MOLECULES IN THE INNER FEW KPC OF THE GALAXY

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INTRODUCTION

Emission and absorption spectra of several molecules have been used to trace the kinematic patterns of molecular material in the inner Galaxy. For a variety of reasons, the great majority of effort in this area has focussed on the region $357 \lesssim \ell \lesssim 3°$ very near the plane $b = 0°$. Extending the observational coverage of the molecular distribution away from this plane and over a wider longitude range is a tedious process only now beginning and severely hampered by relatively small beamwidths and long integration times. Our knowledge of the arrangement of molecular material in the inner few kpc of the Galaxy is primitive and quite incomplete compared to that of the atomic gas sampled at λ21 cm.

Because of its ubiquity and because it appears in emission in a suitable atmospheric window, carbon monoxide (CO) is the most readily accessible tracer of molecular material throughout our Galaxy. Comparison of inner-Galaxy spectra shows clearly that other molecular species exhibit only a limited subset of the behaviour apparent in carbon monoxide and, for this reason, our discussion is heavily oriented toward CO observations. Our discussion concentrates on the behaviour of material within about 2 kpc of the galactic nucleus but does not deal with the complicated behaviour of material within the Sagittarius source complex, which is essentially a local phenomenon.

THE MOLECULAR RING

The earliest molecular maps of the inner Galaxy were of the absorption spectra of H_2CO and OH. Instead of revealing a clear signature ascribable to the "rotating nuclear disk" of Rougoor and Oort (1960), they presented an entirely new picture of cold, dense inner Galaxy material

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moving with large outward radial velocities with respect to the galactic center. These absorption measurements culminated in the interpretation of Scoville (1972) and Kaifu, Kato, and Iguchi (1972) which postulated the existence of an expanding ring of molecular material encircling the center of the Galaxy at a distance of ∿250 pc, presumably formed of matter ejected from it. At $\ell = 0°$, $b = 0°$, the ring feature has a velocity (LSR) of -135 km s^{-1}.

Because these absorption measurements necessarily sampled only gas in front of the Sagittarius source complex, the absence of a positive velocity branch of the ring did not itself indicate a lack of circular symmetry. However, the rear portion of the ring was also not present in CO emission spectra (Solomon et al. 1972) and it was not until later that a high - positive-velocity "expanding" molecular feature was detected crossing the plane $\ell = 0°$ at +165 km s^{-1} by Sanders and Wrixon (1974) and by Scoville, Solomon, and Jefferts (1974); these latter authors detected for the first time molecular emission at velocities ± 200 km s^{-1}, perhaps corresponding to the nuclear disk, and presented a two-arm spiral model to account for their observations.

Both anomalous-velocity molecular features are shown in Figure 1, a longitude-velocity diagram of CO emission in the plane b = -3' extending over the region $358° \leq \ell \leq 2.5°$ with a 2' sampling interval (similar but less extensive or less densely sampled data from this region have been presented by Bania 1977, by Liszt et al. 1977, and by Scoville et al. 1974). Although the similar perceived velocities of the two expanding molecular features are certainly indicative of a fair degree of front-back symmetry in the molecular distribution, the larger-scale kinematic pattern cannot easily be reconciled with the existence of a single ring. The high-positive-velocity feature extends from $\ell \sim -50'$ to $\ell > 145'$ and is not even approximately symmetrically positioned about $\ell = 0°$. The high-negative-velocity gas is more difficult to isolate but probably crosses 0 km s^{-1} at $\ell \lesssim 100'$ which, in the oval locus of an expanding, rotating ring would necessarily be the maximum positive longitude excursion of any emission arising from it (cf. Scoville 1972).

