HIGH-DENSITY, COOL REGIONS OF INTERSTELLAR MATTER IN THE GALAXY

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The distribution of interstellar nucleons is dominated by gas at temperatures ranging from a few K to a few hundred K. At the warmer end of this temperature range, the gas is predominantly in the form of ubiquitously distributed atomic hydrogen. The colder gas is almost entirely molecular; it resides in compressed clumps, confined principally to the inner-galaxy, and is most effectively traced by observations of carbon monoxide. In this paper, we focus on some of the problems which currently hinder derivation of the morphology and total number of nucleons in the galaxy. For the atomic gas, these problems involve optical depth effects in HI profiles, the amount of cold HI residing in molecular clouds, and the form of the outer-galaxy rotation curve. For the molecular gas, the problems involve the uncertainties in the conversion from CO intensities to H_2 densities, including the possibility of composition gradients across the galaxy, the total number and typical size of molecular clouds, and the possibility that the molecular material in the region of the galactic nucleus is distributed differently from the material in the galaxy at large.

MORPHOLOGY OF COLD ATOMIC HYDROGEN

Atomic hydrogen coexists with molecules in dense clumps at temperatures of order 10 K and is diffused through much of the intercloud region at temperatures of about 6000 K. Between these temperature extremes there is a variety of structures whose physical characteristics are determined by the mechanical and radiation influences of their surroundings with which they exist in approximate pressure equilibrium (Heiles, 1980). The condition of pressure equilibrium allows study of the HI gas to proceed in terms of temperature hierarchies (see Baker's 1979 review), which are revealed in general more directly by the observations than are density hierarchies. The hottest gas is so diffuse that it contributes little to the overall density budget. The principal problems involved with estimates of this contribution are the very large thermal broadening which leads to blending in the spectral lines, the low intensities resulting from the low column densities, and the effects

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of stray radiation entering the antenna from other, more intense emission fields. Most HI nucleons reside in cooler material. The problems of blending and stray radiation persist to hinder the analysis; although the intensities are easily measurable, column densities are not because optical depth effects cannot be ignored.

The problem of line blending occurs generally for the entire range of structures in 21-cm profiles, except for a few isolated features found mostly at high latitudes so that descriptions of the galactic HI morphology refer to collective properties. The problem of stray radiation is one which has been generally neglected, but which is of importance for the HI case because of the properties of available antennas (see Kalberla, 1978) and because HI is distributed so widely. Relevant in the present context is Baker's (1976) emphasis of the importance of this problem to the determination of the outer boundary of galactic gas. The blending represents the combined influence of thermal broadening, turbulent and other small-size mass-motion broadening, and the accumulation of probably unrelated material from long lengths of path at overlapping velocities. The turbulent motions are evidently sufficient to prevent gravitational collapse of most HI structures. This line of sight blending is rendered especially important in a practial sense by the widespread distribution of atomic hydrogen. At low latitudes, no empty line of sight, and no region contributing negligible emission, has been found. At low latitudes emission features cannot be isolated for separate study. As a consequence most descriptions of the hierarchy of emission regions pertain to the local neighborhood. Even in the limited local volume, the evidence shows that this hierarchy is comprised of features which differ widely in their temperatures and intensities. The persistence of these differences in the presence of turbulence and systematic motions indicates that many HI features are transient.

Although few HI features at distances corresponding to galactic scales can be studied individually, as a group they are organized in a coherent layer whose scale height, kinematics, and gross optical depth properties can be studied rather directly. Regarding these and other properties of the galaxy, it is convenient to divide the layer into three zones. In the zone at galactic radii $4 \leq R \leq 10$ kpc, the layer parameters and the gross kinematics within it are known. HI cooler than a few hundred K is confined to a layer with a scale height ~120 pc and a representative velocity dispersion ~5Km s^{-1}. The warmer, intercloud HI has a higher characteristic velocity dispersion (~8 km s^{-1}) and a correspondingly higher scale height. Deviations of the mean cool-HI layer from the galactic equator occur systematically with an amplitude ~50 pc, thus less than the thickness of the layer itself. The galactic kinematics in this layer follow directly from the HI data. There are perturbations to the basic galactic rotation which are probably related to spiral-arm structure, but for which the detailed production mechanisms are open to question. These perturbations amount to only a few percent of the amplitude of the basic rotation itself.

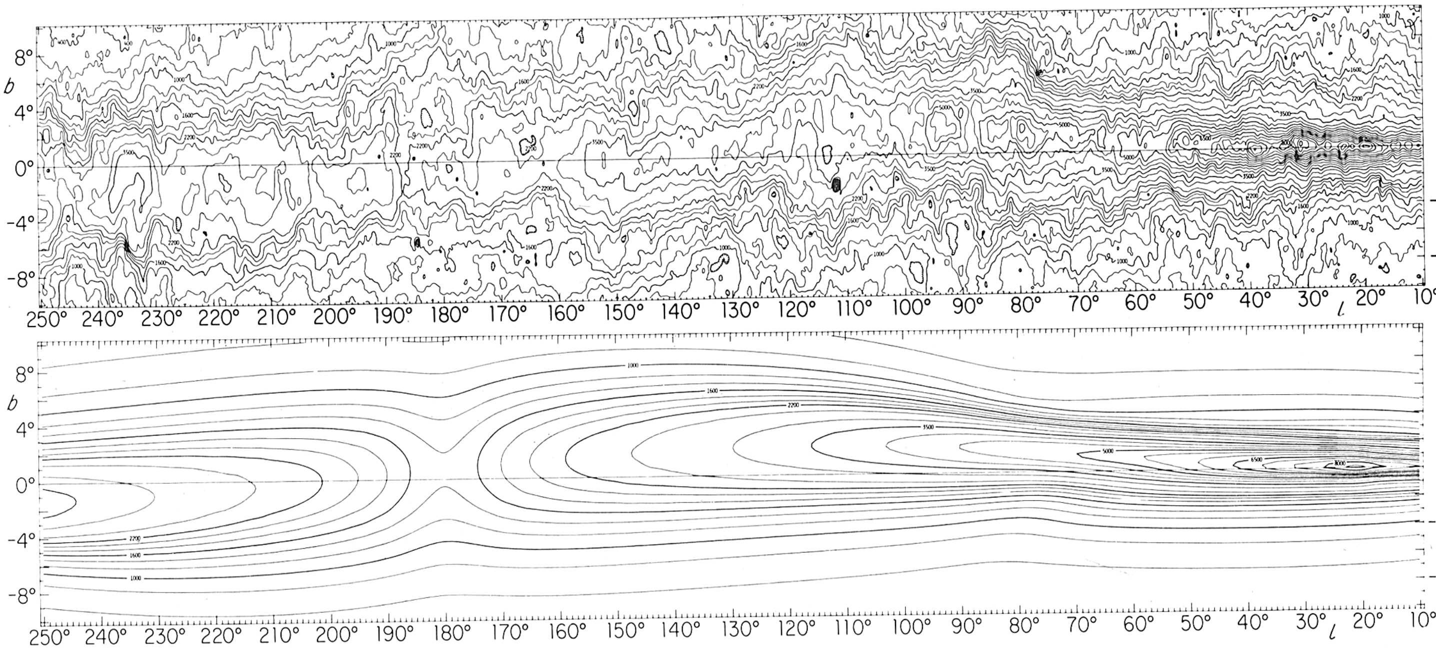

Figure 1. Arrangement on the plane of the sky of the total-velocity integrated HI emission. The upper panel contains the integrals $\int T(v)dv$ calculated from the observations of Weaver and Williams (1973). This integral gives the HI column density only if the gas is optically thin at all velocities. Although at high latitudes $\tau(v)<1$ is a reliable general approximation, at latitudes near the galactic equator, optical thinness pertains only for certain velocity segments of most profiles. The lower panel shows the total-velocity integrals calculated from synthetic data; it incorporates a description of the observed warp and flare of the outer-galaxy HI and accounts for the modulating effects of the kinematic parameter $\Delta v/\Delta r$ on the apparent column densities. Saturation is important at high $|v|$ in the first and second longitude quadrants and near $\ell \to 0^o$ and $\ell \to 180^o$. Although models based on a single component or on a "raisin pudding" gas distribution are too naive to have much relevance to the details of the distribution, they can serve in a pragmatically valid way to test morphological aspects of the gas distribution and radiative transfer through it.

In the outer-galactic zone, at R > 10 kpc, and in the innermost zone at R < 4 kpc, the layer has been less well described principally because the galactic kinematics are poorly known. At R < 4 kpc, the assumption of circular motion fails so that the rotation curve does not follow with much confidence. In the outer galaxy, there is no direct measure of distance corresponding to the geometrically produced maximum-velocity locus in the inner galaxy, so that indirect measures of the rotation curve must be used. Recent evidence of several sorts (e.g. Knapp, Tremaine, and Gunn, 1978; Blitz, 1979; Jackson, FitzGerald, and Moffett, 1979) shows that the rotation curve in our galaxy at R > 10 kpc is remarkably flat. This corresponds to the situation being observed in many spiral galaxies, and implies that the total mass distribution in the galaxy extends well beyond the horizon of presently detected constituents. The warp of the outer-galaxy gas layer away from the galactic equator and the flare of this layer to large thickness is well known, but not understood. Linear scales associated with early descriptions of the phenomenon (e.g. Baker and Burton, 1975) should be revised upward in view of the flat rotation-curve conclusions (see also Heiles, 1980).

