ATOMIC AND MOLECULAR GAS IN THE INNER REGIONS OF THE MILKY WAY AND OTHER GALAXIES

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INTRODUCTION

It seems likely that we inhabit a galactic system which in its gross characteristics exemplifies the present meaning of the word "normal". The general framework for interpreting the distribution and kinematics of the observed gas consists of a well-defined rotation curve, applicable over the great majority of a thin, nearly flat disk; the stars and gas within this disk are generally quite cold, having little energy in random as opposed to well-ordered motions. In fact, neutral gas in the galactic disk is sufficiently regular in its structure that no grand pattern of spiral arms stands out in sharp relief.

As one moves inward in the Galaxy from the location of the Sun, this regularity persists to within about 4 kpc of the center, at which distance the abundance of gas in either atomic or molecular form drops fairly abruptly. Inside this region, the character of the gas distribution undergoes a marked change and the behaviour observed there, while it may be common to even the best-ordered systems, represents a rather spectacular departure from the organization at larger galactocentric radii. As the gas abundance increases once more toward the galactic center it is seen to reside in a multitude of individual features having disparate spatial and kinematic properties. Many of these have large and/or obvious components of non-circular motion, usually taken as indicating expulsion of matter from the galactic center region at both large and small angles with respect to the rotation axis of the galaxy at large. Others, while occurring at velocities whose sign is consistent with rotation motion alone, have contradictory changes in velocity with position. Line profiles taken in the inner regions of the Galaxy are generally decomposed according to catalogs of classifiable features but no generally accepted interpretative framework exists as a means of relating the wide variety of observable phenomena.

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Our characterization of the gas in galactic nuclei is relatively primitive. It has only recently been recognized that the gas component in galactic nuclei may be dominated by material in molecular rather than atomic form; yet, the sensitivity and spatial resolution of current molecular observations are relatively low. Even in our own Galaxy the full range of observable phenomena is still in the process of elaboration, with many surprising results. In the text below we review first the rather limited group of observations of carbon monoxide in the inner regions of other galaxies. This is meant to serve as an introduction to the more complex situation seen locally and to provide a gross standard for judging the extent to which our own system may be considered typical. Relatively recent observations of HI and molecular gas in the galactic center region are then dealt with at greater length, in an effort to describe the most general organization of the gaseous material there.

MOLECULAR GAS IN THE NUCLEI OF OTHER GALAXIES: OBSERVATIONS OF CO

At the present time it is estimated that the nuclei of some 150-200 external galaxies have been examined for ^{12}CO emission, with spatial resolution 1-2 arcminutes. Of these, only 9 have detectable emission. They are M51, M82, NGC 253, NGC 1068 (Rickard et al. 1977), M83 (ibid; Combes et al. 1978), IC 342, NGC 6949 (Morris and Lo 1977), Maffei 2 (Rickard, Turner, and Palmer 1977), and NGC 3628 (Rickard and Palmer 1979). Encrenaz et al. 1979 have detected ^{13}CO in the nuclei of M51, NGC 253, IC 342, and M83, and in the disk of M31. Carbon monoxide has been reported in the outer portions of the LMC (Huggins et al. 1975) and M81 (Combes et al. 1977).