As an alternative explanation of the expanding molecular features, we show in Figure 2 the kinematic arrangement of molecular emission in the plane b = -3' which is generated synthetically by the tilted disk model of the inner Galaxy HI distribution described by Burton and Liszt (1978) and discussed by them in a separate paper in this volume. This model, schematically represented in Figure 3, is characterized by a density variation depending only on distance from its midplane of the disk and by kinematic rotation and expansion motions depending only on perpendicular distance from the disk axis. A more complete discussion of the applicability of this model to the large-scale CO distribution is given by Liszt and Burton (1978). It is clear that the synthetic longitude-velocity arrangement of Figure 2 reproduces most of the observed "ring" characteristics: These include the dissimilar longitude placements of the positive and negative velocity emission branches and their quite different slopes $dv/d\ell$ seen very prominently at positive longitudes. We believe that the presence of two discrete expanding features does not

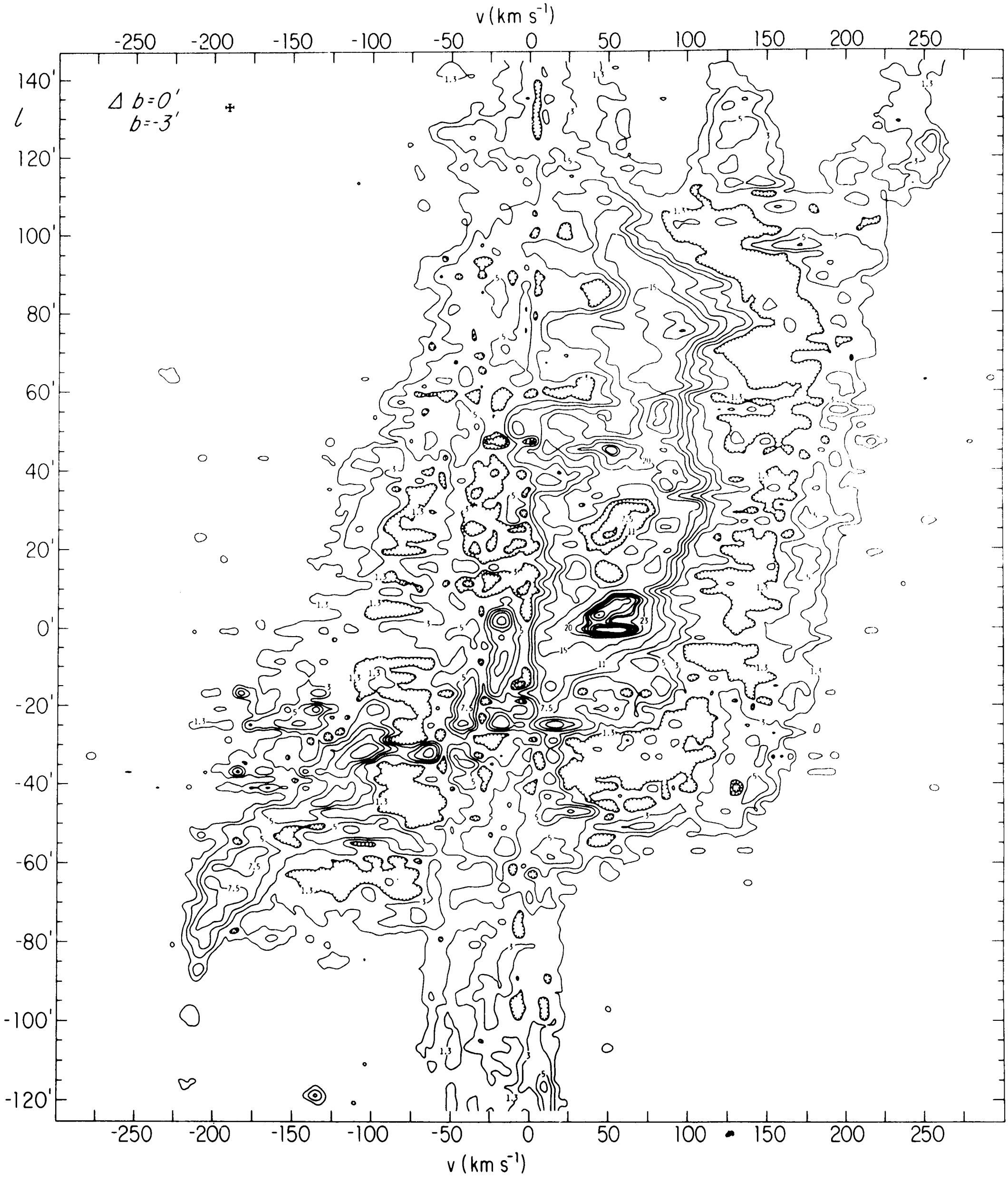

Fig. 1. The longitude-velocity arrangement of λ2.6 mm CO emission at b = -3' taken with a 1' beam at 2' intervals. Intensities are expressed in terms of antenna temperature corrected for atmospheric attenuation, telescope losses and a nominal beam efficiency 0.65 (as also in Figs. 3-5).

necessitate the existence of locatable material bodies, nor do they imply that molecular kinematics are anomalous compared to those of the HI. Rather, projection effects in space and velocity are sufficient to explain their presence in terms of a model which reproduces and lends coherence to a large body of HI observations. One characteristic of the observations which is not accounted for in the synthetic diagram is the non-zero average velocity of the two molecular features near ℓ = 0°, about +15 km s^{-1}. In terms of the disk model, such a result is obtained only if the kinematic center of the disk is displaced slightly further (10'-15') into the fourth longitude quadrant than is Sgr A.

