which dominates the mass of the Galaxy 5 to 10 kpc beyond the sun, is detectable to at least 50 kpc from the center. For a flat rotation curve, $M(R) \propto R$, where $M(R)$ is the total mass interior to some point R. The mass of the dark matter is thus at least four to five times greater than all of the previously known mass in the Milky Way. But what is the nature of this material and how is it distributed? A partial answer to this question comes from an examination of the distribution of atomic hydrogen gas in the outlying portions of the Milky Way. The distribution of this gas has provided new insights into the structure of the Milky Way and is interesting in its own right.

Atomic Hydrogen Beyond the Solar Circle

In 1974 an important survey of the atomic hydrogen in the Milky Way was published by Weaver and Williams (*44*). This was a complete survey of the hydrogen near the plane of the Galaxy which is visible from the Northern Hemisphere. Although the hydrogen in the Milky Way is detected from all directions in the sky, most of it is from a region within ±10° of the plane. Most of the rest is very near the sun and does not provide much information on the overall structure of the Galaxy. The determination of the rotation curve of the outer portions of the Milky Way has made it possible to analyze the atomic hydrogen from the Weaver and Williams survey in such a way as to derive reliable physical properties of the gas. The results have provided a much clearer picture of the distribution of the gas than has been possible in the inner regions, primarily because there is no distance ambiguity to confuse the interpretation of the results. That is, inside the solar circle the radial velocity of a parcel of gas corresponds to two different distances from the sun, whereas in the outer Galaxy the velocity uniquely determines its distance. In addition, all of the gas within ±10° of the plane has been included in the analysis. Most of this gas is relatively transparent at the 21-cm wavelength of atomic hydrogen; that is, it is optically thin. The analysis therefore provides a clear picture of the distribution of the gas to the edge of its extent in the Milky Way. Independent analyses of the outer Galaxy data were performed by two different groups (*45, 46*), using different techniques of analysis, and we discuss the results in some detail in order to emphasize the new features of the Galaxy discovered by these workers.

Figures 4 and 5 are plots of the mass surface density and the deviation of the gas from the midplane of the Galaxy defined by the galactic equator (specifically, the first moment of the vertical distribution of the gas). The vertical axis represents galactic longitude, ℓ: increasing azimuthal angle along the galactic plane centered on the sun (refer to Fig. 2). Zero longitude corresponds to a line toward the galactic center. The horizontal axis is radial velocity, which is converted to distance by using the outer Galaxy rotation curve. Lines of constant galactocentric distance are shown. The left edge corresponds to the solar distance.

In Fig. 4, detectable atomic hydrogen extends to at least 30 kpc from the center. There are several long connected features of enhanced surface density which cross lines of constant galactic