Because ^{12}CO emission is usually optically thick in molecular clouds, and because carbon monoxide is not well described as a two-level system, the inferred surface densities of molecular material depend strongly upon the conditions which are assumed to exist in the emitting region; conversely, the true sensitivity of such molecular observations is difficult to guage. Uncertainty in the abundance of carbon monoxide relative to hydrogen is an added burden, and inference of the molecular surface density from ^{13}CO observations may require as well an estimate of the isotopic abundance ratio, which again is only imperfectly known more locally. While one does not explicitly require any knowledge of beam dilution factors to calculate the beam-averaged column densities of optically thin ^{13}CO in one of the two lower rotational levels, moving to the total population requires knowledge of the rotational excitation temperature. Assuming a value for this quantity is equivalent to assuming a beam-filling factor; if ^{12}CO is optically thick in the emitting regions, its filling factor at any velocity within a broad nuclear line profile is the ratio of the observed and intrinsic brightnesses. On the other hand, comparison of the two isotopic species yields independent information on the beam-filling factors and the conditions in the emitting clouds, particularly in face-on geometries or in the discs of galaxies where velocity gradients across the telescope beam are smaller. Once the carbon monoxide excitation temperature has been assumed, the ^{13}CO optical depth derived from the isotopic intensity ratio gives the intrinsic ^{13}CO cloud brightness. Comparison with the observed line intensity yields another estimate of the beam-filling factor and provides a consistency check on the analysis.

The molecular surface densities derived for the nuclear regions of other galaxies lie in the range 25-100 $M_\odot$ pc^{-2}; for these regions temperatures 30 K and abundance ratios $^{12}CO/^{13}CO = 40$, $^{12}CO/H_2 = 5x10^{-5}$, typical of bright galactic clouds (Leung and Liszt 1976) are taken. For a nearly face-on system like M51, the inferred surface density is about 50 $M_\odot$ pc^{-2} and the observed emission is of order 125 km s^{-1} wide. For a more nearly edge-on system like NGC 253, the line may be twice as broad but similar surface densities are derived after a non-trivial correction to face-on conditions is applied (Rickard _et al_. 1977). The largest molecular surface densities and total masses are derived in NGC 1068. Even with a 6 kpc beam, extending well beyond the H-alpha image shown by Rickard _et al_. (1977), the line is quite strong. Using the parameters given above, the mass in molecular form approaches 50% of the _total_ mass of the system. NGC 1068 is clearly exceptional among the galaxies so far detected and observations with higher spatial resolution are indicated.

With a molecular surface density 50 $M_\odot$ pc^{-2}, the molecular mass within 1 kpc of the center is $2x10^8$ $M_\odot$; for a perpendicular dispersion of 100 pc the average number density of molecules is 4 cm^{-3}. Such densities are found in the _disk_ of the Milky Way (Burton and Gordon 1978, Solomon and Sanders 1979) while the abundance of molecular gas is known to be larger in the nucleus (see below). However, the inferred molecular surface densities are, in general, sufficiently large to compensate for the central minima often encountered in atomic hydrogen (van der Kruit and Allen 1978) and the total amount of gas present increases toward the nucleus. The ratio of molecular to atomic gas surface density decreases , often quite sharply, as one moves away from the nucleus (where only a few percent of the gas may be atomic). The carbon monoxide integrated intensity falls by factors 3-10 at distances 5-6 kpc from the centers of the observed galaxies (Rickard, Turner, and Palmer 1977, Combes _et al_. 1978) while the column density of HI usually grows. In the disk of our galaxy the ratio of molecular to atomic surface densities is 6-15 some 6 kpc from the center where the HI number density is 0.3 cm^{-3} (Burton and Gordon 1978). In M31, which has a very strongly depressed central gas abundance, HI is present in the disk at levels of 20 $M_\odot$ pc^{-2} or more (Emerson 1976) and the measurement of Encrenaz _et al_. (1979) implies that somewhat less than half the gas is molecular in form. The contrast between the H_2/HI ratios observed in the nuclei and disks of other galaxies is quite high; as seen below this is true locally also.