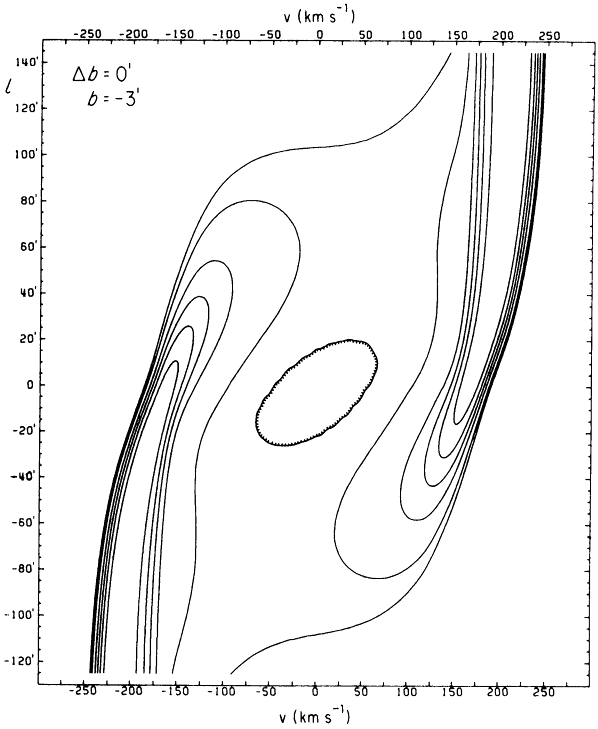

Fig. 2. Synthetic longitude-velocity arrangement of λ2.6 mm CO emission at b = -3' generated by the tilted disk model. Intensity contours are drawn at levels 0.6 K, 1 K, 2 K, 3 K, 4 K, 4.5 K.

THE TILTED NATURE OF THE MOLECULAR DISTRIBUTION IN THE INNER GALAXY

In Figure 4 we show the latitude-velocity arrangement of molecular emission at the longitude of Sgr A (West), ℓ = -3'. It can be seen there that the high positive and negative velocity emission features are symmetrically placed about b = -3' but are not contiguously distributed. Such behaviour is predicted to occur in the context of a flattened general gas distribution (containing expansion motions) whose symmetry axis is tilted out of the plane of the sky in the sense indicated in Figure 3. Below the apparent major axis of such a distribution outwardly directed motions will be perceived as negative and above it as positive. The latitude extent of the molecular emission in Figure 3 results from this tilt, not from the scale height of the molecular distribution. This latter property is only manifested in the small overlap in latitude of the positive and negative velocity features. The "inverted integral sign" signature of Figure 4 gives a clear indication that the molecular distribution is tilted as predicted by the model. If this aspect of the geometry were ignored, inplausibly large shearing effects would be required to reproduce such a pattern. The presence of the predicted model signature in latitude-velocity maps constructed over a range of galactic longitude supports the conclusion that the tilted distribution is filled rather than annular.

