# PART 6

# LARGE-SCALE GALACTIC STRUCTURE

"The Magellanic Stream is coming down on the galactic plane, and it's going to get its own back on the Galaxy, you see, and give it a great boot."
D. S. Mathewson, in the discussion following the paper co-authored by M. N. Cleary and J. D. Murray

# CURRENT PROBLEMS IN 21 cm LINE STUDIES OF THE LARGE-SCALE STRUCTURE OF THE GALAXY

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**Abstract.** A number of current problems in 21 cm line studies of the Galaxy as a whole are discussed. Because of the difficulties involved with straightforward mapping, it is important to isolate integrated and other properties of the hydrogen profiles, the interpretation of which does not require accurate distance determinations. In addition, methods of analysis are necessary which either account for or exploit the sensitivity of hydrogen profiles to velocity irregularities and to geometrical configurations. The model-fitting approach to the interpretation of the hydrogen profiles is useful in this respect. Extragalactic hydrogen studies which show the relative ordering of the various components of spiral structure can inspire research in our own Galaxy. Such investigations are necessary for an understanding of the forces governing the spiral structure. It seems that the neutral hydrogen is primarily a tracer of locations where the overall distribution of stars is producing a gravitational sink. Other spiral tracers, in particular the molecules, are better considered as tracers of regions where the gas has been compressed, perhaps (at least on a large scale) by the shock front predicted by the density-wave theory.

## I. Introduction

My charge is to report on 'the present status of 21 cm work on the spiral structure of the whole Galaxy'. Excluded from this report (but included in others in these proceedings) are the high-velocity clouds, the galactic center region, and the spur and loop features. It seems reasonable to restrict the report to phenomena showing some continuity over length scales typically 1 kpc or larger, at latitudes less than about 10° from the galactic plane. Insofar as my remarks pertain to continuing investigations, they will be rather general.

The emphasis in 21 cm line work on the large-scale galactic structure has changed somewhat since the previous IAU symposium on galactic radio astronomy held in Noordwijk (van Woerden, 1967). Relevant areas in which research activity has increased include investigations of the kinematic characteristics of the neutral hydrogen and the relationship of these characteristics to theoretical predictions, the motion and spatial distribution of hydrogen relative to other constituents of the galactic disk, and integrated and other properties of the hydrogen profiles which do not require very accurate distance determinations for their satisfactory interpretation. On the other hand, there have been fewer attempts at detailed spatial mapping of regions near the galactic plane.

## II. Kinematic Aspects of the Neutral Hydrogen Distribution

Since the first observations of the 21 cm line in 1951, what was sought was the density and velocity distribution of the hydrogen. It has been clear that these problems are

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intimately related, since distances are calculated from a measured velocity and thus require previous knowledge of the velocity field throughout the Galaxy. For the derivation of the well-known Leiden-Sydney map (see Oort *et al.*, 1958), which displayed contours of the volume-density of the hydrogen in spatial coordinates, it was reasonable to base the density derivation on the working hypothesis of circular symmetry. Even though it was clear that this hypothesis was not exactly true, it was not clear whether the deviations from circular symmetry involved mainly the density distribution or mainly the velocity one. If the latter case, it was thought that the deviations from circular rotation, which over most of the galactic disk are typically only a few per cent of the circular motions of differential rotation, would result in errors in the distances of this same order.

One way to demonstrate the lack of circular symmetry is to divide the Galaxy by a line through the Sun and the galactic center. If the density and velocity fields of the Galaxy were circular, then the borders of the 21 cm profiles taken at corresponding longitudes on either side of this line would occur at oppositely signed, but otherwise equal, velocities. Such a comparison is made in Figure 1. Dots in the figure

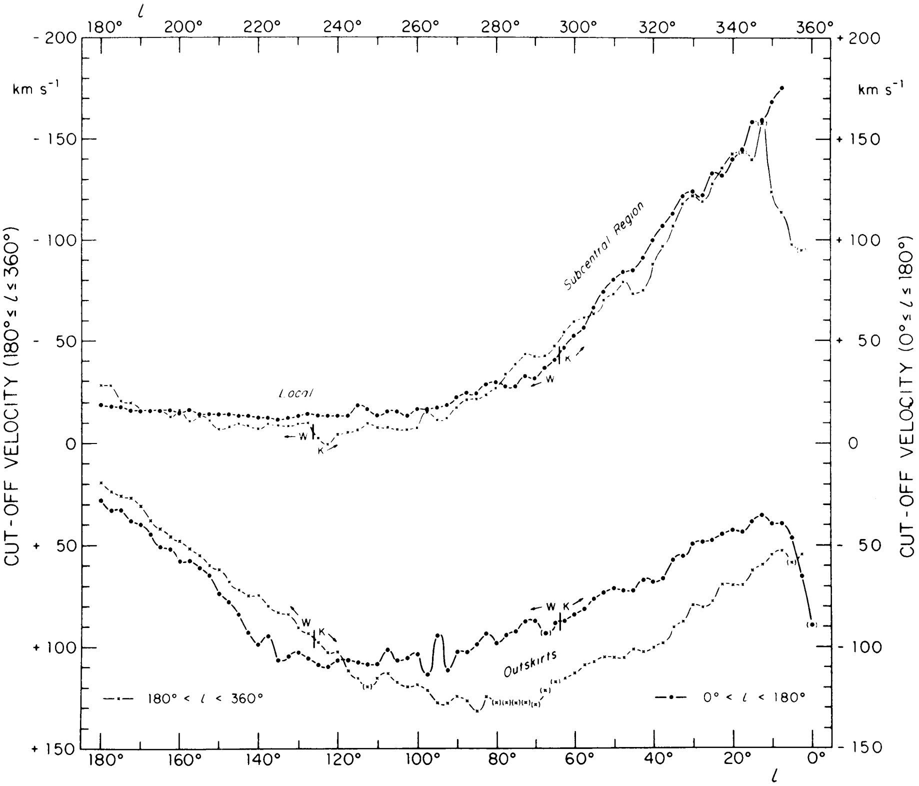

Fig. 1. Non-circularity of the galactic hydrogen distribution as indicated by systematic differences in the cut-off velocities measured from the wings of profiles observed (by Westerhout, 1966; and by Kerr and Hindman, 1970) on either side of the Sun-center line (Burton, 1973).

represent the velocity cut-offs of profiles observed in the longitude range 0° to 180° and crosses represent the same thing taken from profiles observed on the other side of the Sun-center line, from 180° to 360°. The fact that the crosses and dots are non-coincident proves the existence of deviations from circular symmetry.

At least some of the deviations from circular symmetry require explanation in velocity terms. The cut-off velocities of profiles representing hydrogen near the subcentral ('tangential') points show irregularities which were originally (Kwee *et al.*, 1954) attributed to subcentral-point regions that did not contain enough gas to determine the profile cut-off. However, Shane and Bieger-Smith (1966) showed that this explanation in terms of the density distribution requires that there be essentially no hydrogen (about a factor 100 less than the average) along regions of 4 or 5 kpc in extent, and that these regions are furthermore preferentially oriented with respect to the observer. This is unacceptably artificial, and in addition is not consistent with other characteristics of the emission profiles. Consequently the irregularities in the subcentral point cut-off velocities, (which are the same irregularities which show up as bumps on the rotation curve), can better be attributed to deviations from circular motion with length scales of about 1 kpc and amplitudes of the order of 5 km $s^{-1}$. Amplitudes of 5 km $s^{-1}$ amount to less than 3% of the circular motion over most of the Galaxy.

The opinion has been expressed that, because of these deviations from the circular rotation curve adopted as a working model, the resulting maps should be considered drawn on a rubber sheet which might be stretched by amounts corresponding to distance errors caused by the velocity irregularities. This opinion seems now to be somewhat too optimistic. It appears that the sort of velocity irregularities known to exist throughout the Galaxy probably determine the appearance of the line profiles in a way that dominates over density manifestations (Burton, 1971, 1972; Tuve and Lundsager, 1972, 1973). This sensitivity is demonstrated by Figure 2. In the upper part of the figure is the profile observed at $l=90°$ in the galactic plane. In the lower part of the figure the velocity (with respect to the local standard of rest) which would be expected at this longitude in the case of circular Schmidt (1965) rotation, is plotted as the full-drawn line. Deviations from such circular rotation would result in perturbations to this smooth curve of the sort illustrated by the dashed line. These perturbations imply that at some velocities the velocity will vary slowly with distance relative to the smooth-curve situation; there will be more hydrogen contributing to the profile at such a velocity than at a velocity where the variation of velocity with distance is rapid. The sensitivity of line profiles to such velocity irregularities is suggested by a model profile calculated for the case of a thoroughly uniform density distribution but in the presence of the perturbed velocity-field. The resulting profile (shown by the dashed line in the figure) shows the same sort of structure as the observed profile, including the positive-velocity peak, which would be impossible to account for in terms of Schmidt-type rotation. It would require density contrasts of 50 or 100 to 1 to account for intensity differences equivalent to those obtained by systematic streaming motions of only a few km $s^{-1}$.