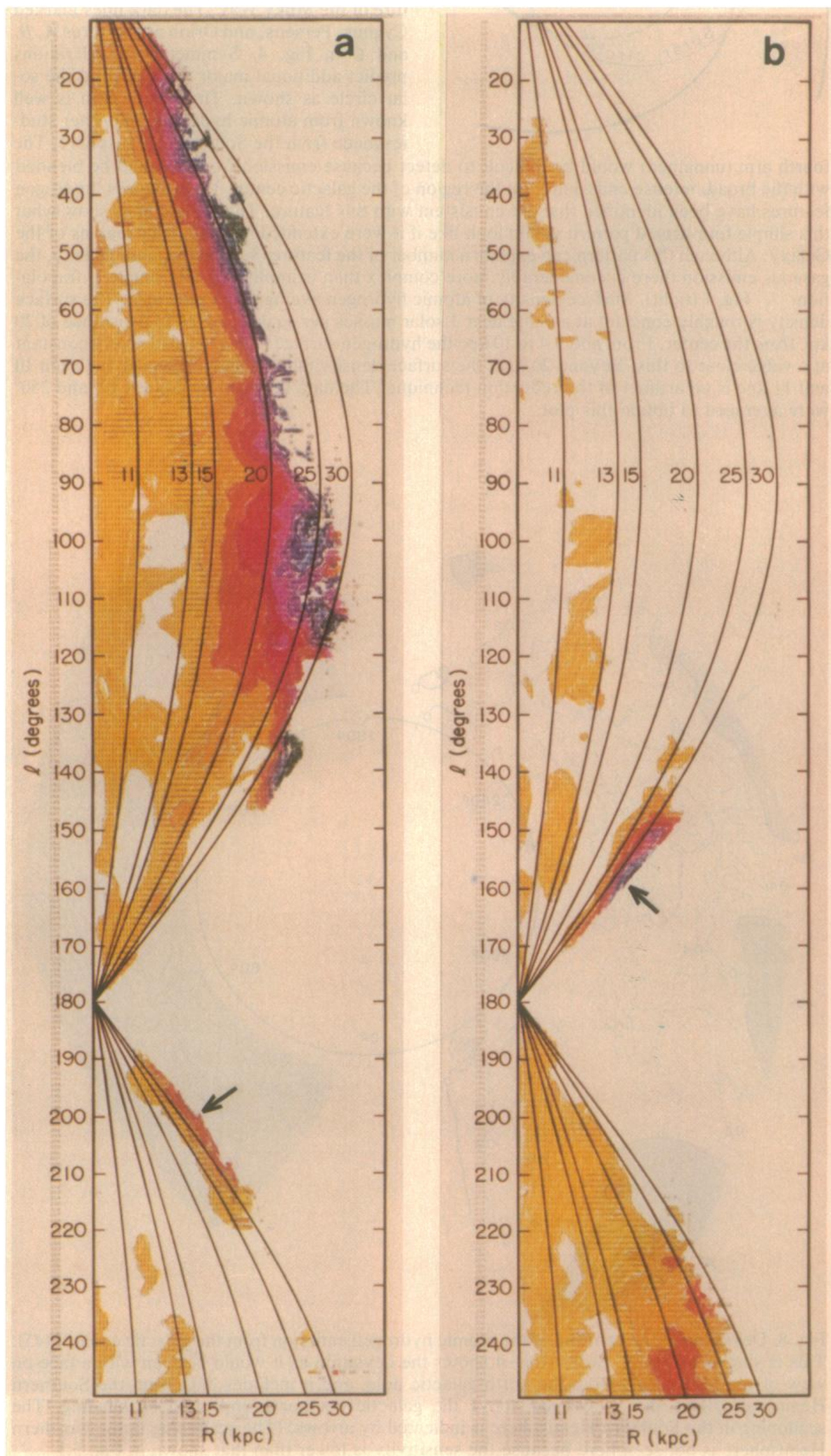
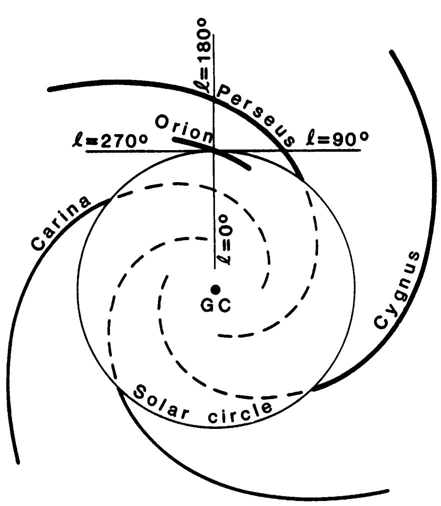


Fig. 5. Deviations of the mean plane of the atomic hydrogen emission from the galactic equator: (a) positive deviations and (b) negative deviations. Contours are in units of 100 pc. The large-scale warp between longitudes 10° and 180° is fairly gentle to a distance of ~ 18 kpc from the center, where it appears to increase sharply. Scalloping is indicated by arrows at positions where deviations at the edge of the disk are opposite to the large-scale warp.