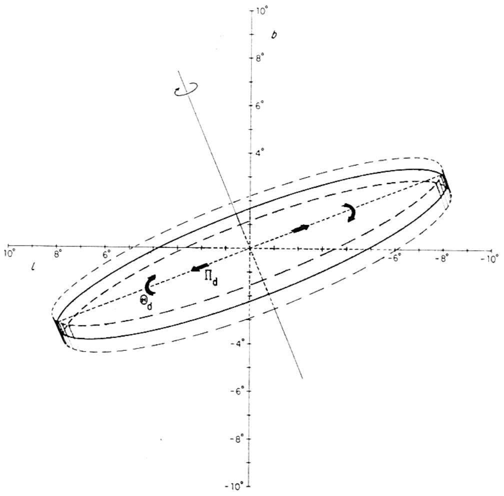

Fig. 3. Appearance of the model tilted gas distribution described by Burton and Liszt (1978) as projected onto the plane of the sky. The solid-line approximate ellipse represents the equatorial plane of a disk of radius 1.5 kpc, whose axis has been tilted through the angles 22° and 12°, respectively, in and out of the plane of the sky. The vectors indicate schematically the model expansion and rotation functions.

Although molecular emission from the inner Galaxy is largely confined at $b = 0°$ and to the region $357 \lesssim \ell \lesssim 3°$, our model predicts that other molecular features should be present at $\ell > 3°$ or $\ell < 357°$ when $b < 0°$ and $b > 0°$, respectively. Figure 5 shows the longitude-velocity arrangement of CO emission at $b = -1°$ made with 20' sampling intervals, along with a similar HI map made with a coarser spacing. The molecular feature observed at high velocities with a large negative slope $dv/d\ell$ is the familiar HI "connecting arm" of Rougoor (1964). As discussed by Burton and Liszt (1978), this arm is well accounted for by our tilted disk model, again without requiring the existence of a separately locatable material body.

Quite generally, CO emission follows the ridge lines present in HI observations and is readily detectable (antenna temperatures above one

Kelvin) whenever the antenna temperature at λ21 cm exceeds ∿5 K. These ridges are formed by projection effects and often represent but a small portion of the total distance over which a given line of sight remains in the disk. Alternatively, in other directions, such as $\ell = 3°$ in Figure 5, the perceived velocity gradient is large over the entire line of sight and only a very weak and broad (200 km s^{-1}) HI feature is observed. Corresponding emission is not apparent in most of our molecular observations only because the signal-to-noise ratio required to detect it cannot be obtained except after several hours' integration. Nonetheless, it is present in sufficiently long integrations and argues strongly for a molecular distribution which fills fairly uniformly the entire disk volume.