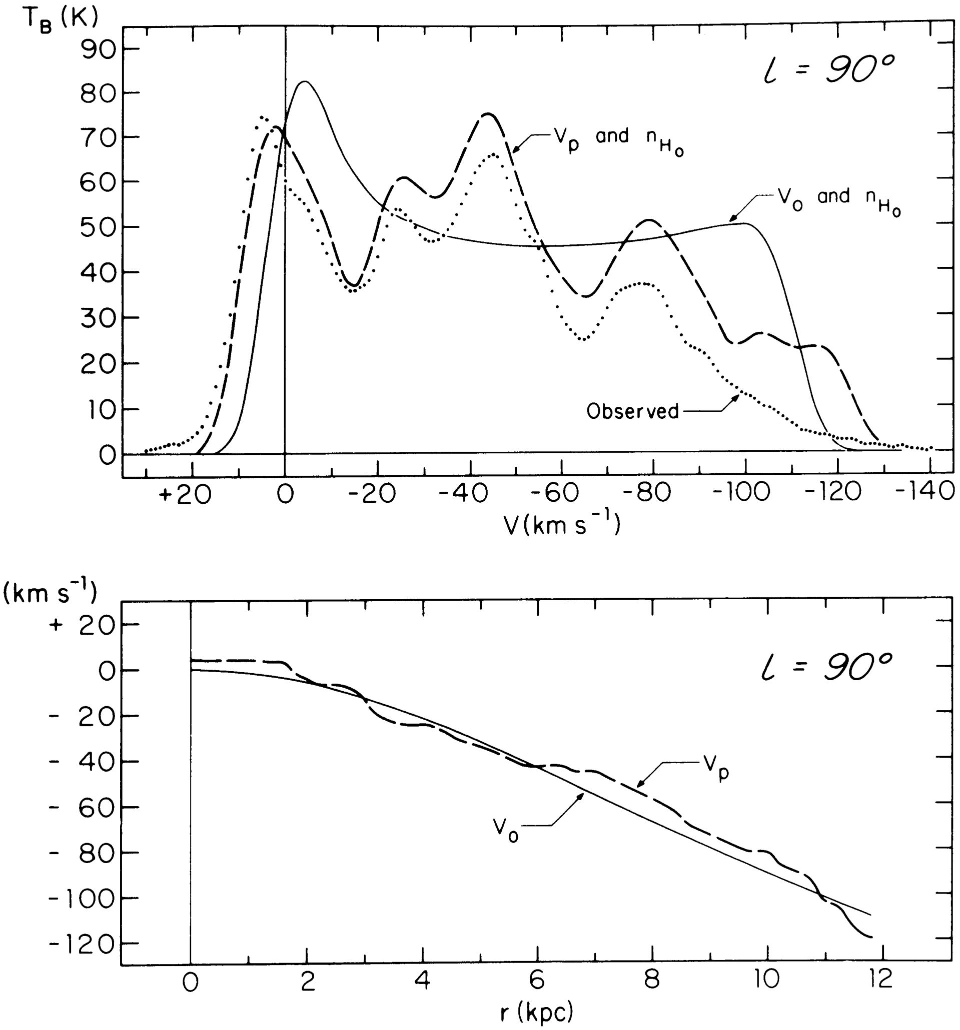

Fig. 2. Diagram illustrating both the sensitivity of hydrogen line profiles to velocity irregularities and the profile-fitting method used in the derivation of Figure 4. The profile observed at $l = 90°$, $b = 0°$, is indicated, as are model profiles calculated for the case of uniform density with a circular-rotation velocity-distance relationship, $V_0$, and with a perturbed relationship, $V_p$.

Although it *is* clear on general grounds that irregularities in the velocity, density and temperature will accompany one another, what is *not* clear is the extent to which a particular peak in a hydrogen observation owes its characteristics to streaming motions, to a density concentration, or to a variation in temperature. This means that hydrogen density variations near the galactic plane cannot be determined with any accuracy directly from observations; it is also generally not possible to determine the true velocity dispersion from observations near the plane.

## III. Model-Fitting Approach to Investigating the Galactic Distribution of Hydrogen

The opinion has been expressed, too, that because of these problems, the realistic end product of large-scale hydrogen studies is a complete velocity-longitude diagram, rather than a spatial map. This seems rather pessimistic. In my opinion the problems are primarily procedural. On the one hand, new methods of galactic structure analysis are needed, whereas at the same time efforts should be made to isolate problems which can be investigated without requiring very accurate distances or density determinations.

As far as the methods of analysis are concerned, it is worth mentioning one approach to the derivation of the large-scale galactic structure which has recently been applied to a variety of problems involving hydrogen observations. The model-fitting approach involves selecting a model's physical parameters according to the appearance of simulated observations. In the case of the hydrogen, it is required that the adopted velocity, density and temperature distribution reproduce the appearance of the observed profiles. Figure 3 illustrates the model-making approach for the interior portion of the Galaxy between longitude 40° and 90°. In the upper left of the figure is the observed velocity-longitude map of temperature contours. In the upper right is a contour map composed from model profiles; the model's parameters were chosen by comparing the observed with the model contour maps. The map in the lower part of the figure indicates the spatial distribution of the chosen parameters; in this case the regions of above-average density and the sense of the streaming motions are indicated. The classical approach involves a direct transformation from the observed velocity space to the spatial distribution (upper-left observations to lower map). The model-fitting approach requires agreement between the two upper maps, which are both in the observed space. In this way the effects inherent in the complicated geometry of the transformation from velocity to distance are accounted for. Once agreement between the two upper maps is established, the model's parameters can be further judged in other ways.

The model-fitting approach is also useful in investigating the compatibility of various theoretical predictions with the observations.

## IV. Predictions of the Density-Wave Theory Relevant to the Overall Distribution of the Hydrogen

The density-wave theory provides for the maintenance of structures in the disk, against the shearing forces of the rapid differential rotation (e.g., Lin *et al.*, 1969; Lin, 1971). Stars and gas moving in approximately circular orbits experience the assumed spiral component of the gravitational potential in such a way that they tend to pile up in troughs of low potential. For the circumstances pertaining to our Galaxy, the gas motions involved with this piling-up are predicted to have amplitudes of about 6 km $s^{-1}$, with components in both the azimuthal and radial directions. The azi-