MACROSCOPIC OPTICAL DEPTH OF THE HI LAYER

Determination of the total number of HI nucleons in the galaxy requires that the macroscopic optical depth characteristics of the gas be known. The HI column density $N_{HI} = 1.823 \times 10^{18} \int T_k\ \tau(v)dv\ cm^{-2}$ is only measurable if the gas along the particular line of sight is transparent at all velocities. If that is the case, the observed brightness temperature profile $T_B(v) = T_k\{1-\exp(-\tau(v))\}$ is $\sim T_k\tau(v)$. The volume density smoothed over a path of length Δr then follows directly from $\int T_B(v)dv/\Delta r$. In the limiting case of complete saturation, $T_B(v)\sim T_k$ and $\int T_B(v)dv/\Delta r = T_k|\Delta v/\Delta r|$, where Δv is the velocity extent of the portion of the profile considered. Thus the arrangement of the geometrical parameter $|\Delta v/\Delta r|$ is relevant for both the high and the low optical depth cases; a high optical depth situation will be revealed by length-corrected integrated profiles which vary in direct proportionality with this geometrical parameter.

The true HI macroscopic optical depth situation is confused: there are valid arguments for high overall optical depths as well as for low ones. The integrated intensities observed in the direction of the galactic anticenter are approximately the same as those observed from the much longer path through the galactic center. This fact was used by van de Hulst, Muller, and Oort (1954) to argue for high optical depths and a single harmonic mean temperature in these directions. Low optical depths, on the other hand, are indicated for general directions through the inner galaxy by the temperatures typically observed to be approximately twice as high at positive velocities (in the first longitude quadrant) as at negative velocities and by the ridge of emission at high velocities which is enhanced in accordance with the influence of the $|\Delta v/\Delta r|$ parameter (Burton, 1972). This discrepancy originates in the

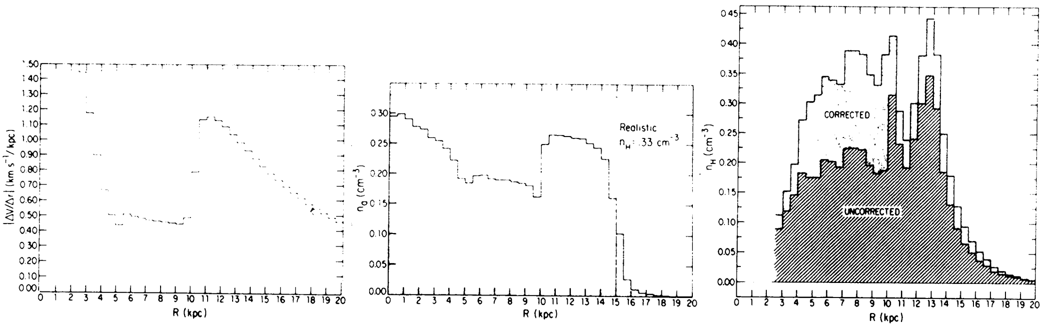

Figure 2. Influence of optical-depth effects on the space-averaged volume densities of HI gas near the galactic equator. The left panel shows the variation of the kinematic parameter $|\Delta v/\Delta r|$ resulting from galactic rotation observed from our vantage point within the disk. In the case of complete saturation, an abundance derived directly from the profile integrals would mimic this variation, because in that case $\int T_B(b)\,dv/\Delta r = T_k|\Delta v/\Delta r|$. Many basic properties of HI in the galaxy can be approximated with a one-component gas of constant volume density $n_{HI}=0.33\ cm^{-3}$; the middle panel demonstrates that the apparent morphology derived from such a model shows the influence of $|\Delta v/\Delta r|$, and suggests the optical-depth correction appropriate to the observed situation represented in the panel on the right.

double-valued velocity-distance relationship, which could only be of importance in this regard if the gas on the near side of the sub-central locus were sufficiently thin to allow the gas on the far side to contribute to the profiles.

Figure 2 and its caption describe the influence of the kinematic parameter. Many of the overall characteristics of HI observations in the galactic plane are simulated by model spectra corresponding to a ubiquitously distributed, one-component gas of T_k = 135 K and n_{HI} = 0.33 cm^{-3}. If the integrated model spectra are assumed to give column densities directly, as if the gas were thin, then the derived apparent volume density differs from the input constant density in the manner shown in the figure, mimicking the variations in the parameter $|\Delta v/\Delta r|$. The apparent density derived in the same straightforward way from observed integrated spectra also reflects this variation (except at $R < 4$ kpc where the decrease in HI gas density at $b=0^\circ$ is probably real). The controlled conditions inherent in the modelling procedure can be used to derive corrections that should be applied to the observed profile integrals to give reliable volume and column densities. The correction for partial saturation is greater at $R < R_o$ because of the double-valued nature there of the velocity-distance relationship. At $R > R_o$, the form of $|\Delta v/\Delta r|$ and thus the details of the correction for partial saturation depend on the outer galaxy rotation curve, about which there is currently much discussion. It seems indicated, however, that the density of the atomic hydrogen gas remains roughly constant over the major part of the galactic disk from $R \sim 4$ kpc to at least $R \sim 15$ kpc. The numerical value of this density is about 0.4 cm^{-3},

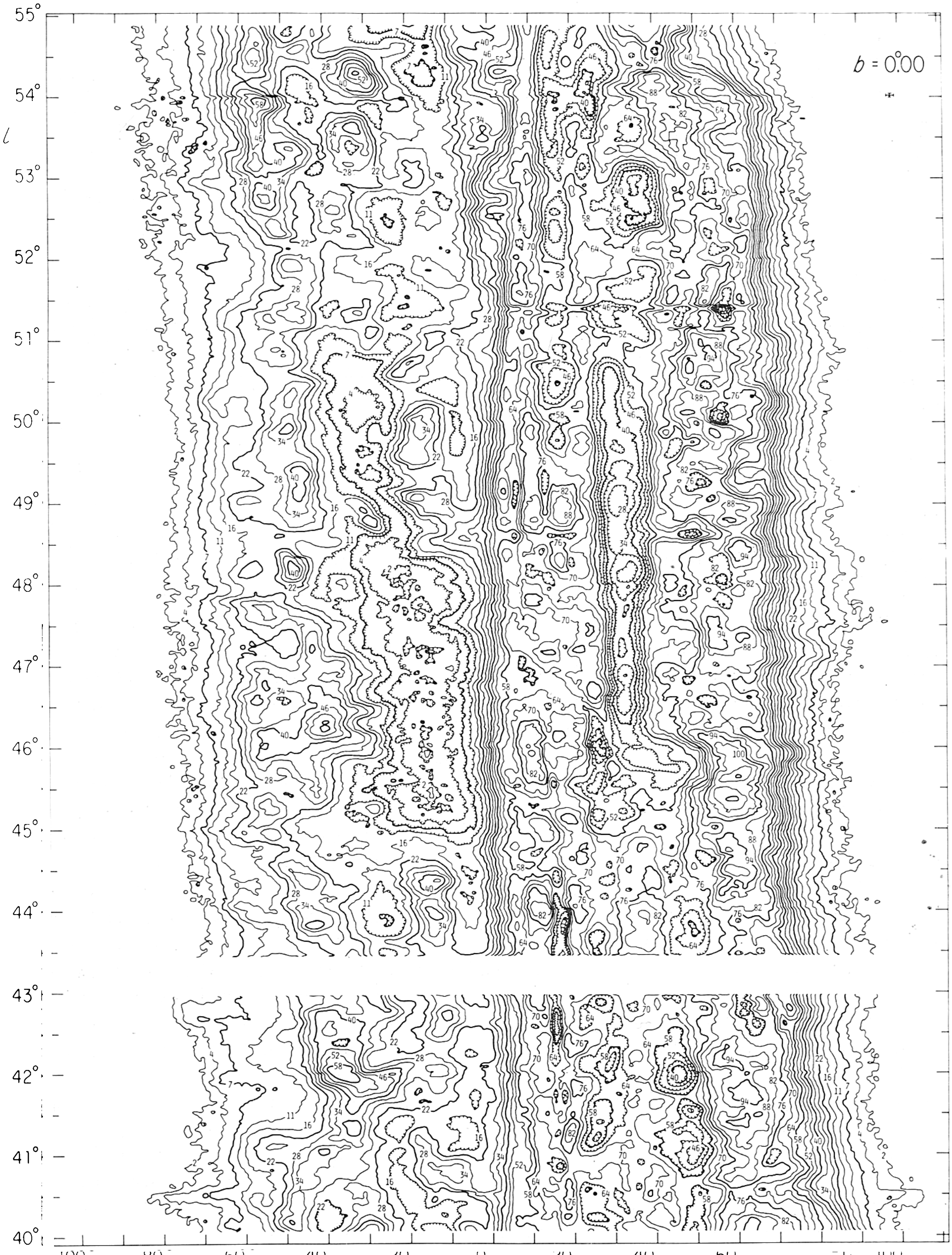

Figure 3. ℓ-v map of HI emission observed at b=0° at the high angular resolution, 3!2, afforded by the Arecibo telescope (Baker and Burton, 1979). The map is peppered with small-angular-size intensity minima identified with self-absorption in cold clouds.