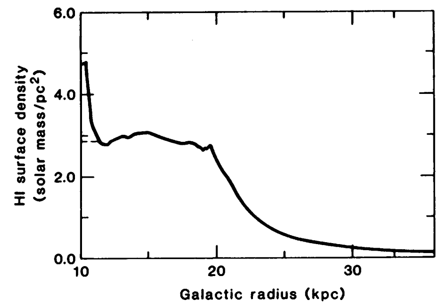


Fig. 6 (left). Face-on view of the spiral structure of the Milky Way. The dark lines marked Cygnus, Perseus, and Orion are features *A*, *B*, and *C* in Fig. 4. Symmetry considerations predict additional major arms beyond the solar circle as shown. The Carina arm is well known from atomic hydrogen and other studies made from the Southern Hemisphere. The fourth arm (unnamed) would be difficult to detect because emission from it would be blended with the broad, intense emission from the region of the galactic center. Nevertheless, hydrogen features have been identified that are consistent with this feature. The dashed lines show what this simple four-armed pattern would look like if it were extended into the inner regions of the Galaxy. Although this pattern can explain a number of the features seen in the inner Galaxy, the gaseous emission there is considerably more complex than is implied by this simple extrapolation. Fig. 7 (right). Surface density of atomic hydrogen averaged over the disk. The surface density is roughly constant at a value near 3 solar masses per square parsec to a distance of 20 kpc from the center. From about 4 to 10 kpc the hydrogen surface density is also nearly constant at a value close to this. Beyond 20 kpc, the surface density falls sharply. The peak between 10 and 11 kpc is an artifact of the reduction technique. The data between longitudes 10° and 250° were averaged to obtain this plot.

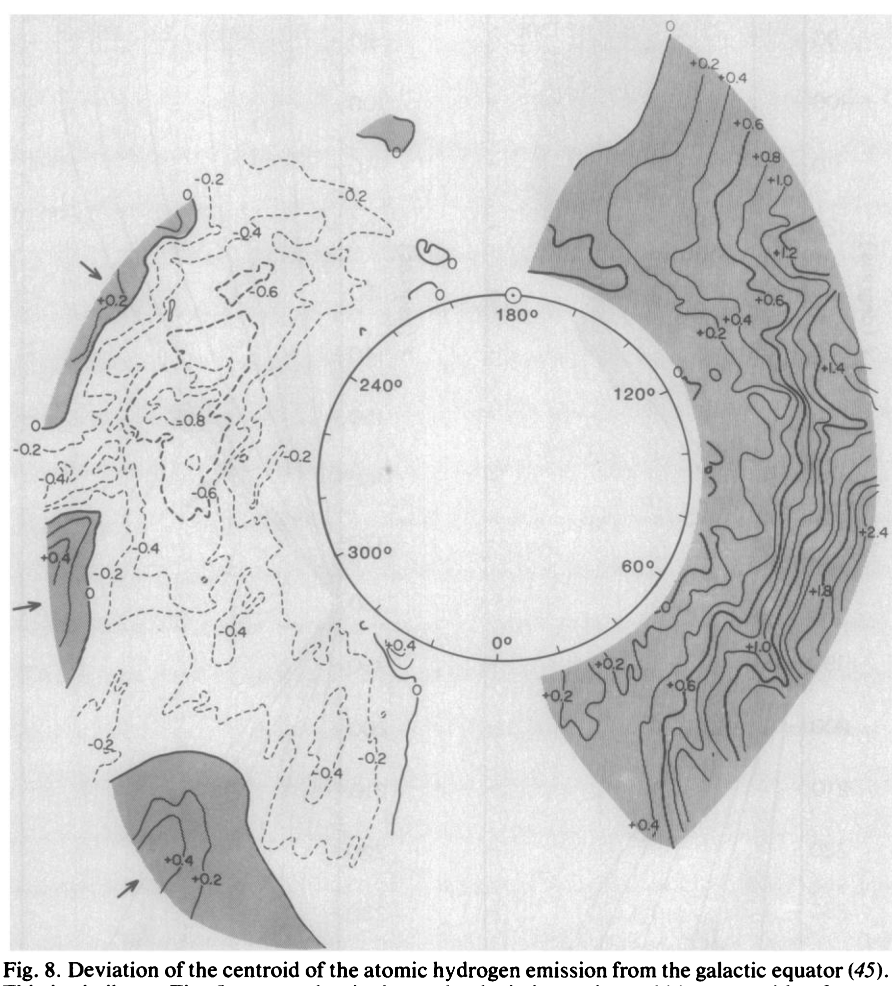


Fig. 8. Deviation of the centroid of the atomic hydrogen emission from the galactic equator (*45*). This is similar to Fig. 5, except that it shows the deviation as it would be seen with a face-on view of the Milky Way from the north galactic pole, and it includes data from the Southern Hemisphere. Gas that is warped above the galactic equator is indicated by shading. The scalloping in the Southern Hemisphere is indicated by arrows. (The scalloping in the Northern Hemisphere is not seen here because the sensitivity is lower than that shown in Fig. 5.)