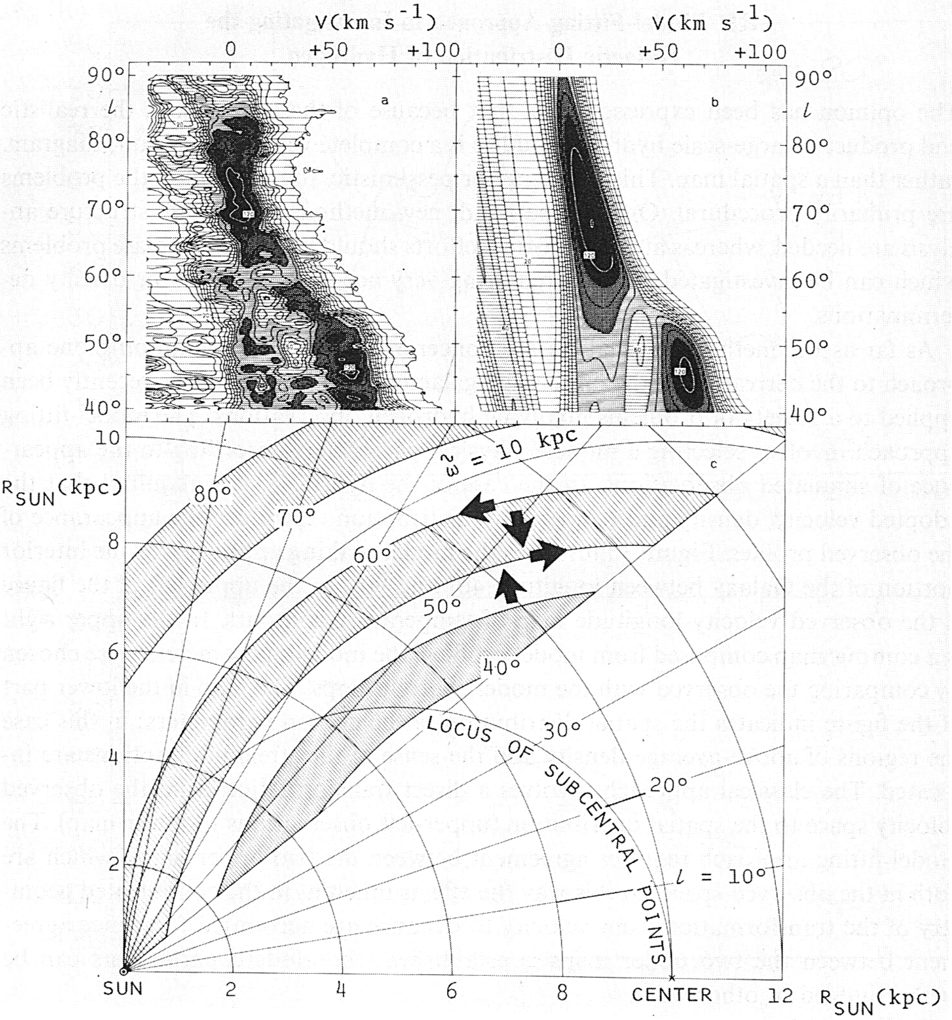

Fig. 3. Diagram illustrating the model-making approach for a portion of the galactic plane (Burton, 1971). The classical approach involves a direct transformation from the observations to the spatial map. The model-fitting approach involves choosing the spatial distribution of the various parameters by examining simulated observations.

muthal streaming component gives an entirely satisfactory explanation of the bumps observed in the galactic rotation curve (Barbanis and Woltjer, 1967; Yuan, 1969; Burton and Shane, 1970; Burton, 1971). Evidence for the predicted radial component in the gas is less direct, but it does seem that a systematic flow pattern is necessary to produce the arm-interarm contrasts of the sort observed in the profiles (Burton, 1971).

Since the velocity field is the physical parameter to which the hydrogen profiles are most sensitive, and since knowledge of the velocity-field is crucial for a complete observational confrontation of any theory of spiral structure, it seems reasonable to take the consequences of the premise that the velocity dominates the hydrogen profiles' appearance. By assuming for the sake of argument that *all* profile structure has a kinematic origin, a model profile may be fit to each observed profile by per-

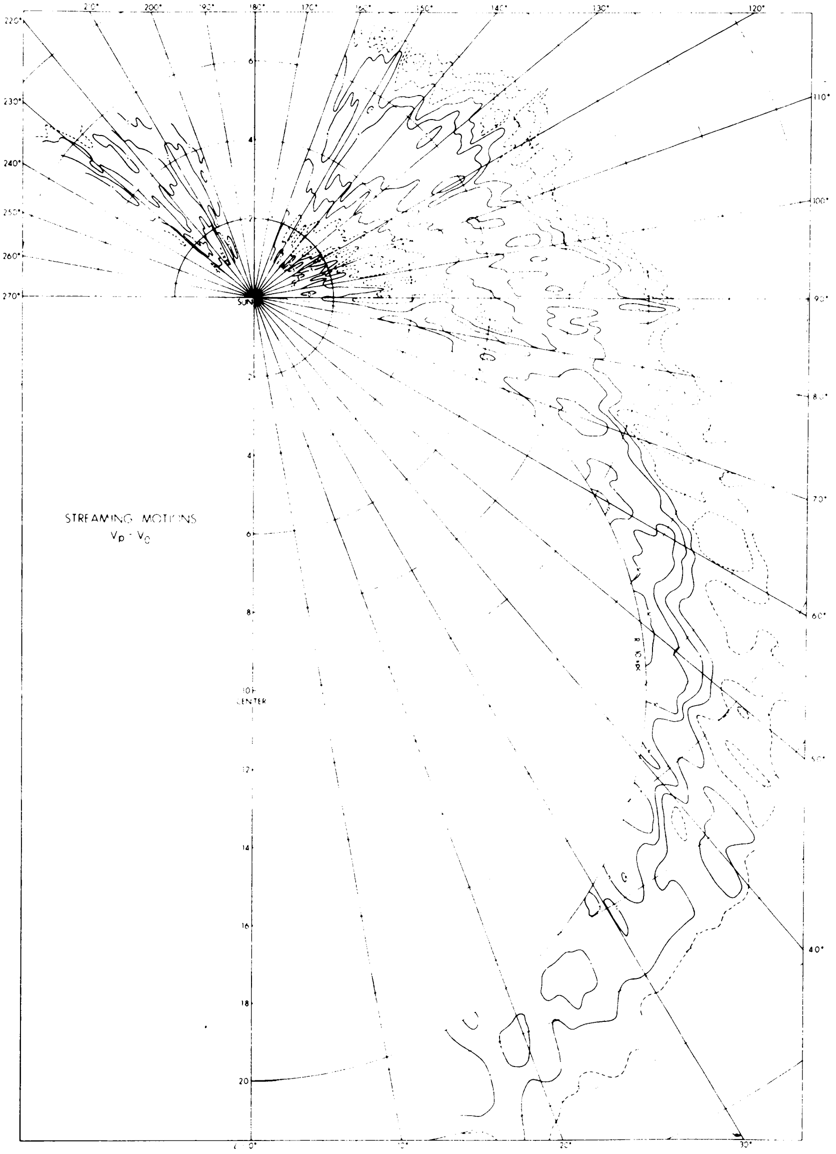

Fig. 4. Line-of-sight streaming motions required, by themselves, to account for the structure of profiles observed in the galactic plane (Burton, 1973). Full-drawn contours indicate that the sense of the peculiar motion is away from the observer; the contour interval is 5 km s$^{-1}$.

turbing the line-of-sight velocity from the basic circular velocity situation, maintaining a completely uniform density distribution (Burton, 1972). The method is illustrated in Figure 2. The resulting line-of-sight streaming motions, which are the differences between the perturbed and basic velocity-fields, are shown in Figure 4 plotted in spatial coordinates. Along a particular line-of-sight the peculiar motions vary approximately sinusoidally. There is also a trend in the contours to be elongated along what one might (perhaps through analogy with other galaxies) allow to be called 'spiral arms'. The amplitude and distribution of the motions are consistent with those predicted by the density-wave theory. This approach also provides a velocity field which can be compared with observations of other spiral tracers.

Model-fitting applied to typical galactic plane regions has shown that streaming motions of about 5 km $s^{-1}$ are necessary to fit the observations, and that reasonable fits to most profile features can be obtained if, in addition to these motions, an effective velocity dispersion of about 4 km $s^{-1}$ and an average volume density of emitting hydrogen atoms of 0.4 $cm^{-3}$ (for gas with a spin temperature of 135 K) also are adopted. A uniform density cannot be ruled out by the gross appearance of the profiles, but it can be ruled out on general grounds, considering that coherent structures in velocity and in density must, for dynamic reasons, accompany one another. However, discussion of the density contrast between the arm and the interarm regions requires a theory relating the velocity and density fields. A density contrast between 3 and 7 to 1 seems reasonable and is also consistent with theoretical predictions.

It is appropriate to mention here the controversy excited by the hydromagnetic theory for spiral structure put forward by Piddington (1973). Piddington's alternative to the gravitational-wave theory involves a hydromagnetic wave caused by a magnetic field exerting its force perpendicular to the plane of the Galaxy. A complete and quantitative description of the theory is not available; however, the most concrete prediction made by the hydromagnetic theory concerns the projected gas surface density of the spiral arms. As opposed to the approximately 5 to 1 arm-interarm density contrast of the density-wave theory, Piddington's theory firmly requires the hydrogen to be distributed uniformly or in a random manner. This requirement does not seem plausible. The continuity from longitude to longitude of profile features over angles corresponding to, in a number of cases, at least 5 kpc proves that some physical parameters are ordered over these lengths. The most unambiguous evidence in this respect comes from the recent Westerbork observations of external galaxies (see proceedings of IAU Symposium No. 58). Observations of the neutral hydrogen in, for example, M51, NGC 4258, and M81 all show hydrogen concentrated to spiral arms. In addition, these observations reveal an overall 'grand design'. (Evidence for an overall 'grand design' in the hydrogen distribution in our own Galaxy is still rather inconclusive.)