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although probably sufficient HI emission is concealed in cool, beam-diluted structures that this value should be treated as a lower limit. The rather constant density variation is in marked contrast to the distribution of total galactic mass density (contributed mostly by stars) which increases strongly toward the galactic center. The HI density decrease in the inner parts is a characteristic which our galaxy shares with other spirals.

COLD HI IN MOLECULAR CLOUDS

The evidence which reveals partial saturation in 21-cm spectra contains information also on the physical characteristics of the gas, but before this information can be interpreted it is necessary to decide if τ simply increases monotonically as the length of path at a particular velocity through a rather uniform gas increases (as in the model entering Figures 1 and 2), or if τ increases incrementally due to the collective behavior of cold, generally unresolved structures in the telescope beam (as is probably the case). A nonuniform distribution of temperature and density is expected on general grounds, and observational evidence for such a situation is well established. Thus Heeschen (1955) and Davies (1956) found low-latitude emission regions with kinetic temperatures about one-half the usually adopted value. Shuter and Verschuur (1964) and Clark (1965) showed that temperatures observed in 21-cm absorption spectra resemble those of cold emitting features. Because this cold gas is opaque, the higher temperatures generally observed require that a warmer, but thin gas be present also. Clark (1965) suggested a "raisin-pudding" model, in which cool opaque clouds are immersed in a warm transparent medium. Such a multi-component situation has been given extensive theoretical justification (e.g. Field, Goldsmith, and Habing, 1969), although the details of the physical properties, and the distinctiveness of the different regions, are not yet accurately established by observation. General arguments and observations of local structures indicate that simple cloud/intercloud models are naive (see Heiles, 1980), although such models can validly serve useful purposes. Whatever the details of its distribution, the cold material must not be so prevalent that the spectra saturate at low temperature. Measurements of HI absorption against extragalactic continuum sources (e.g. Radhakrishnan *et al*., 1972) show high opacity HI to occur commonly; if this material were to dominate the emission spectra, the spectra would be quite saturated. This contadictory situation is avoided because of beam dilution of the opaque material.

Insight into the overall optical depth characteristics of the galactic gas layer is emerging from the identification of the common occurrence of residual cold atomic hydrogen in galactic molecular clouds. These clouds are generally sufficiently diluted in the telescope beam that emission profiles show large-scale optical thinness, although the clouds are individually opaque. The existence of residual atomic hydrogen in local, optically identified, dark dust clouds was demonstrated by Knapp (1974), and by others for individual local

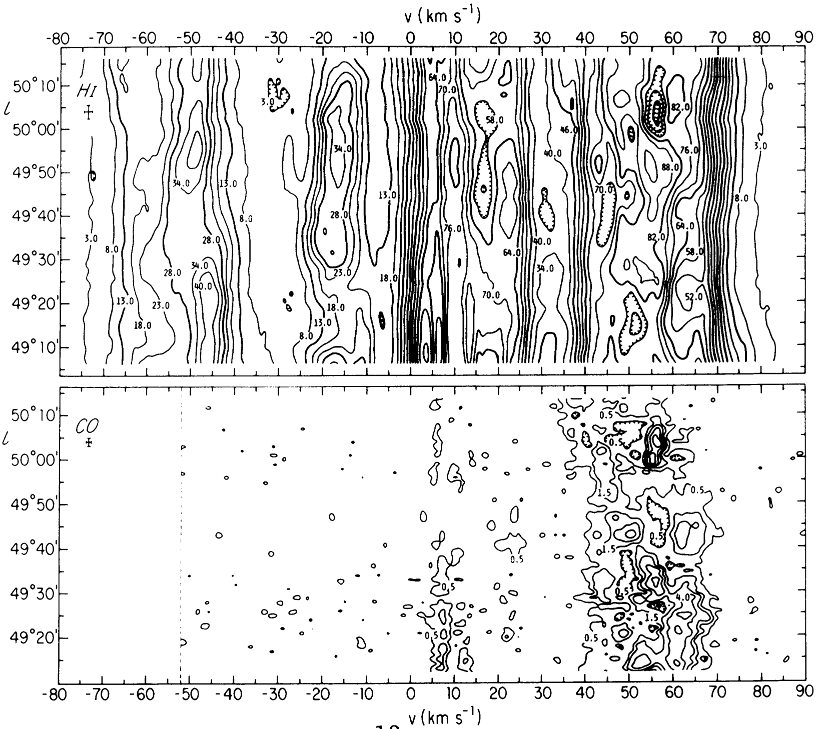

Figure 4. Comparison of HI and ^{12}CO emission observations made near ℓ=49°.5 with approximately similar resolution showing that molecular clouds have a residue of cold HI which is responsible for several aspects of the appearance of the HI emission (Liszt, Burton, and Bania, 1980). The cold HI in the molecular-cloud ensemble is severely diluted in the large beams of most surveys. Its effect is particularly important to derived HI overall densities and masses. The CO emission and HI absorption counterparts are apparently well-mixed, with comparable kinetic temperatures as implied by the CO data, $T_k \sim 10$K. The optical depths are ~0.4. The HI column densities are typically 2 x 10^{19} cm^{-2}.

features. It seems well-established now that residual cold HI occurs throughout the galaxy in the members of the molecular-cloud ensemble traced by observations of CO. Baker and Burton (1979) fully sampled all of the galactic equator accessible to the Arecibo telescope, and found that those observations (see Figure 3) are characterized by the striking appearance of a large number of narrow HI self-absorption features typically too small (~5') to have been resolved or even detected by the larger beams (~0°.5) of earlier HI surveys. Burton, Liszt, and Baker (1978) showed that these HI features are strongly correlated with emission from carbon monoxide clouds. Figure 4 shows examples of this correlation. As a consequence of the correlation, HI emission observations can be used for investigation of the statistical and morphological characteristics of the cold, high density, star-forming regions in the galaxy.

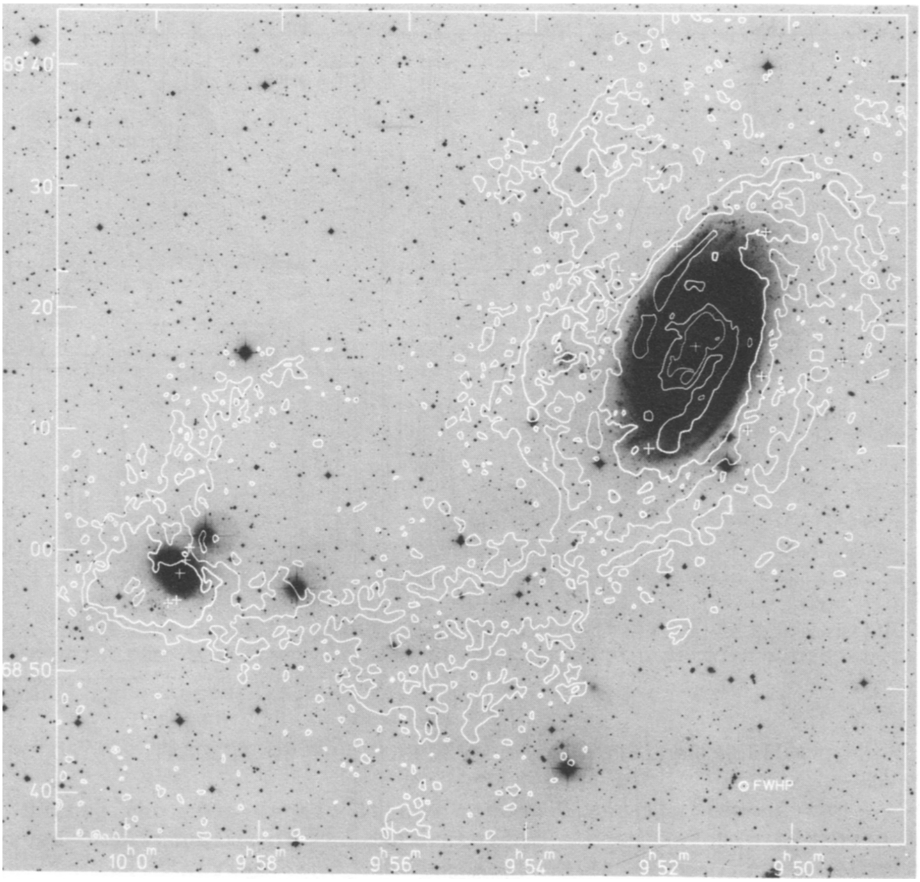

Figure 5. HI emission from M81 and its surroundings (van der Hulst, 1979) superimposed on a deep IIIa-J plate (de Ruiter et al., 1976). The HI distribution extends well beyond the luminous galaxy and the HI spiral arms are broader than the luminous ones; in these respects our galaxy is probably similar.