radius and correspond to large-scale, coherent, trailing spiral arms. Features *B* and *C* correspond to the well-known Perseus and Orion arms. Feature *A* has been called the Cygnus arm (*46*) because it occurs chiefly in the constellation Cygnus. The lengths of the Cygnus, Perseus, and Orion arms are 25, 20, and 5 kpc, respectively. Although these features have been identified by others (*47*), the coherence and relative contrast of the arms are nowhere shown better than in Fig. 4. The lengths of the Cygnus and Perseus arms indicate that the Milky Way does indeed have a large-scale, coherent spiral pattern, at least in its outer parts.

The pitch angle measures the openness of the arms. The pitch angle of the Cygnus arm is 21° and that of the Perseus arm about 25°, assuming they are logarithmic spirals. For the Orion arm the pitch angle is ~ 29° but is very uncertain. The pitch angles are typical of open spirals designated Sbc or Sc. The Orion arm does not appear to be a major arm like the other two, and is probably a short spur. Figure 6 shows what the arms would look like if viewed from above the Galaxy. If the Milky Way is reasonably symmetric, one would expect two more arms as shown in Fig. 6. These occur in the Southern Hemisphere and both correspond to known features in the atomic hydrogen gas—one to the well-known Carina arm, the other to features in the outer Galaxy maps of Henderson *et al.* (*45*) and Sills (*48*).

The surface density of the Orion arm is underestimated because there is a considerable amount of gas in the arm outside the latitude boundary of the Weaver and Williams survey. When the proper corrections are made, the surface densities along the arms and from arm to arm are roughly constant. Indeed, a plot of the surface density of all of the gas averaged over longitude (Fig. 7) shows that, as in the inner portions of the Galaxy, the surface density is constant to a distance of 20 kpc from the center and declines monotonically beyond that distance.

The bright portions of the spiral arms are seen only to about 20 kpc from the galactic center (from Southern Hemisphere data, the Perseus arm extends only ~ 10° beyond what is seen in Fig. 4). Some faint spiral arms have been identified at even larger distances (*48*, *49*), but these would be difficult to see in Fig. 4 because of insufficient contrast and the rapid decline in the atomic hydrogen surface density shown in Fig. 7. Nevertheless, the arms shown in Fig. 4 are those that would be identified by extragalactic radio telescopes similar to terrestrial ones that might be observing the Milky Way.

The black dots in Fig. 4 are the giant molecular clouds observed as part of the survey to measure the rotation curve. These are fairly well concentrated in the spiral arms. This is not surprising since the spiral arms of other galaxies are usually best identified by the bright hot stars and HII regions, which, in the Milky Way, are closely identified with giant molecular clouds. The HII region/molecular cloud complexes are not seen much beyond 20 kpc; massive star formation (and possibly all star formation) in the Milky Way apparently ceases at about that distance, although detectable atomic hydrogen extends to at least another 10 kpc.

To summarize, the outer portions of the Milky Way have large-scale, coherent spiral arms of roughly constant surface density to about 20 kpc from the center. In the outer portions, the Milky Way appears to be a fairly regular four-armed spiral with some spurs, and the giant molecular clouds are fairly well concentrated in the arms. Massive star formation appears to cease at about 20 kpc from the center, but the hydrogen extends at least 10 kpc beyond that distance.

Figure 5 shows the distribution of gas above and below the mean plane of the Galaxy which is defined by the gas inside the solar circle. Between $\ell = 10°$ and 180° the gas is primarily above the mean plane, and beyond $\ell = 180°$ it lies primarily below. This is the well-known fedora brim warping of the outer parts of the galactic plane. Figure 5 also shows two new features of the hydrogen emission. At $R = 11$ kpc, from $\ell = 30°$ to 70°, and $R = 12$ kpc, from $\ell = 95°$ to 165°, there is a corrugation—a discontinuous string of gas which is displaced below the galactic plane, although most of the gas is above. Beyond $\ell = 220°$, what appears to be a continuation of this string is again displaced in a direction opposite to the large-scale galactic warp. This string corresponds to a radial corrugation of the disk.