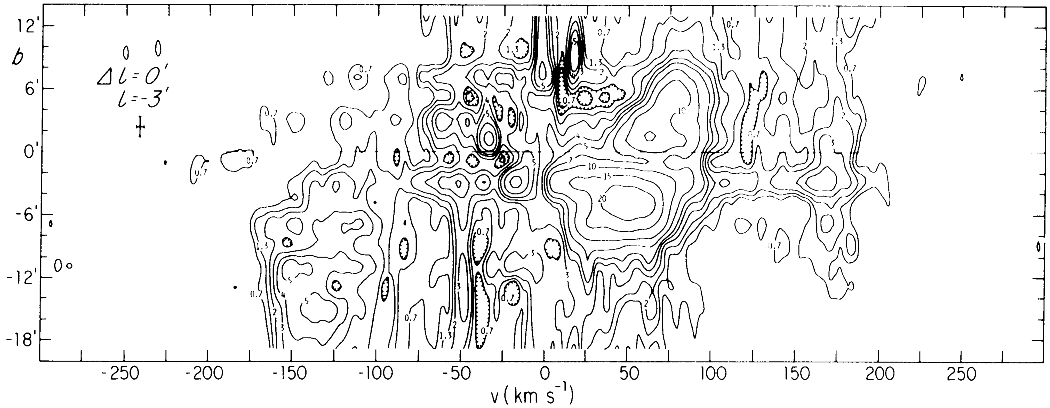

Fig. 4. The latitude-velocity arrangement of λ2.6 mm CO emission at $\ell = -3'$ taken with a 1' beam at 2' intervals.

PHYSICAL CONDITIONS IN THE INNER GALAXY MOLECULAR GAS

Because the more intense CO emission is optically thick and the relative CO abundance ill-determined, the mass of the molecular constituent of the inner Galaxy gas distribution is necessarily very uncertain. With a radius 1.5 kpc and scale-height 0.1 kpc as for the HI, the molecular mass is related to density in the midplane of the model by $M \sim 7\text{x}10^7 \, n_{H_2} \, M_\odot$. Thus even for relatively low molecular densities ∿100 cm^{-3}, the mass of the inner Galaxy material will be large. The crudest estimates of the required densities arise from the condition that collisional excitation of the CO rotation ladder alone be sufficient to produce excitation temperatures as large (5-7 K) as those needed to produce emission lines at levels 2-4 K. At a kinetic temperature of 100 K, this density is of order 100 cm^{-3}. Photon trapping could lower the required density by perhaps as much as a factor 3-4 at this temperature, but no more if the relative CO abundance is limited to $[CO]/[H_2] \lesssim 5\text{x}10^{-4}$. Alternatively, one could uniformly clump the molecular gas, but these clumps would be rather different from ordinary galactic molecular clouds which at their most copious have an intercloud spacing of order 1 kpc (Burton and Gordon 1978). Unless the clump separation were much less than even 200 pc, velocity projection effects would not be able to concentrate molecular emission in the ridges that are observed.

As discussed by Liszt and Burton (1978), a consistent clumped model could perhaps lower the mass of gas in the disk to $\sim 10^9$ $M_\odot$. Within 1 kpc of the disk axis, such a model would contain $\sim 4\%$ of the total (stellar) mass derived by Oort (1977) from analysis of the nuclear disk in terms of pure rotation. The inner Galaxy gas is, however, unique in the extent to which the molecular component dominates the atomic gas. Because the HI profiles are well modelled by an optically thin gas (Burton and Liszt 1978), the mass in atomic hydrogen probably does not exceed $\sim 10^7$ $M_\odot$, or 1% of the total gaseous mass.