This correlation has important consequences. The number of HI nucleons in these clouds is underestimated in density derivations based on emission profiles, although probably only about 1% of the H nuclei residing in the clouds are in HI. More important are the modulations on the general HI emission intensities which result from the accumulated effects of opaque clouds which are individually non-overlapping in space and severely diluted in the cone of observation. The effects of this absorption from the galactic cloud ensemble seriously complicate interpretation of HI emission profiles (see Liszt, Burton, and Bania, 1980). They are most severe where $|\Delta v/\Delta r|$ is small; thus they can account for the frequent occurrence of maximum emission temperatures at velocities away from those corresponding to the subcentral locus,

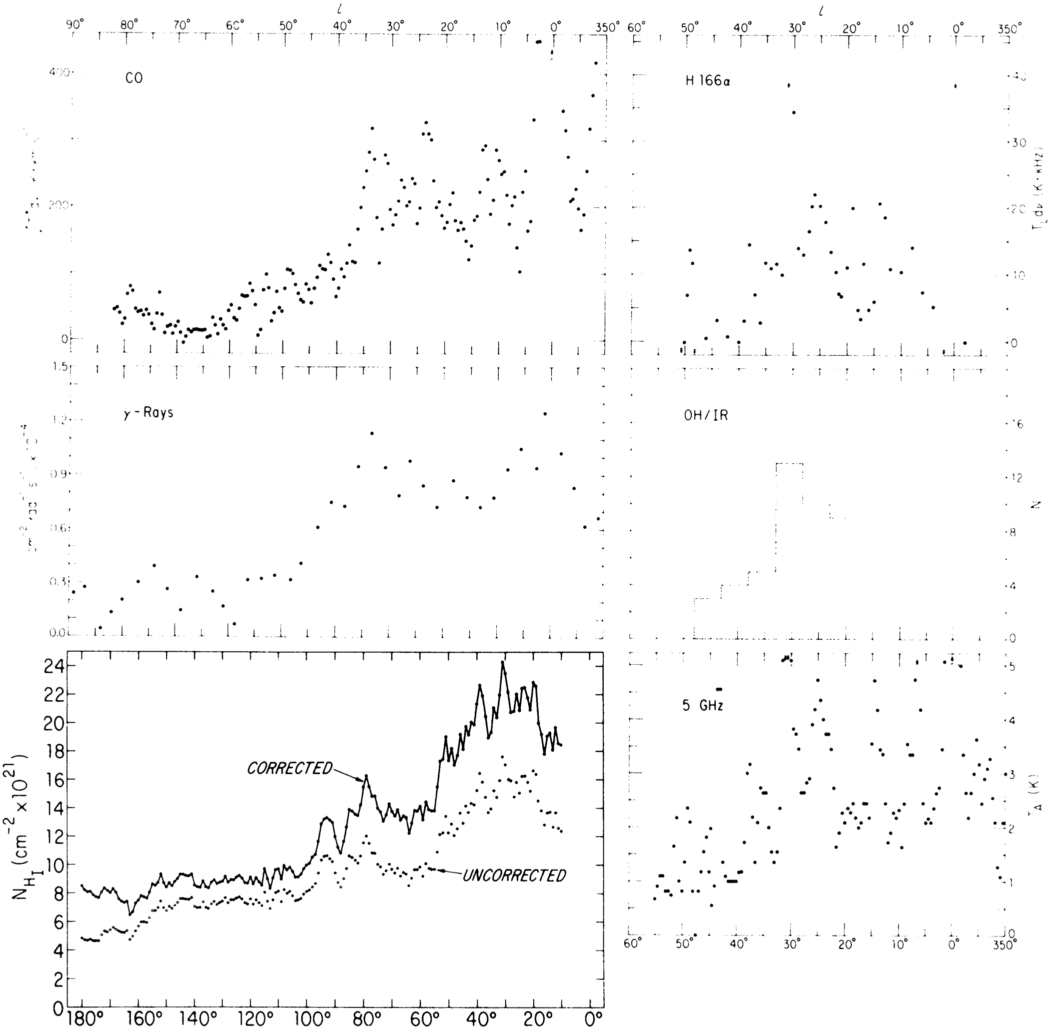

Figure 6. Comparison of the longitude distributions along the galactic equator of six galactic tracers (CO: Burton and Gordon, 1978; H166α: Lockman, 1976; γ-radiation above 100 MeV: Kniffen, Fichtel, and Thompson, 1977; 5 GHz continuum: Altenhoff et al., 1970; OH/IR: Johansson et al., 1977; HI: Burton, 1976). Excepting atomic hydrogen, all tracers accessible on transgalactic paths show a consistent morphological confinement to the inner galaxy.

where the maximum temperatures would generally lie for a thin gas. In the entirely plausible circumstance (not yet convincingly demonstrated for our own galaxy) that molecular clouds occur preferentially in spiral arms, the resulting modulation in HI emission profiles would probably be sufficient to cause the arms to appear as minima in these profiles. In the plots of $\int T_B(v)dv$ against ℓ in which peaks or steps have often been sought as evidence of arms, the eventual HI arms would

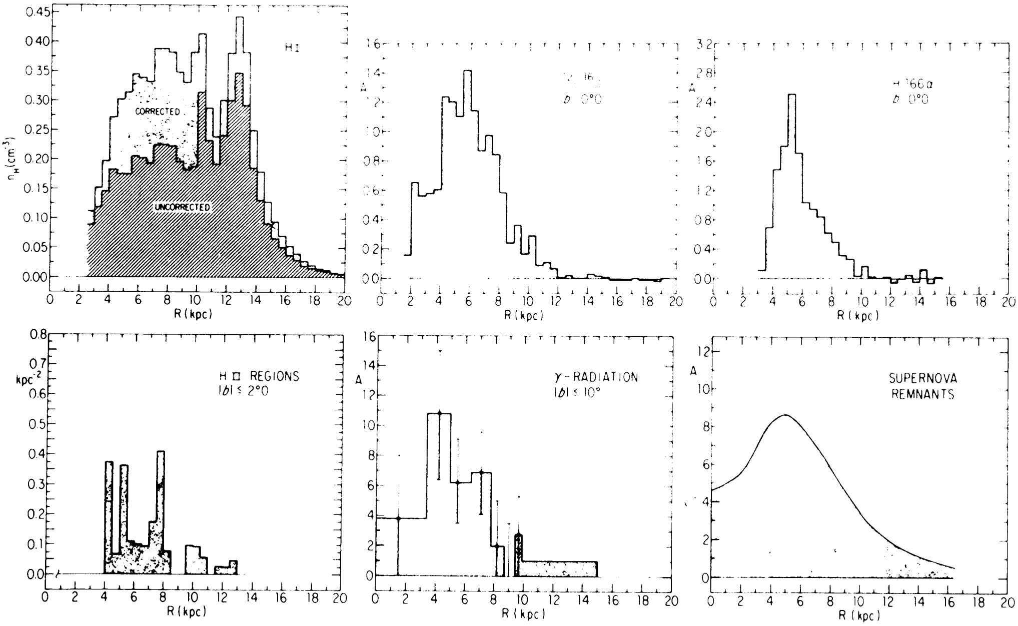

Figure 7. Comparison of the radial distributions of six constituents of the galactic disk (Burton and Gordon, 1978, and references there).

in such a case appear as minima.

MORPHOLOGY OF TRACERS OF THE COMPRESSED INTERSTELLAR MEDIUM

During the past decade it has become clear that among the observed constituents of the interstellar medium, atomic hydrogen is unique in its distribution. The galactic disk as defined by atomic hydrogen has a diameter at least twice as large as that defined by the ionized and molecular states of hydrogen, as well as by other molecules, supernova remnants, pulsars, γ-radiation, and synchrotron radiation. These other tracers refer either to high density regions of the interstellar medium or to consequences of active star formation. If our galaxy were viewed from an external perspective, the sun would be seen to lie near the outskirts of the optically luminous disk (see Figure 5).

The longitudinal distribution of those tracers accessible along transgalactic paths reveals the degree of confinement to the inner galaxy in a straightforward way (Figure 6). Conversion of the longitudinal distribution to the radial abundance distribution can be done using the kinematic information inherent in the spectral-line data or by using a geometrically-based unfolding process for tracers such as the radio continuum or γ-rays (Figure 7).