A number of spiral structure problems are more easily studied in external galaxies than in our own. Two related areas in which extragalactic hydrogen studies can inspire work in our own Galaxy involve the relative behavior of the various spiral arm constituents and the detection of evidence for the predicted galactic shock.

## V. Distribution of the Hydrogen Relative to Other Constituents of the Galaxy

The problems of the relative ordering and of the general states of motion of the various components of spiral structure are fundamental to an understanding of the forces ordering this structure. In other galaxies, Lynds (1970) in particular has demonstrated the tendency of dust lanes to mark out narrow bands on the inside of luminous spiral arms. Observations of the continuum radio emission from M51 by Mathewson *et al.* (1972) showed that the maximum intensity of the radio emission also follows the dust bands on the inner edge of the bright arms. Hydrogen-line observations of M51 (Shane *et al.*, in preparation) show on the other hand that the neutral gas arms follow the stellar ones. The shock version of the density-wave theory formulated by Roberts (1969) has been successful as a framework in which these phenomena may be discussed. The theory provides for a compression which triggers the gravitational collapse of large concentrations of gas and dust and at the same time leads to synchrotron radiation enhancement caused by the compression of the magnetic fields which are frozen into the gas. The star formation process will take about 60 million years, and during this time the shock front will move to its presently observed position. It is clear that in this sort of situation the various spiral tracers will not all trace out the same physical parameters. It seems promising to pursue these problems also in our own Galaxy.

The neutral hydrogen seems to be primarily a tracer of the locations where the overall distribution of stars is producing a gravitational sink. It is an efficient tracer because of its ubiquity. An observational problem relevant to studies of our Galaxy, as well as of other galaxies, involves locating the spiral structure defined, say, by stars of type A. In general the problem is to have information on the distribution of the *total* mass of a spiral arm, so that we know the strength of the gravity in the gravitational wave. Composite photographs of the sort made by Zwicky (1955) of M51 show an underlying yellow-red spiral structure which is smoother than the knotty arms delineated by the H II regions. It seems plausible that the characteristics of the velocity fields of the hydrogen and other young tracers may show more regularity than shown by the density distributions.

It is expected that stellar populations with velocity dispersions less than about 35 km $s^{-1}$ also will respond to the gravitational wave. Humphreys (1970, 1972) in particular has isolated systematic motions amongst the O and B supergiants in two regions which she interprets in these terms. In Figure 5 the locations of O and B stars are plotted in spatial coordinates. If one were to find structure in the spatial distribution of the stars in this figure, relevant problems include the question of the validity of the working hypothesis that the effects of the interstellar absorption are well enough known so that they do not dominate the analysis, and the question of the completeness of the data (some regions being studied in more detail than others). These problems become less important if the kinematic information is also used. Symbols in the figure are open or filled depending on the sign of the observed velocity deviations from circular rotation as defined by the Schmidt (1965) law. The additional information makes it easier to locate patterns of 'openedness' or 'filledness' amongst the sym-

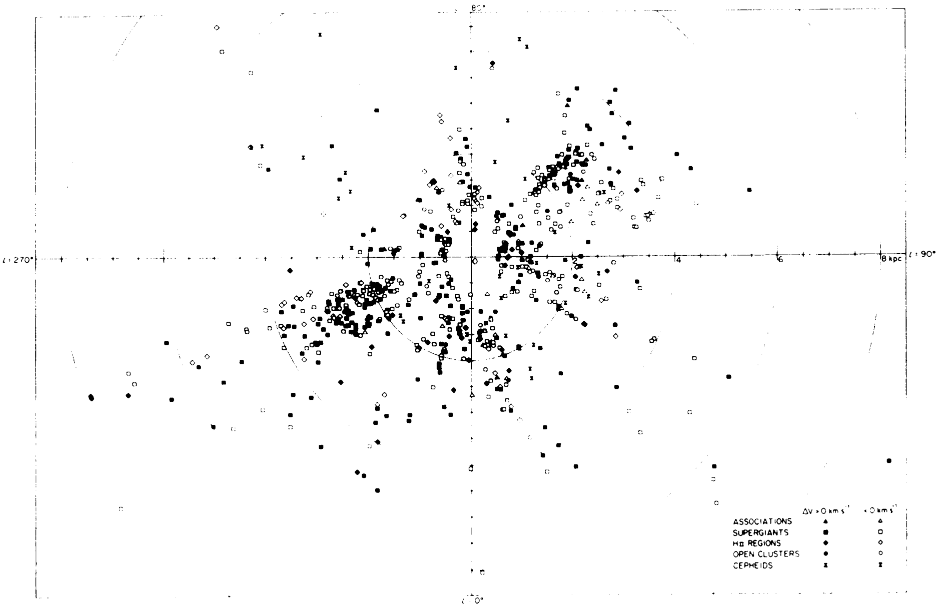

Fig. 5. Spatial distribution of a compilation of young optical spiral tracers. The sense of the line-of-sight peculiar motion of each object is indicated.

bols than it is to follow patterns in the density of symbols. Burton and Bania (1974) have modeled the kinematic patterns using a velocity field of the sort predicted by the linear density-wave formulation of Lin *et al.* (1969). At locations corresponding to the spectroscopic distances of each of the observed O and B stars they calculated a model velocity residual which was the difference between the LSR velocity predicted by the theory and the Schmidt velocity at that location. The various parameters specifying the model were varied in order to maximize the correlation between the observed and model peculiar motions. Figure 6 shows the response of the correlation coefficient to changes in the parameters specifying the locations of two nearby arms. The correlations show definite maxima at values indicating strong statistical significance, suggesting that ordered large-scale streaming motions of the density-wave sort exist in the young stars and that kinematic model fitting is a useful approach to isolating patterns in these motions. The velocity field inherent in the model best-fit in this way is shown in Figure 7. Contours represent streaming motions relative to the LSR. The locations of the potential minima which in the framework of the linear theory would govern these motions are also shown in the figure. Other best-fit parameter values sought by maximizing the correlation coefficients in the same way are the streaming motion amplitudes and the tilt angle. The resulting values are 5 km s$^{-1}$ and 8°. It is interesting that the kinematically derived tilt angle, 8°, is in good agreement with the value derived from hydrogen observations. These same stars' apparent spatial distribution gives the conflicting value of ≈20°. There also seems to be no

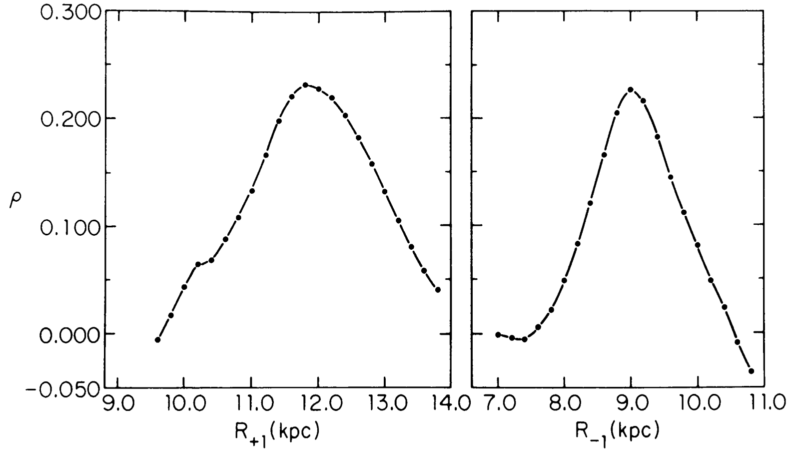

Fig. 6. Response of the coefficient describing the degree of correlation between the observed and the modelled kinematics of the optical tracers to variations in the parameters $R_{+1}$ and $R_{-1}$ specifying the galactocentric distances at which two model spiral arms cross the Sun-center line. The responses peak at statistically significant correlation levels.

evidence in the kinematics for the interarm link a number of authors have identified as the 'Orion spur', or for a major local spiral arm.

The optical velocity residual is a quantity analogous to the velocity residual which was derived for the gas by exploiting the extreme sensitivity of the hydrogen line profiles to perturbations of the velocity field. A comparison of the optical residuals with the gas residuals found at the stars' location is shown in Figure 8. There is a correlation, and although it is weak, application of Student's *t*-test shows that it is certainly significant. This positive correlation between the stellar and gaseous motions supports the general prediction that these motions are ordered by gravitational forces.