The large-scale warp is fairly small to a distance of ~ 18 kpc from the center and then rises very sharply. Maps of atomic hydrogen in some edge-on galaxies show a similar effect (*50*). As in the Milky Way, the warps of these galaxies become particularly pronounced toward the edge of the stellar disk.

Figures 5 and 8 show a wholly unexpected feature of the edge of the galactic disk—a high-frequency scalloping. If one traces the outermost edge of the gas in Fig. 5, starting at $\ell = 20°$, the gas is consistently above the plane of the Milky Way. The maximum value of the warp is reached near $\ell = 45°$, slowly decreasing to $\ell = 135°$. Between $\ell = 135°$ and 150° the warp again becomes very large. But from $\ell = 145°$ to 170° the displacement of the outer lip of gas changes sign even though that of the gas at smaller radii does not. From $\ell = 190°$ to 230° there is another sign change, and from $\ell = 220°$ to the survey boundary, yet another. This up and down displacement of the outer edge of the gas can be traced for three more cycles in Fig. 8, which is a plot of the vertical displacement of the gas as it would be seen from above the Galaxy. In Figs. 5 and 8 the lip of gas that is scalloped in a sense opposite to the large-scale warp is indicated by an arrow. This remarkable scalloping of the outer edge of the atomic hydrogen has an azimuthal wave number of ~ 10 and is remarkably regular. Its origin is unknown.

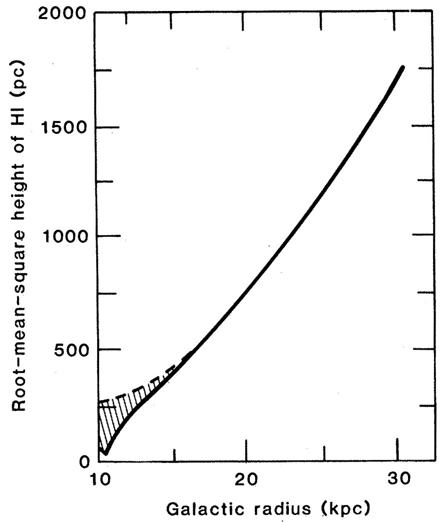


Fig. 9. Thickness of the hydrogen layer as a function of distance from the center. The shaded portion represents a correction due to the incompleteness of the latitude coverage of the data used in the analysis at low velocities. These data are used to show that the large mass implied by the flat rotation curve cannot reside in a thin disk and is thus presumably spheroidally distributed.

The second moment of the vertical gas distribution in the Milky Way (that is, the root-mean-square displacement of the gas from the midplane defined by Fig. 5) is a measure of the thickness of the gas layer. Figure 9 shows a plot of this quantity averaged over the range $\ell = 90°$ to 250°. Unlike the inner part of the Milky Way, where the thickness of the atomic gas shows little variation with distance from the center (outside the nuclear regions), the outer Galaxy shows a steeper than linear increase in the thickness as a function of distance—an increase of about a factor of 10 from the vicinity of the sun to a distance of 30 kpc from the center. The increase in the thickness of the gas beyond the solar circle has been known for many years (*51*), but it is only with the recent analyses of the outer Galaxy atomic hydrogen (*45, 46*) that the increase has been quantitatively well established.

The Massive Halo

Although the evidence that the Milky Way (like most spiral galaxies) has large quantities of nonluminous matter is reasonably well established, the evidence that this matter is distributed in a spheroidal halo rather than an extended dark disk came mainly from theoretical rather than observational arguments. The thickness of the hydrogen gas layer, however, can be used to address this question. The gas thickness is determined by the gravity of the disk, which tends to confine it, and the gas pressure, which tends to disperse it. If information on the gas pressure can be obtained as a function of distance from the center, it is possible to determine whether any of the dark matter must reside in a halo.