Information about the total amount of material requires, of course, measurements which extensively sample the relevant volume. Particularly important in this regard is the recent work by Cohen et al. (1980) and by Solomon, Sanders, and Scoville (1979) which has substantially aug-

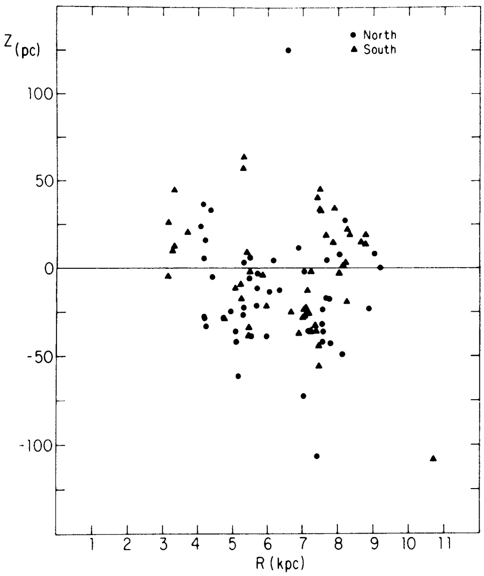

Figure 8. Distance from the galactic plane plotted against distance from the galactic center for luminous HII regions (Lockman, 1979). The HI and CO layers show similar systematic excursions from b=0°.

mented the CO data at latitudes away from b=0°. Available evidence for all of the inner-galaxy tracers shows that they are centered on the same mean layer, but that the centroid of this layer deviates systematically from b=0° (see Figure 8). There is no consensus regarding the cause of these deviations. Layer-thickness measurements combined with the radial abundances yield projected surface densities (Figure 9).

H_2 DENSITIES FROM CO INTENSITIES

The most stable low-temperature form of the most abundant element in the interstellar medium is molecular hydrogen. It predominates over all other gaseous material in optically opaque, compressed regions where the molecule is shielded from photodissociation after formation on grain surfaces (Solomon and Wickramasinghe, 1969). This material is of course not represented in 21-cm observations of the hyperfine transition of atomic hydrogen. Having no dipole moment, H_2 has no observable transition in the radio or optical windows. Ultraviolet extinction due to interstellar dust limits observations of the H_2 Lyman absorption bands to the directions of reddened stars within a kiloparsec or so of the sun. The molecule second in abundance to H_2 is CO. Because the most important source of excitation of the CO rotational transitions involves collisions with H_2, observations of CO provide by implication much information on H_2. This information takes two important forms: pertaining to the distribution of H_2 and to cool, dense regions in general, the CO information can be interpreted without intervening assumptions; pertaining to the density of H_2 nucleons, the CO-based estimates involve critical uncertainties.

Emission lines from the J=1→0 transition of the principal isotope ^{12}CO have a high optical depth and therefore provide the excitation

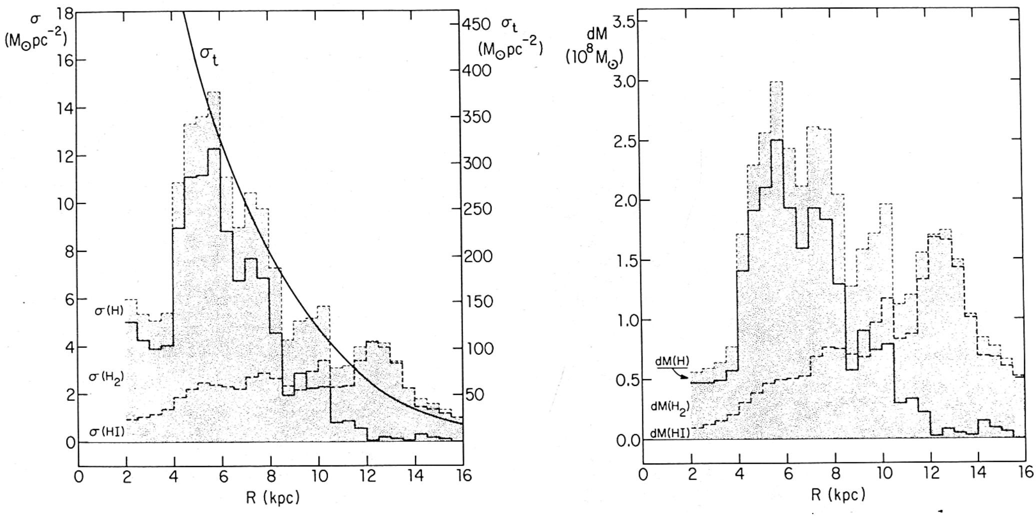

Figure 9. Radial distribution of projected surface densities and differential masses of atomic and molecular hydrogen (Gordon and Burton, 1976). Some of the uncertainties involved in the conversion of CO intensities to H_2 densities are mentioned in the text.

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temperatures of molecular clouds, but not the column densities. Emission from the J=2→1 transition of the much less abundant isotope ^{13}CO is unsaturated, however, so that column densities follow directly from observed intensities. Because of the weaker intensities of the ^{13}CO spectra, the first estimates of H_2 densities were based principally on ^{13}CO data and on hypotheses, supported by limited data, regarding the abundance ratio $^{12}CO/^{13}CO$ (Scoville and Solomon, 1975; Gordon and Burton, 1976). The amount of ^{13}CO data available has now increased significantly (see Figure 10, and Solomon, Scoville, and Sanders, 1979). The ^{13}CO data show similar variations on a galactic scale as the ^{12}CO data and an approximately constant ratio of intensities. These results give pragmatic support to the use of the principal isotope for density-mapping purposes, and provide no evidence that the assumption (which is important to the density derivations) of constant isotopic abundance ratio across the galaxy is invalid.

Conversion of the CO intensities to H_2 densities involves several possible sources of uncertainty. Some of these potential uncertainties require for their resolution additional theoretical work on questions of molecule formation and dissociation, and on radiative transfer; others, in particular those regarding abundance ratios, require diverse observational work. Thus the numerical value of the abundance ratio $^{12}C/^{13}C$ = 40 was suggested by Wannier et al. (1976), although some workers use the terrestrial value, 89. Additional sources of uncertainty concern the fraction of C which is bound in CO, and the abundance ratio C/H, as well as the degree of constancy of these quantities over the galaxy.

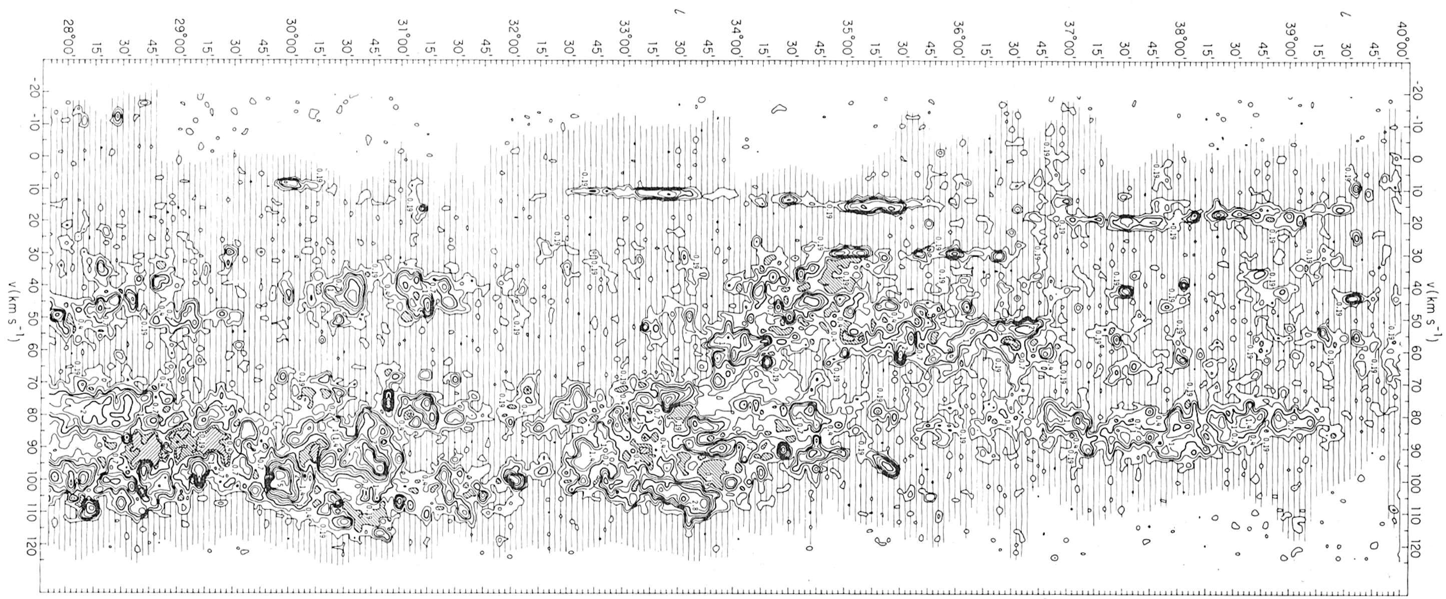

Figure 10. ℓ-v arrangement of emission from the ^{13}CO isotope in the galactic equator (Liszt, Burton, and Xiang, 1980). Emission from this isotope has lower opacity than emission from ^{12}CO, and therefore provides more direct information on the gas densities. Stochastic-ensemble models of this sort of observational material suggest that many of the complex features result from blending of physically unrelated clouds. Many of the small-scale features result from the sampling characteristics inherent in a single-latitude strip map. Straightforward measurement of the angular extent of the observed features might give incorrect cloud diameters, just as direct measurement of the velocity gradients might give misleading kinematic information.