Opposed to the relatively smooth underlying structure of the older spiral population is the extremely patchy appearance of the H II regions. In our Galaxy, observations of H II regions and of most of the molecules probably contain less direct information on the overall structure than the neutral hydrogen observations do. These spiral tracers are probably best considered to be tracers of regions of star formation, or, in general, of regions where the gas has been compressed, and in this respect their investigation may prove to be the best way to locate the shock front predicted by the density-wave theory. There is no very direct observational evidence yet for the existence of large-scale spiral shocks in this Galaxy.

There is a very close degree of correlation amongst the velocities and amongst the locations of clouds of OH, $H_2CO$, CO, and H II regions. It has been reported that the carbon monoxide molecule is spread ubiquitously throughout the Galaxy, and that its velocity and spatial coverage is similar to that of the neutral hydrogen. At this time, however, there have still been few observations of CO at directions not coincident with known H II regions; observations made at 'typical' regions by different groups do not appear to agree. Although the results are still very preliminary, ob-

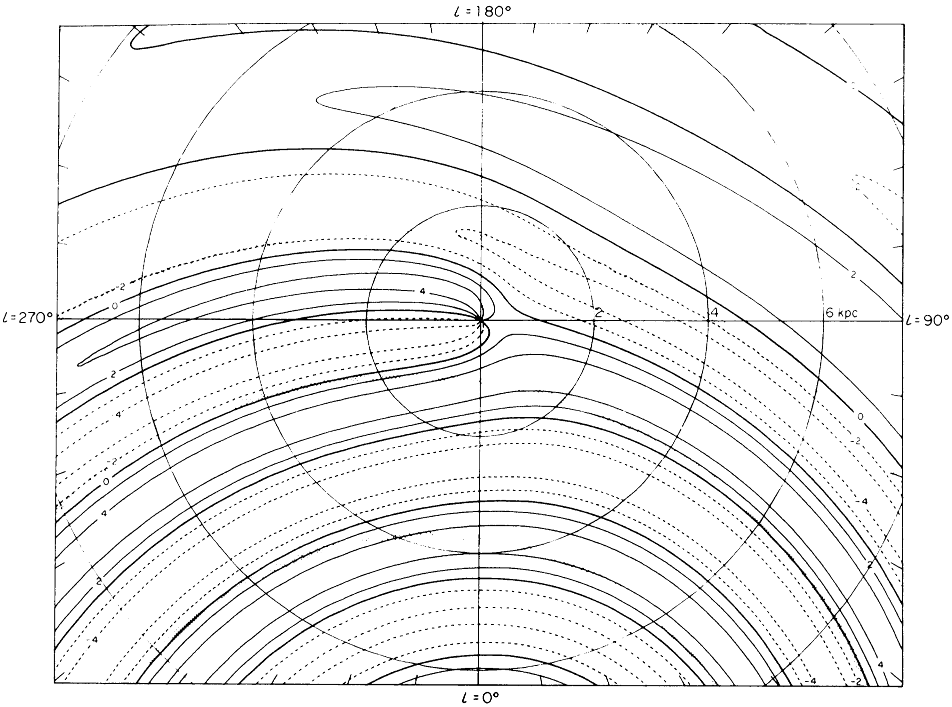

Fig. 7. Line-of-sight streaming-motion patterns derived as a best fit, in the framework of the linear density-wave theory, to the kinematics of the compiled observations of supergiants and associations. The stippled bands show the locations of gravitational potential minima. The most important parameters of the adopted best-fit model are the following: $R_{+1} = 11.4$ kpc, $R_{-1} = 8.9$ kpc, tilt angle = 8°, streaming amplitude = 5 km $s^{-1}$.

servations made at NRAO by Gordon, Lockman, Bania and myself at a limited number of regions, in the galactic plane, chosen to be away from H II regions do not show CO – to a peak-to-peak detection limit of about 0.3 K – at all the velocities covered by the neutral hydrogen. It is our group's suspicion that CO, as the other molecules, is concentrated to compressed regions and so is a tracer of such regions, and thus perhaps of the predicted shock front, but is not a tracer in the same sense as the neutral hydrogen.

The patchiness and the very complicated environment expected in star formation regions make comparison of the distribution of H I and of molecules difficult on a detailed scale. However, some aspects of the relative distribution do emerge if the comparison is carried out on a large scale. Figure 9 shows observations of neutral hydrogen taken at longitude 25° displayed as contours of antenna temperature in latitude-velocity coordinates. The lower panels show, for comparison also in latitude-velocity coordinates, some results from B. E. Turner's (private communication) extensive survey of OH emission and absorption made on the NRAO 140-ft telescope. To allow a qualitative comparison of the patchy OH distribution with the smoother hydrogen distribution, the hydroxyl data were added over a 15° range of longitude.

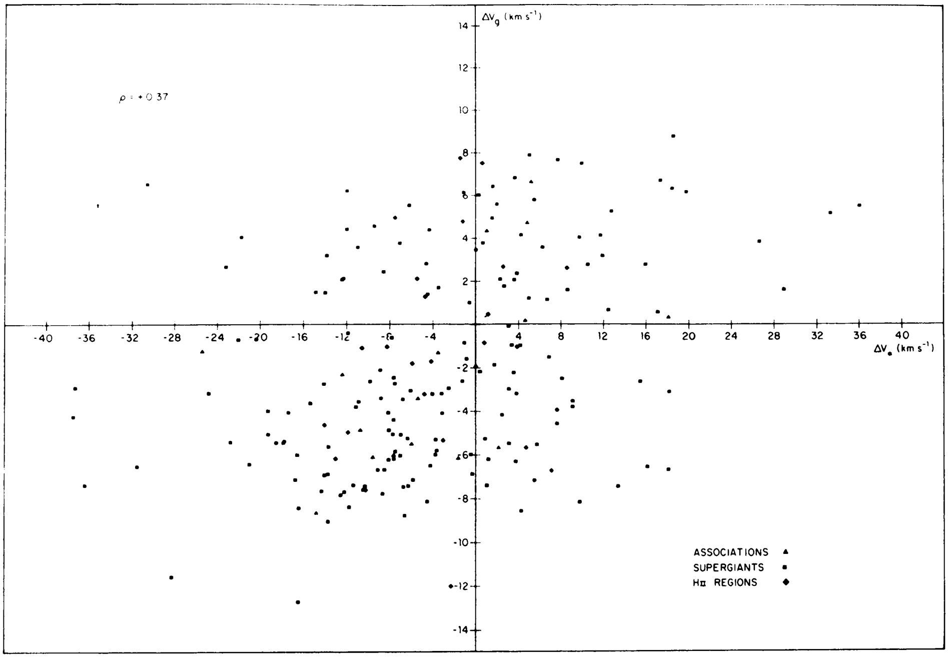

Fig. 8. Comparison of line-of-sight motions of the optical objects in Figure 5 with the motions of the gas found, at locations corresponding to the optical objects, from the data in Figure 4. Figures 5–8 are from Burton and Bania (1974).

Comparison of the hydrogen and hydroxyl situations in terms of velocity coverage indicates that there is agreement in coverage at the positive velocities, which at these longitudes correspond to the portion of the Galaxy interior to the solar orbit. On the other hand, little hydroxyl is observed at the negative velocities where the hydrogen emission is still strong. This comparison indicates the already familiar conclusion that regions associated with star formulation do not extend to such large galactic radii as does the neutral hydrogen.