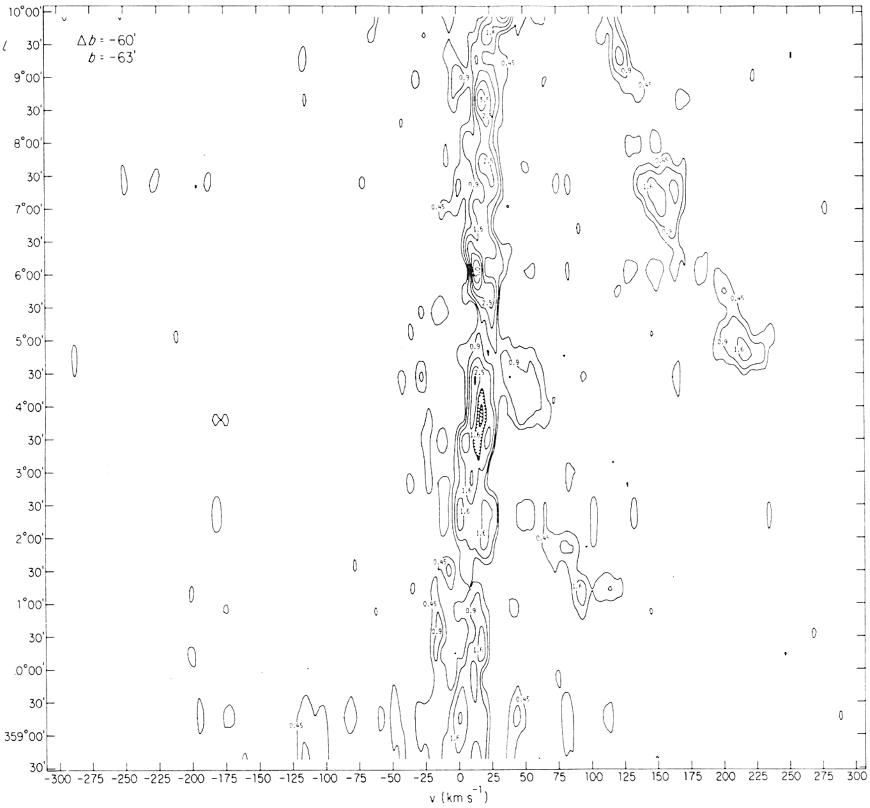

Fig. 5a. The longitude-velocity arrangement of $\lambda 2.6$ mm CO emission at $\ell = -63'$ taken with a 1' beam at 20' intervals.

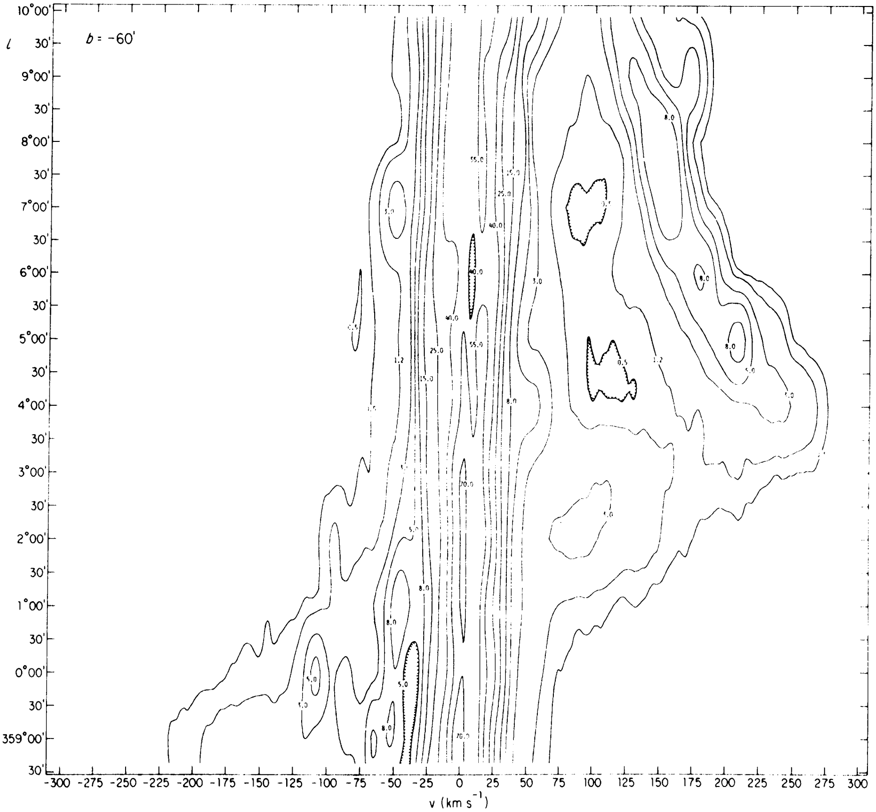

Fig. 5b. The longitude-velocity arrangement of λ21 cm HI emission taken with a 21' beam at 1° intervals. Intensities are expressed in terms of antenna temperature corrected only for losses.

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