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There are other potential uncertainties which can be confronted through direct analyses of the CO survey observations themselves. Thus the question of optical depths of the ^{12}CO and ^{13}CO lines is a puzzling one in view of the proportionality between intensities observed and in view of the observed line shapes. Presumably the resolution of this puzzle is to be found in macroscopic turbulence within the clouds and in the manner in which the emission is sampled in the telescope beam. Interpretation of the sampling characteristics is also necessary before the role of shadowing can be understood. If shadowing of one opaque cloud by another at the same velocity on the same line of sight occurs commonly, the total number of emitters will be underestimated. This problem, and the related one concerning the volume-filling factor of the molecular clouds, require knowledge of the size and typical separation of the members of the galactic molecular cloud ensemble.

INTERPRETATION OF EMISSION FROM THE MOLECULAR CLOUD ENSEMBLE

The investigators agree concerning such morphological aspects of the molecular cloud distribution as its confinement to the annulus $4 \lesssim R \lesssim 8$ kpc and its z-dispersion of ~50 pc. Controversy remains, however, regarding basic intrinsic properties of the molecular clouds, their distribution within the cloud ensemble, and the manner in which the ensemble is perceived in the observations. Thus there has been an emphasis on "giant" molecular clouds (e.g. Solomon and Sanders, 1980; Szabo, Shuter, and McCutcheon, 1980) and on clouds with typical diameters $\gtrsim 5$ pc (e.g. Burton and Gordon, 1978). The random velocity component of the clouds has been held to be ~4 pc (Burton and Gordon, 1978) and 9 km s^{-1} (Stark and Blitz, 1978; Stark, 1979). Resolution of these disagreements is crucial to discussions of the total cold-gas mass, to questions of possible cloud-cloud accretion, to the role of clouds as sites of star formation, and to the statistical acceleration of stars through encounters with clouds. Some of the conclusions about which there is little consensus have been derived from the observational survey data in ways which are perhaps too straightforward for the peculiar task of studying (from an embedded perspective) an ensemble which, although composed of individually discrete, opaque clouds, is perceived as macroscopically transparent.

Recently Liszt and Burton (1980) have approached the general problem of interpreting the ^{12}CO survey data (of the sort shown in Figure 11) by simulating spectra from the galactic ensemble of clouds. The controlled conditions inherent in such modelling allow study of the consequences of the observing procedure, including those of telescope beam size and sampling interval, of the importance of such matters as cloud blending and shadowing, and of the influence of the galactic velocity field. Most aspects of the large-scale CO surveys can be simulated with stochastic-ensemble models in which cloud size and total number of clouds are the dominant parameters. Figure 12 shows an example of ^{12}CO emission synthesized for an ensemble of identical 18-pc clouds. Significant differences occur between the intrinsic

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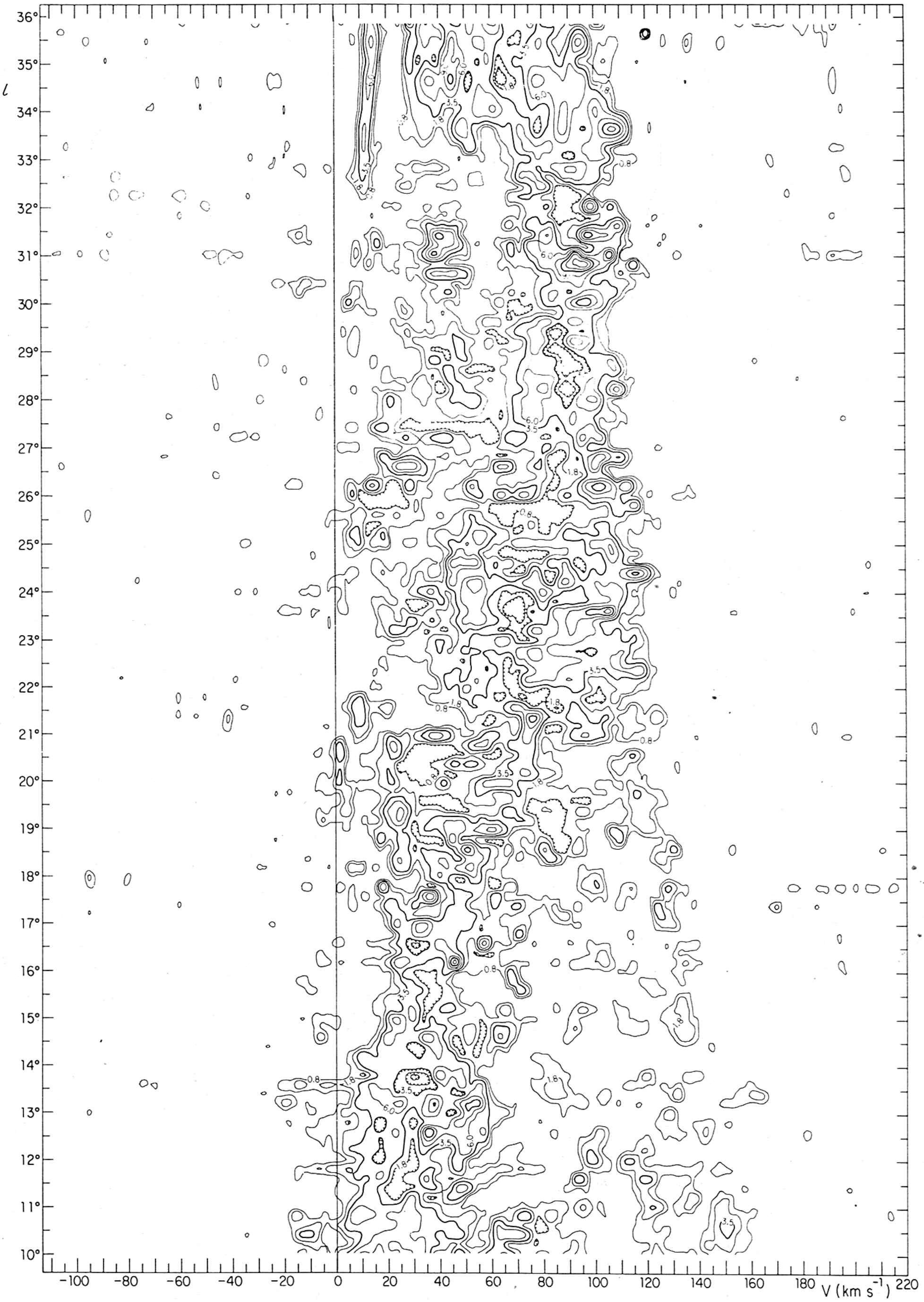

Figure 11. ℓ-v arrangement of ^{12}CO emission observed along the galactic equator (Gordon and Burton, 1976). This is the sort of material used to confront stochastic models of the molecular cloud ensemble.