Figure 9 also allows a comparison of the scale height of the neutral hydrogen with that of the OH. It is well known that interior to the solar orbit the hydrogen gas is confined to a thin and quite flat layer. The average full thickness of the layer to half-density points is about 220 pc between $R=4$ and 9 kpc. Over much of this region the deviation of the centroid of hydrogen emission from the galactic equator is less than 30 pc (Gum *et al.*, 1960). A scale height of 220 pc corresponds at $l=30°$ to an angle of 1°.5. The scale height of the OH indicated in the figure is substantially less than that. Although Turner's observations extend beyond $|b|=1°$, very little OH emission or absorption is found more than 1° from the galactic plane. The OH radiation has essentially fallen to zero at the half-intensity level of the hydrogen. An estimate of the scale height characterizing the OH in this region is 100 pc, less than half of the hydrogen thickness. Molecular data are only now becoming complete enough to allow this sort of comparison, but it seems that this sort of investigation is desirable

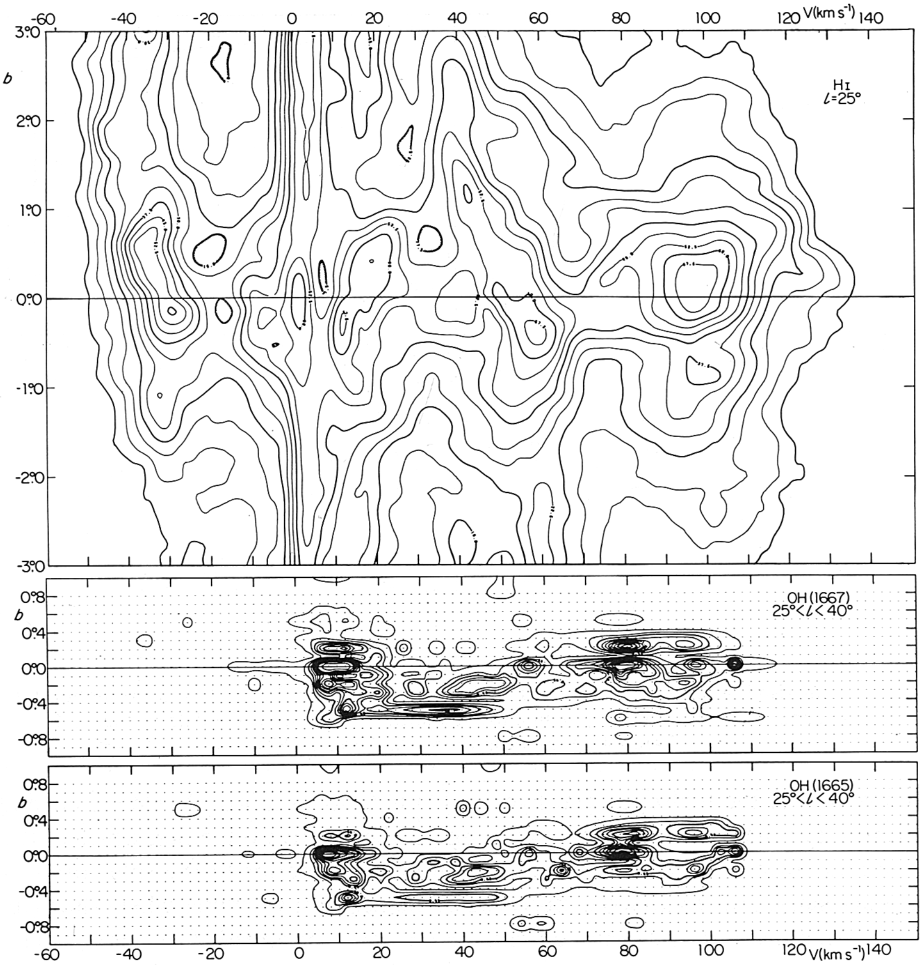

Fig. 9. Comparison, on the same scale, of H I and OH latitude-velocity contour maps showing that the $z$-height of the neutral hydrogen's distribution is about twice that of the hydroxyl radical's distribution. The H I observations in this figure and in Figures 10 and 11 are from Burton and Verschuur (1973). The OH data are from the survey of B. E. Turner; the amplitude of emission and absorption lines observed at $25° < l < 40°$ are indicated.

in view of the increasing evidence that as galactic tracers the molecules are tracers of regions of compression whereas the hydrogen is most efficient as a tracer of the galactic gravitational potential. If a galactic shock is responsible for the compression, then the scale height of the molecules indicates the $z$-height to which this shock occurs. This height will depend strongly on the hydrogen density because of the strong dependence of the Alfvén speed on density (see Wentzel, 1972). There will be no more shock, thus no more compression and presumably no star formation, at heights above the critical hydrogen density at which the Alfvén speed equals the shock speed.

In general, investigations of $z$-dependences in the hydrogen seem promising; however, both observations and theoretical predictions presently lag behind the state of affairs obtaining in the galactic plane. Figure 10 shows hydrogen observations made in a cut through the galactic plane at constant longitude $l = 75°$. Evident here are a number of well-known phenomena. These include the deviation of the mean hydrogen layer from $b = 0°$ in the outer regions of the Galaxy (at this longitude negative velocities are attributed to galactocentric distances greater than 10 kpc). Distances are of

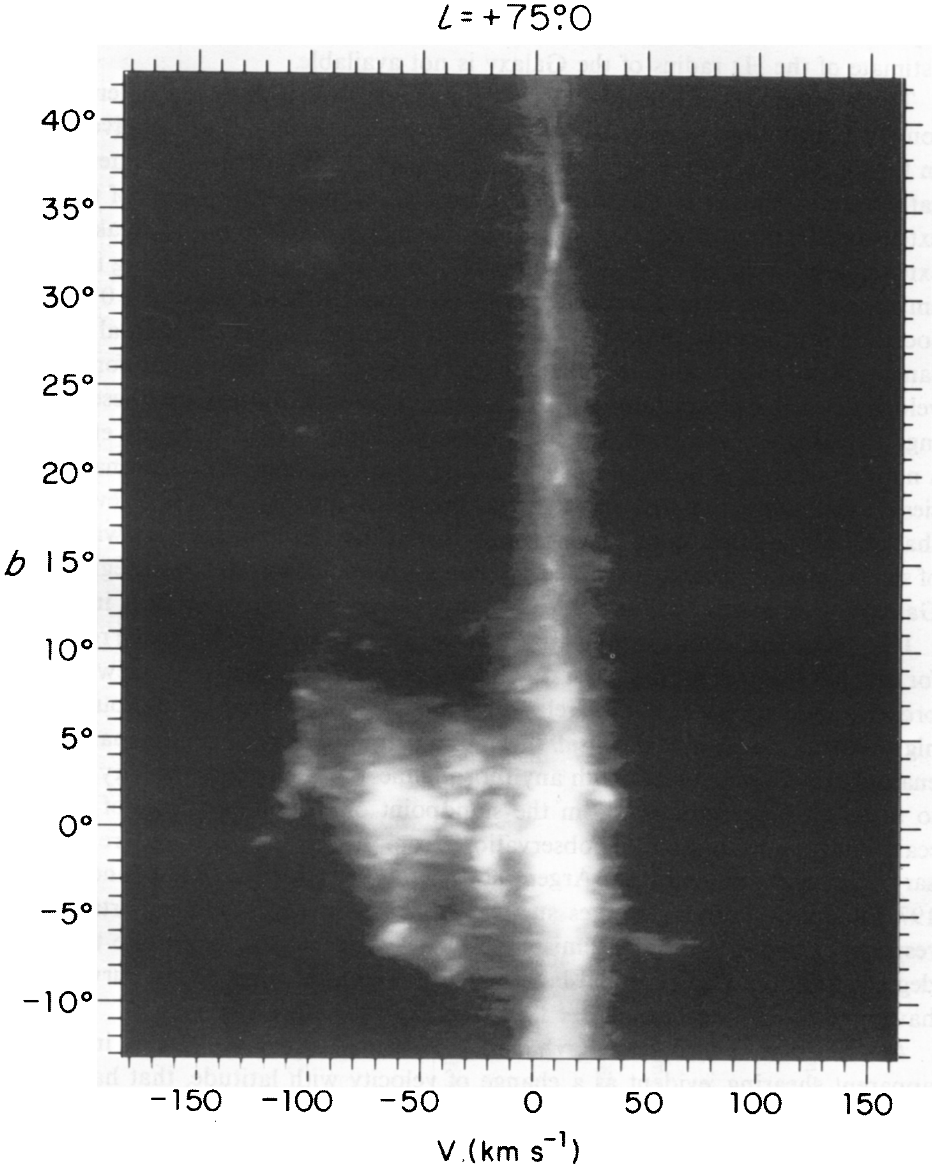

Fig. 10. Grey-scale representation of H I intensities in a latitude-velocity scan through the galactic plane at $l = 75°$. These observations illustrate the hat-brim effect, the high-$z$ extensions and the apparent shearing motions of hydrogen at large distances from the galactic center.

course harder to measure in the outer regions than in the inner ones: in the inner regions one is worried about deviations of a few per cent from a reasonably well-determined basic state of rotation, whereas in the outer regions this basic state itself remains an extrapolation based on a dynamic model. We do know that the hydrogen layer extends beyond the tracers found in the compression zone tentatively associated with the region interior to the density-wave's co-rotation distance. The hydrogen layer also extends to larger distances than the youngest stars, although a reliable estimate of the H I radius of the Galaxy is not available.