Under the assumption that the turbulent velocity of the gas is constant in R and that it provides the sole contribution to the gas pressure, Gunn (*52*) showed that the increasing thickness of the atomic gas is inconsistent with the dark matter being in the disk. Kulkarni *et al.* (*46*) included the effects of cosmic-ray pressure and magnetic field pressure and independently came to the same conclusion. They showed that if the ratio of the total gas pressure to the gas density was not an increasing function of R (which it appears not to be), and H_*, the thickness of the stellar layer, is larger than that of the gas (as is observed locally), then the thickness of the gas layer, T, at radii R_1 and R_2 can be written

$$\frac{T_2^2}{T_1^2} = \frac{R_2 H_{*2}}{R_1 H_{*1}}$$

if all the mass implied by the rotation curve is in a thin disk. The subscripts refer to values at each distance.

From Fig. 8, for gas at 10 and 30 kpc, the value of the left-hand side of the equation is about 100. This would require the thickness of the stellar layer at 30 kpc to be comparable to its radius, which is inconsistent with the idea of a thin disk. If the thickness of the stellar layer becomes smaller than that of the gas layer at some distance, it can be shown that the continuing increase in the thickness of the gas layer is also incompatible with the dark matter being in the disk. This heuristic argument is independent of the form of the stellar mass distribution and thus does not require any assumptions about an exponential stellar disk. A similarly motivated study of the edge-on spiral galaxy NGC 891 (*53*) concludes that the dark matter implied by the rotation curve is in a spheroidal halo.

Most of the mass of the Milky Way and of spiral galaxies in general thus appears to be contained in the dark spheroidal halos. Gunn (*52*) has argued that elliptical galaxies also have dark, massive halos. Most of the mass in the universe therefore seems to be in the form of nonluminous matter, which has so far been detected only by the gravitational effect it has on the matter we can directly observe. What can we infer about such matter?

We know from observations of our own and other galaxies that the matter is not in the form of an ordinary stellar population (*54, 55*), although very-low-mass stars are not yet entirely ruled out. The halo in the Milky Way also cannot be gas in any form. If the gas were predominantly atomic, its average density within 50 kpc would be about 0.3 atom per cubic centimeter, comparable to the mean density of atomic gas in the disk of the Galaxy. Such a large quantity of gas would be easily detectable from observations of the 21-cm line in our own and other galaxies. If the gas were primarily ionized hydrogen, the bremsstrahlung emission—radiation generated by the electrical interaction of the charged particles—would be easily detectable. In any event, without an external energy source the ionized gas would quickly recombine to form atoms. If the gas were predominantly molecular, it would be detectable in the ultraviolet portion of the spectrum by means of the Lyman absorption bands against the light of distant quasars. In the one case where such lines are believed to have been detected (*56*), the column density of the hydrogen gas is too small to account for a massive galactic halo. The halo cannot also be the result of micrometer-sized dust particles similar to those found in the disk of the Milky Way. In that case, the extinction of starlight caused by the dust would be so strong that other galaxies could not be detected with optical telescopes.

What remains? One possibility is that the halo consists of starlike objects not sufficiently massive to have initiated the nuclear reactions typical of ordinary stars. These objects would have masses less than 0.08 solar mass and might resemble the planet Jupiter. They might be detectable in the infrared, but with great difficulty. Another possibility is that the halo consists of an unknown type of astronomical body larger than that of the microscopic dust but smaller than that of the smallest stars. Still another possibility has been raised by the recent controversial measurement of the neutrino mass (*57, 58*). The halo could consist of a cold gas of massive neutrinos that condensed at the time of formation of the galaxies.

Whatever the form of the massive halos in the Milky Way and in other galaxies, at least two things seem clear: the halos are exceedingly transparent and nonluminous at all wavelengths and the matter that comprises them is probably the dominant form of matter in the universe. An understanding of the universe as a whole, as well as the origin and formation of galaxies, demands an understanding of this new and strange component of the Milky Way, and it is sure to be one of the major challenges for astronomy in the coming years.

References and Notes

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3. A parsec is 3.26 light-years and is slightly smaller than the distance from the sun to the nearest star. It is also roughly equal to the mean distance between stars in our portion of the Milky Way. A parsec is equal to about 200,000 times the distance from the earth to the sun.
4. A number of recent observations indicate that the circular velocity of the sun is closer to 220 km/sec, and the distance to the center closer to 8.5 to 9 kpc. These values do not substantially alter any of the following discussion.
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