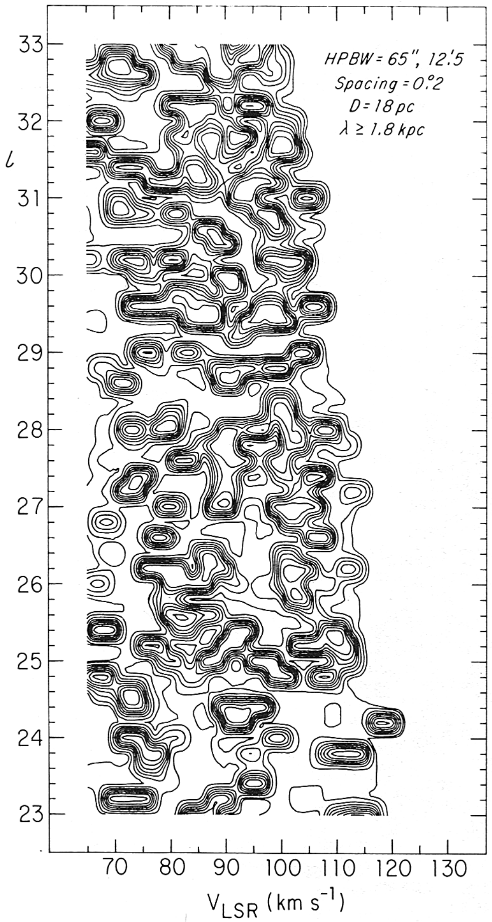

Figure 12. Synthesized ℓ-v map at $b=0^o$ of ^{12}CO emission from an ensemble of molecular clouds (Liszt and Burton, 1980b). The ensemble represented here contains 43200 identical clouds of 18-pc diameter, with a mean-free-path separation of 1.8 kpc at the peak of the molecular annulus. The spectral features which result from these identical clouds show, for several reasons, a great deal of inhomogeneity.

distribution of cloud diameters and the distribution of the sizes of features measured parallel to the galactic plane, principally because the scale height of the molecular distribution is not small compared to the typical cloud sizes and because of blending. Many of the large, complex features appearing in CO ℓ-v maps are due to blending of physically unrelated clouds. Straightforward measurement of the angular extent of these features might give too-large diameters; of their linewidths, too-large dispersions; of their intensity structure, false information on clumping; and of their velocity gradients, misleading kinematic information. The modelling results suggest to us that the typical cloud diameter in the inner galaxy is 15-20 pc. Neither very large ($D \gtrsim 40$ pc) nor very small ($D \lesssim 10$ pc) clouds contribute much of the aggregate cloud surface area. Larger clouds may contain an appreciable but not overwhelming fraction ($\lesssim$50%) of the total cloud volume. The one-dimensional cloud-cloud random velocity dispersion in the galactic plane is 3-4 km s^{-1}, too small to account straightforwardly for the observed z-dispersion of 50 pc. At galactocentric radii 5-6 kpc the volume filling factor of the molecular ensemble is

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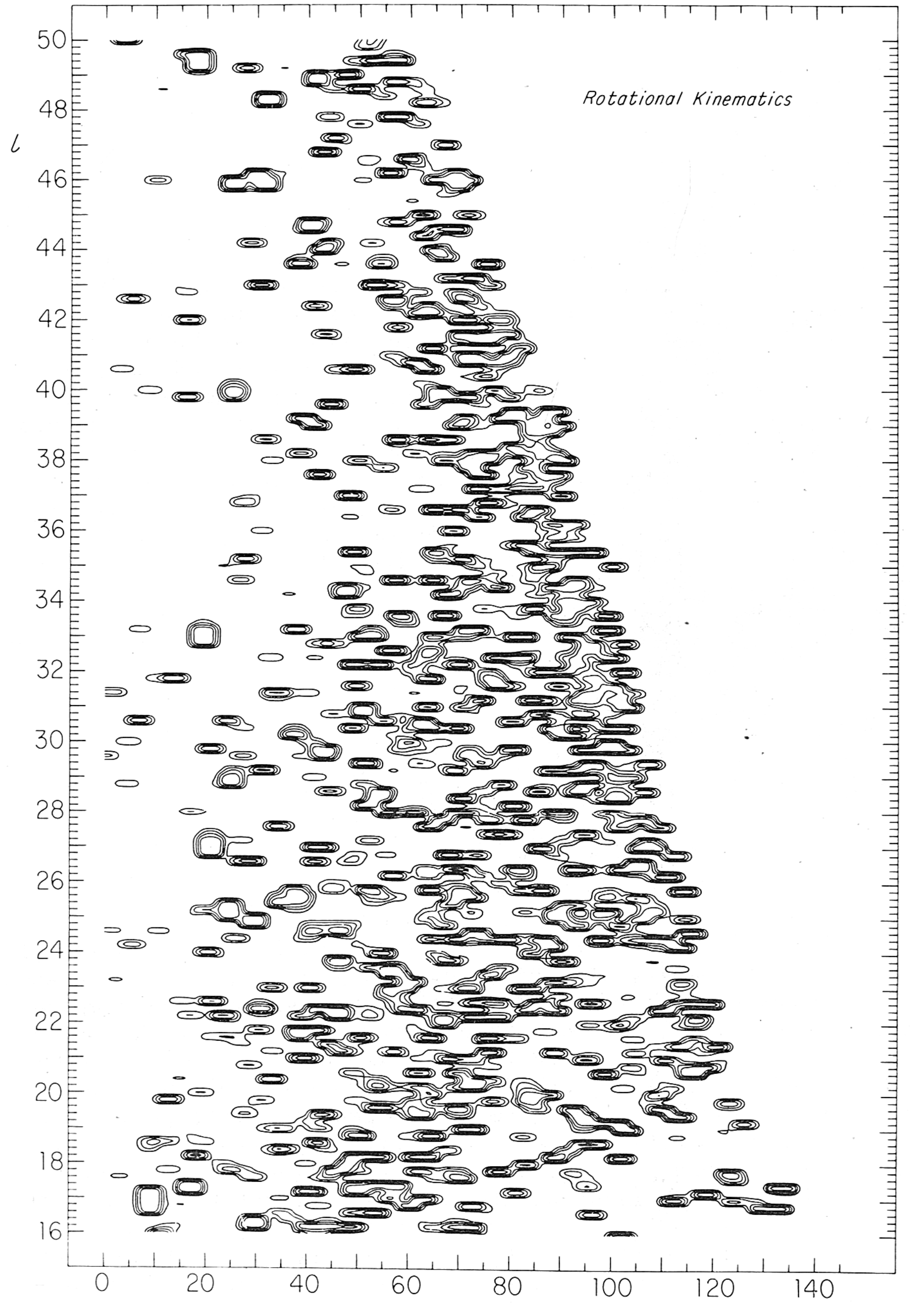

Figure 13. Synthesized map at b=0^o of ^{12}CO emission from the molecular-cloud ensemble, calculated for a rotationally symmetric velocity and density distribution of 18-pc clouds (Liszt and Burton, 1980b).

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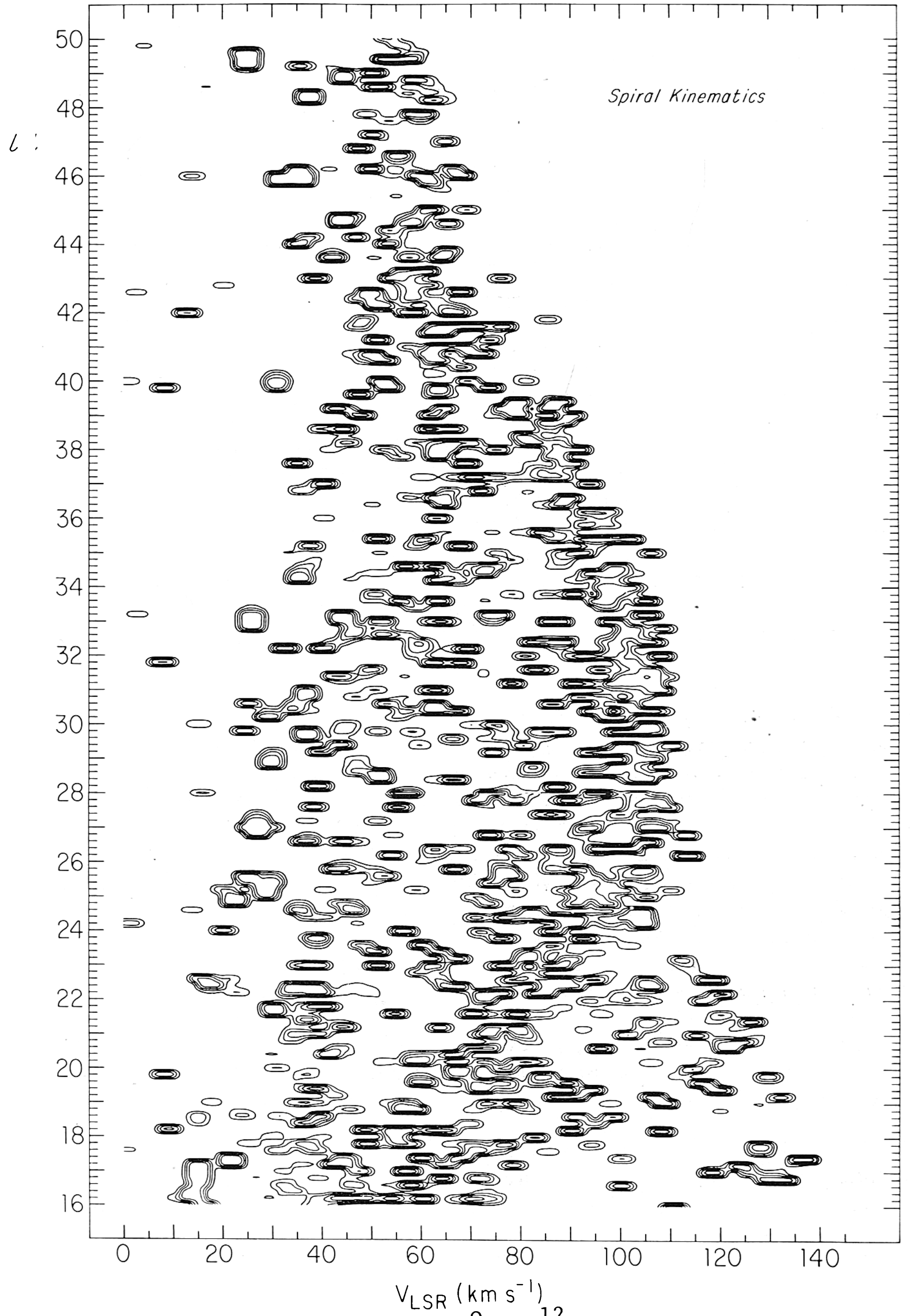

Figure 14. Synthesized map at b=0° of ^{12}CO emission from the molecular-cloud ensemble, calculated for a spiral-shock velocity field (Roberts and Burton, 1977), but with a rotationally symmetric cloud distribution (Liszt and Burton, 1980b).