The well-known 'hat-brim' effect, in which the hydrogen in the outer region is found to bend up to positive latitudes in the first quadrant, but to negative latitudes in the fourth quadrant, is also apparent in Figure 10. The lower-level intensities are rather underexposed in this figure, although an example is apparent of the high-$z$ extensions (Habing, 1966; Kepner, 1970; Verschuur, 1973) found as weak emission extending from the plane to $z$-distances of 3 or 4 kpc. What is intriguing is that this emission is rather clearly associated with prominent structures near $b=0°$. This association is evident in velocity and in terms of continuity over substantial longitude ranges. Similar continuity in longitude and in velocity has been found for the high-velocity clouds by Verschuur (1973), Davies (1972), and Mathewson (these proceedings). The high-$z$ extensions, the high-velocity clouds, and the hat-brim effect share a number of systematic regularities, although of course these observational similarities do not require that only one dynamic process is at work. There is no evidence yet that any of the other spiral tracers, in particular the tracers associated with regions of star formation, partake in these non-planar phenomena in the outer regions of the Galaxy. More generally, it is not known to what extent the total mass is involved.

It has been suspected for some time that the Magellanic Clouds may be responsible for the hat-brim effect (e.g., Burke, 1957; Kerr, 1957); recently Mathewson (these proceedings) suggested that the relationship of the Large Magellanic Cloud with the high-velocity clouds also is causal. It is a pity that most of these non-planar phenomena have only been studied with any thoroughness in the parts of the sky accessible to northern observatories. From the standpoint of current problems of the large-scale galactic structures, more observations from the southern hemisphere are necessary. The new surveys by the Argentine group (Garzoli, 1972; Bajaja and Colomb, 1973) and especially the Parkes survey of Kerr *et al.* (1974) are important in this respect. Extensive southern hemisphere observations at latitudes more than a few degrees from the plane are still lacking. Table I lists the most recent surveys which have been made for studies of the large-scale galactic structure.

Another area of current research can be illustrated by Figure 10. This involves the apparent shearing, evident as a change of velocity with latitude, that has been attributed to most of the major spiral arm features (e.g., Fujimoto and Tanahashi, 1971a, 1971b; Harten, 1971). A very severe observational problem which plagues much work on the hydrogen distribution at low latitudes is the problem of blending whereby two or more features occur at approximately the same velocity in the profiles. Throughout the Galaxy structural features are expected to cross, blend and

TABLE I

Recent surveys of hydrogen emission from near the galactic equator

| Authors | Publication date | Beam | Bandwidth (kHz) | Approximate region | Approximate interval | Form of publication |
|---|---|---|---|---|---|---|
| N. H. Dieter | 1972 | 36′ | 10 | $l=10°$ to $250°$<br>$b=-15°$ to $15°$ | $\Delta l=2°$<br>$\Delta b=2°$ | $(b, V)\|_l$ maps |
| S. L. Garzoli | 1972 | 28′ | 10 | $l=270°$ to $310°$<br>$b=-7°$ to $2°$ | $\Delta l=1°$<br>$\Delta b=2°$ | $(l, V)\|_b$, $(b, V)\|_l$, and $(l, b)\|_V$ maps |
| E. Bajaja and F. R. Colomb | 1973 | 28′ | 10 | $l=220°$ to $294°$<br>$b=-29°$ to $-11°$ | $\Delta l=2°$<br>$\Delta b=2°$ | $(l, V)\|_b$, $(b, V)\|_l$, and $(l, b)\|_V$ maps |
| W. B. Burton and G. L. Verschuur | 1973 | 30′ | 10 | $l=20°$ to $230°$<br>$b=-20°$ to $20°$ | scanned<br>$\Delta b=2°$ | $(l, V)\|_b$ maps |
|  |  | 10′ | 10 | $l=15°$ to $140°$<br>$b=-30°$ to $30°$ | $\Delta l=5°$<br>scanned | $(b, V)\|_l$ maps |
| R. D. Davies and R. J. Cohen | 1973 | 32′ | 33 | $l=355°$ to $10°$<br>$b=-5°$ to $5°$ | $\Delta l=1\overset{\circ}{.}0$<br>$\Delta b=0\overset{\circ}{.}25$ | $(b, V)\|_l$ maps |
| P. O. Lindblad | 1974 | $12\overset{\prime}{.}5$ | 10 | $l=12°$ to $72°$<br>$b=1°$ to $10°$ | $\Delta l=3°$<br>scanned | $(b, V)\|_l$ maps |
|  |  | 26′ | 5 | $l=339°$ to $12°$<br>$b=-15°$ to $15°$ | $\Delta l=3°$<br>scanned | $(b, V)\|_l$ maps |
| S. C. Simonson and R. Sancisi | 1973 | 36′ | 16 | $l=354°$ to $24°$<br>$b=-5°$ to $5°$ | $\Delta l=0\overset{\circ}{.}5$<br>$\Delta b=0\overset{\circ}{.}5$ | profiles, $(l, V)\|_b$ and $(b, V)\|_l$ maps |
| M. A. Tuve and S. Lundsager | 1973 | 51′ | 10 | $l=336°$ to $270°$<br>$b=-16°$ to $16°$ | $\Delta l=4°$<br>$\Delta b=2°$ | profiles |
| H. Weaver and D. R. W. Williams | 1973 | 36′ | 10 | $l=10°$ to $250°$<br>$b=-10°$ to $10°$ | $\Delta l=0\overset{\circ}{.}5$<br>$\Delta b=0\overset{\circ}{.}25$ | profiles |
| G. Westerhout | 1973 | $12\overset{\prime}{.}5$ | 10 | $l=13°$ to $235°$<br>$b=-2°$ to $2°$ | scanned<br>$\Delta b=0\overset{\circ}{.}2$ | $(l, V)\|_b$ maps |
| F. J. Kerr, R. H. Harten, and D. L. Ball | 1974 | 15′ | 10 | $l=236°$ to $345°$<br>$b=-2°$ to $2°$ | $\Delta l=1°$<br>scanned | $(b, V)\|_l$ maps |

generally be rather tangled in the observed velocity space (see Knapp, 1972). It is extremely difficult to detect physically realistic velocity gradients unless the various features can be unambiguously separated. In some cases, observations are necessary with a larger velocity resolution than now available. All of the major large-scale surveys of low-latitude hydrogen have been carried out with a velocity resolution of about 2 km $s^{-1}$. It is in practice difficult to separate features closer together than about three bandwidths. The complexity is present even in the highest angular-resolution observations. Figure 11 shows observations made on the 300-ft telescope at $b = +2.^{\circ}0$ in the first quadrant of longitude. This figure also illustrates that separation of features is undoubtedly easier in the outer regions of the Galaxy where the basic velocity-distance relationship is single-valued, although the large-scale noncircular motions and the bending of the mean layer can contribute themselves to apparent velocity shearing motions (see Yuan, these proceedings). In the inner parts of the Galaxy separating features is especially difficult. In velocity-longitude maps of observations made near the galactic plane in the first quadrant there is an obvious tendency for intensities at positive velocities to be higher than at negative velocities. This is because of the double-valuedness of the velocity-distance relationship at positive velocities and offers a simple proof that the hydrogen gas seen in emission is optically thin, on the largest scale, at the longitudes where the drop-off of intensities occurs near zero velocity. Because of the doubled-valuedness at positive velocities there will on the average be twice as much hydrogen contributing there, if the gas is thin, than at negative velocities. A similar cut-off is also observed at the corresponding longitudes in the southern data.

Besides the current areas of large-scale 21 cm research already mentioned, a few additional problems are listed here:

- length scales of typical coherent patches of gas found near the galactic plane, as a function of galactocentric distance $R$;
- variation of the apparent velocity dispersion as a function of $R$, and, to the extent possible, of $z$;
- observational consequences of self-absorption features to the overall interpretation of the emission profiles;
- observational consequences of the two-component model of the neutral gas;
- isolation of saturation effects as a means of identifying spiral arms and for the investigation of the characteristic temperature and scale-height of the gas.

For these problems very accurate distances are not crucial; what is crucial is a careful identification in the profiles of the relevant effects.