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~.007, the typical mean free path between clouds is 1.8 kpc, and the space-averaged H_2 number density is probably about 3 H_2 cm^{-3}. Molecular material almost certainly dominates the interstellar medium in the inner-galaxy.

Much of the motivation for carrying out the large-scale surveys of CO has focussed on the hope of mapping the spiral structure of our galaxy. This hope parallels the earlier situation regarding HI, but for the case of CO it was reinforced by a range of results reached by the late 1970's. Comparison of optical studies with aperture synthesis radio data showed that the narrow dust lanes in external galaxies portray spiral arms in a much more definite way than does the HI structure. Theoretical studies confirmed that the diffuse atomic gas would likely respond in a linear manner to the passage of a density wave, whereas the cold, dense molecular material would experience a non-linear response along a very narrow shock front. This narrow shock front might indeed precipitate the formation of the CO clouds. In addition, the early CO data showed that the molecular clouds occupy only about 1% of the total volume of the galactic layer, leading to a tendency to consider unimportant the velocity-crowding and blending responses to the kinematic parameter $|\Delta v/\Delta r|$ which dominate spectra from HI (which occupies essentially 100% of this volume in one state or other). It is particularly this tendency to which the ensemble modelling is relevant.

Figure 13 shows a large-scale simulated ^{12}CO ℓ-v map calculated for the case of a rotationally symmetric velocity and density distribution. The concentration of emission near the terminal-velocity locus indicates that the kinematic parameter is influential; otherwise there is in this map little of the structure which characterizes the Figure 11 observations and which might be viewed as true concentrations in space. Figure 14, however, does show such structure. The simulation responsible for the figure incorporates an azimuthally symmetric ensemble distribution, but the spiral velocity field predicted for a non-linear density wave model. A significant arm-interarm contrast occurs even though the input azimuthal density variation entails no such contrast. We conclude that the transformation from the galactic spatial and kinematic coordinates to the observed position-radial velocity maps involves for CO data the same sort of consequences that have frustrated galactic mapping efforts based on HI 21-cm data, despite the very small volume-filling factor of the ensemble of molecular clouds. Further numerical experiments show that the kinematic loops observed in the inner regions of the galaxy result primarily from perturbations of the galactic velocity field and only secondarily from localized density variations. Use of a pure-rotation velocity field to infer the spatial location of spiral arms in the molecular ensemble is probably inappropriate. Arm-interarm cloud abundance variations cannot be simply inferred from intensity-velocity profiles. Even if they are present, such arm-interarm contrasts do not necessarily constrain the lifetimes of molecular clouds to be small. Regarding evidence of spiral structure in the currently available CO surveys, we adopt an agnostic

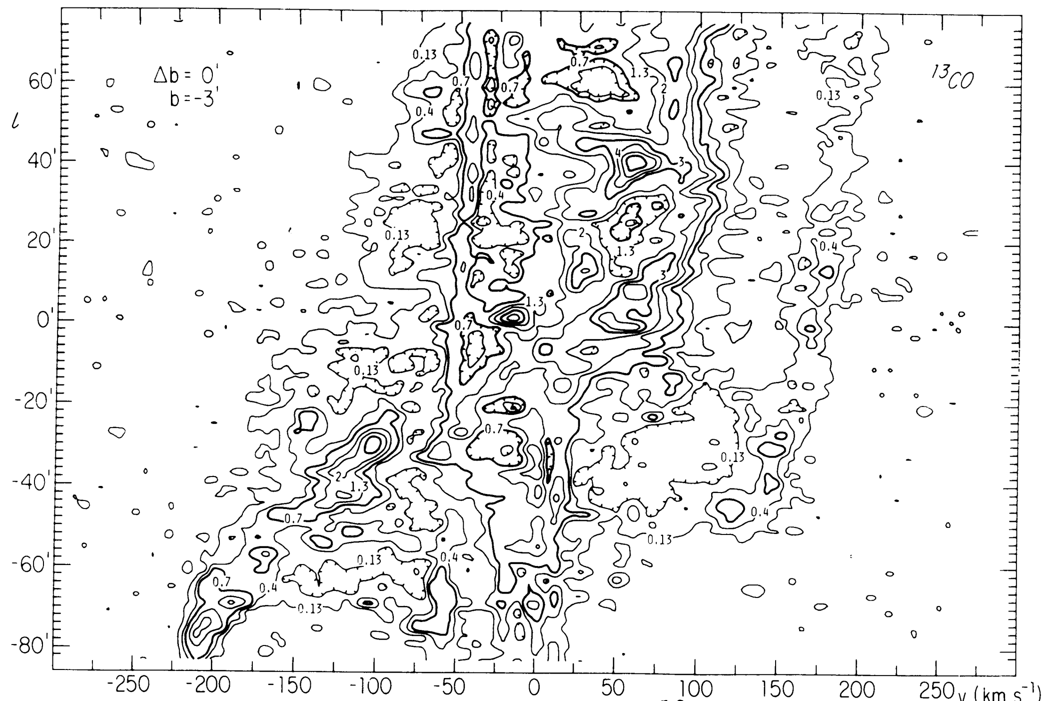

Figure 15. Distribution of emission from the ^{13}CO isotope near the galactic center. The molecular emission from the nuclear region is intense, and differs from the emission from the galaxy at large in its apparent ubiquity and its broad velocity dispersion.

position. In analogy to the HI structure, we believe the most direct evidence from the CO tracer for such structure to reside in the ordered perturbations to the variations of terminal velocities with longitude.

TWO SPECULATIONS RELEVANT TO THE TOTAL GALACTIC NUCLEON COUNT

The possibility of very cold (3-5 K) generally undetected molecular gas. The excitation temperature of the molecular clouds which are detected in the CO surveys and which contain no heat source from, for example, recently formed stars, is typically ~14 K. The constancy of this temperature implies that it is an intrinsic cloud property. The sensitivity of the current emission surveys would not provide detection of very cold gas at $T_k \lesssim 5$ K. If it exists, such gas would appear in absorption spectra. But, at millimeter wavelengths continuum-radiation sources are too weak to provide a suitable background. The CO line emission from the Sagittarius molecular complex represents a special case. This emission is sufficiently broad that it serves as a background, and, indeed, against the SGR complex deep, narrow dips in the CO emission spectra have been identified with absorption by very cold

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foreground gas at T_k = 3.5 K (Liszt *et al.*, 1977; Zuckerman and Kuiper, 1980). Linke, Stark, and Frerking (1980) show absorption evidence for very cold HCO^+ and HCN clouds in radiative equilibrium with the 3 K cosmic background radiation. It is necessary to remain open to the possibility that very cold regions are quite common throughout the galaxy, but that they are not adequately accounted for because of the lack of suitable background sources.

The possibility of smoothly distributed molecular gas in the innermost galaxy. Interpretations of CO surveys agree on the relative deficiency of CO in the region of the galaxy interior to R ~ 4 kpc. These interpretations involve techniques which, in essence, count discrete clouds. In the innermost galaxy, the shearing forces of rapid differential rotation are such that large, discrete clouds may not form (see Stark, 1979). Under these conditions there are plausible reasons to doubt that the ultraviolet shielding will be sufficient to allow extensive molecular formation. Nevertheless, the observations show all of the characteristics which would be expected for a ubiquitous distribution of molecular gas (Liszt and Burton, 1978). Thus they show smoothly varying intensities, with little of the patchy appearance characterizing emission from the galaxy at large, and an arrangement of intensities which follows in detail the predictions of a response to galactic kinematics and which would be expected only if the space were pervaded by the gas. Particularly important in this regard are the very large velocity widths of the observed molecular features (see Figure 15). Based on the assumption of a smooth molecular distribution, Liszt and Burton (1978) argue that the inner few kiloparsecs of the galaxy contains $M_{H_2} > 10^9$ $M_\odot$, and that the CO/HI ratio is anomalously large there. Linke, Stark, and Frerking (1980) support these high H_2 column densities using absorption data.

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