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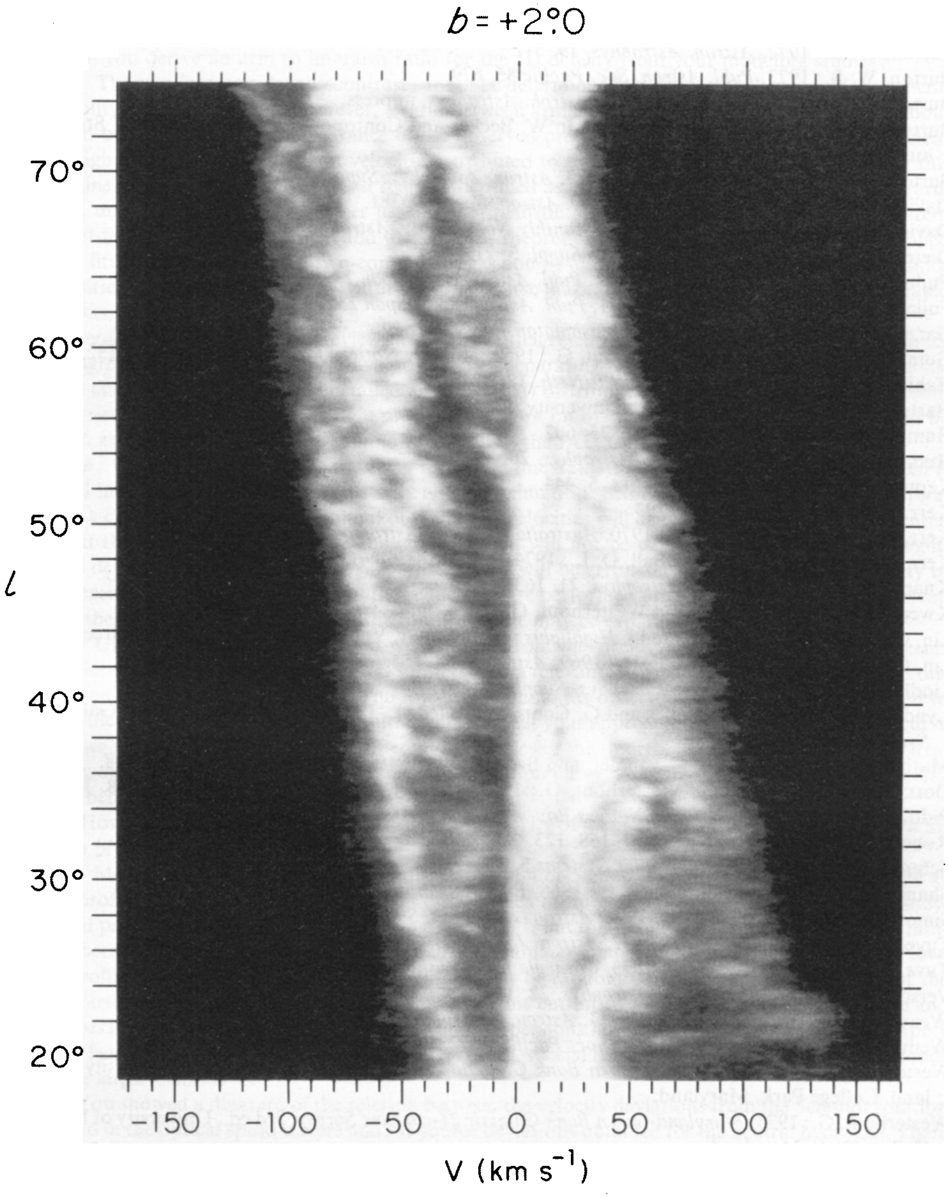

Fig. 11. Grey-scale representation of H I intensities in a longitude-velocity scan parallel to the galactic plane at $b = +2\overset{\circ}{.}0$. The intensity drop-off near zero velocity, suggesting that the emitting gas is optically thin, is especially evident.

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# DISCUSSION

*Price:* Can you derive an arm to interarm ratio for the H I density from your modeling studies?

*Burton:* The arm/interarm density contrast cannot be determined in a direct way, because of the general inaccessibility of density values. However, a ratio between arm and interarm densities greater than about 20 to 1 can be ruled out by the appearance of the observed profiles, considering especially the persistent ridge of high intensities near $b = 0°$ at velocities attributed to the locus of subcentral points. Along this locus the line of sight scans across several regions identified as arm ones and also across several interarm regions. A uniform density, on the other hand, is not realistic. A density contrast of 5 to 1 is consistent with model-fitting to the observations and with various theoretical predictions. So far no one has applied the model fitting approach using a two-component gas composition. The results might be different since equal densities of gas at different temperatures will of course make unequal contributions to the simulated observations.

*Van Woerden:* Burton's beautiful review clearly shows that research into galactic structure and dynamics makes progress, notwithstanding the grave problems of separating the velocity and density distributions. Important clues may come from the detailed analysis of H I distributions and motions now possible with synthesis telescopes. As examples, I might mention the work on M81 and M101 reported by Oort and by Allen *et al.* at Canberra (*IAU Symp.* **58**) and by myself at the IAU General Assembly.

*Pishmish:* It is well known that in reducing the 21 cm line data, it is assumed that neutral hydrogen is distributed in rings. But obviously this is only an approximation. If the H I concentration forms a spiral instead of a circle the maxima (or minima) of the radial velocities will again correspond to the tangential points. But the radius vector drawn to the tangent point will not be perpendicular to the line of sight. Hence the determination of the distance from the center will be erroneous if one ignores the spirality of the H I concentration. It is possible that if the reductions are performed properly assuming a spiral instead of a circle the north-south asymmetry of the rotation curve may be explained. Has anyone tried this?

*Burton:* Unless essentially all hydrogen were absent from the circles' tangential points, which seems unlikely, the argument of Shane and Bieger-Smith (1966) is relevant. If you adopted the tangent-to-spirals situation you would have to explain why no low-level emission is observed at the profile cut-offs used to determine the rotation curve. In addition, although I see that your approach would result in rotation-curve irregularities which would be located at different longitudes in the 'North' than in the 'South', these irregularities would be perturbations to the same basic rotation curve. Actually there seems to be a secular difference between the two observed curves.

*Price:* How do you derive your value of dispersion velocity of 4 km $s^{-1}$ in our Galaxy, and isn't it a bit lower than previously used?

*Burton:* Model profiles calculated using a dispersion of 4 or 5 km $s^{-1}$ show the same general shape as observed profiles. Results of Gaussian analysis of hydrogen profiles observed near the galactic plan show that typical profile features are broadened by 6 or 7 km $s^{-1}$, but this should be regarded as an upper limit primarily because of the inevitable blending which contaminates almost all features. The only part of low latitude profiles which probably give a direct indication of random cloud velocities is the wing of the profile contributed by gas near the subcentral points. This cut-off of the profiles is a kinematic one and yields dispersions in the range 4 to 6 km $s^{-1}$. I think dispersions larger than 6 or 7 km $s^{-1}$ do not apply for typical features near the plane in our Galaxy. Of course, special features such as the high-velocity clouds have much larger dispersions.

*Oort:* You showed a diagram of the relation between the velocity deviations from the Schmidt rotation curve found in the optical spiral tracers and the source deviations obtained for the neutral hydrogen. There was some correlation between the two but not any strong one. Can you explain why the correlation is not more pronounced?

*Burton:* There are several sources of uncertainty, both in the observations and in the analysis, which would probably weaken what might be stronger correlations. A particular source of error which may enter the analysis is the possible lack of consistency between the stellar (spectroscopic) distances and the gas (kinematic) distances. On the other hand, the correlation may in part be weak due to the different dispersions of the gas and stars, different effects of magnetic fields, etc. There certainly remains a lot of work to be done in attempting comparisons among the various spiral tracers.

*Yuan:* I would like to comment on the motion of young stellar objects in your discussion. One should be aware of the presence of the strong selection effect, since most of young objects are situated in the galactic shock and their motions are best described by the non-linear theory. I believe that the unsatisfactory correction between gas and stars Oort pointed out will be resolved if the non-linear theory is used.

*Burton:* The correlation between the motions of the young stars and of the gas has been looked into, in more detail than I was able to present here, by Bania (1973, M.A. Thesis, University of Virginia) and in a paper by myself and Bania (in press). The correlation improves if it is taken into account that the stars, whose formation was triggered in a shock, will be kinematically decoupled from the interstellar medium because the viscous drag on such small objects as protostars is small compared to that acting on the gas.

*Price:* Can information on H I velocity dispersion in external galaxies be derived from synthesis observations yet?

*Van Woerden:* The Westerbork line receiver does not at present allow reliable determination of velocity dispersions; the filter half width is 27 km $s^{-1}$, equivalent to a dispersion of 12 km $s^{-1}$. In 1975 we shall have a new receiver with various options of bandwidth, and I expect the problem of velocity dispersions for H I in external galaxies will then be investigated.