The kinematics of molecular gas in other galactic nuclei are not well studied with the available spatial resolution of 1-2 kpc at a distance 3 Mpc. Rickard _et al_. (1977) fit models with a 50 km s^{-1} expansion component to the observations of M51 and M82, but these are much smaller than the non-circular velocities which can be observed in the core of our galaxy. The systems in which the full velocity extent of the observed emission most nearly approaches that seen more locally are those viewed most nearly edge-on, M82, NGC 1068, and NGC 253; their widths, 300-375 km s^{-1}, may be compared with the 500 km s^{-1} extent of the HI or molecular gas observed in the inner 3 kpc of the Milky Way (see the discussion and references below). There is an excellent correlation between the full velocity extent of the nuclear carbon monoxide emission and the inclination of the system from which it arises (see Rickard et al. 1977). For the nuclei listed above, regression analysis implies full widths for face-on and edge-on conditions of 60 km s^{-1} and 360 km s^{-1}, respectively, leading to a nominal dispersion in the emitting gas of order 15-20 km s^{-1}. In the nucleus of our galaxy, the distributed HI and carbon monoxide have a dispersion $\sim$10 km s^{-1} (Burton and Liszt 1978), while the line widths seen in bright molecular complexes around Sgr A and Sgr B are 50-100 km s^{-1} (Liszt et al. 1975, Scoville, Solomon and Penzias 1975). These large widths are atypical and may in any case arise because of strong velocity gradients in the galactic center region; the linewidths seen in other galaxies must be determined by ordered rather than random motions.

THE DISTRIBUTION AND KINEMATICS OF NEUTRAL GAS OBSERVED AT RADIOFREQUENCIES IN THE CORE OF OUR GALAXY

MOLECULAR OBSERVATIONS

The salient feature of the inner-galaxy molecular gas is the obvious impossibility of an explanation, similar to that invoked originally for HI, in which non-circular motions are viewed as weak perturbations of a purely rotating system. Beginning with the first examinations of this region, our attention has focussed almost entirely upon the highly visible non-circular motions.

The earliest observations of molecular gas in the nucleus were in the absorption spectra of OH (Robinson and McGee 1970, McGee 1970) and H_2CO (Gardner and Whiteoak 1970, Scoville, Solomon, and Thaddeus 1972, Scoville and Solomon 1973); these results, along with those obtained in carbon monoxide by Solomon et al. (1972) are discussed at length by Robinson (1974). Dominated by gas situated between the Sun and the nuclear continuum sources, the absorption spectra revealed a prominent feature at $v \sim -135$ km s^{-1} (relative to the Local Standard of Rest) around $\ell = 0°$, with peak optical depths at $b \sim -0.2°$. The motions within this feature were interpreted by Scoville (1972) and by Kaifu, Kato, and Iguchi (1972) as arising from an "expanding molecular ring" of radius $\sim$250 pc, rotation velocity $\sim$50 km s^{-1}, and expansion velocity $\sim$150 km s^{-1}; the mass inferred for this relatively small body, 10^8 $M_\odot$, exceeds that of all the HI within 2 kpc of the galactic center. Although the absorption measurements were not expected to reveal the back side of this body with equal prominence, carbon monoxide emission spectra also did not show it clearly. However, Scoville, Solomon and Jefferts (1974), who made the first substantial maps of ^{12}CO in the inner galaxy, and Sanders and Wrixon (1974a), detected in carbon monoxide a feature at +165 km s^{-1} toward the galactic center. This was subsequently considered by Bania (1977) and by Oort (1977) as arising from the back side of the body producing the original ring feature. Alternatively, Scoville et al. (1974) proposed a two-armed spiral to account for several of the inner-galaxy properties.

The absorption-line data have been studied more recently by Cohen and Few (1976) and by Whiteoak and Gardner (1979) in OH and H_2CO; the ^{12}CO emission line has been investigated by Liszt et al. (1977), by Bania (1977), and by Liszt and Burton (1978). The OH spectra continue to show little evidence for gas at high positive velocities whereas the anti-maser in H_2CO renders the back side of the gas distribution at least partly visible. Cohen and Few (1976) noted that a small model incorporating elliptical streaming and no net outflow might produce a feature similar to the original expanding ring. As Peters (1975) had constructed such a model to account for the 3-kpc arm and "135 km s^{-1} expanding arm" features also observed at low galactic latitudes, they considered the possibility that the expanding molecular ring might be a manifestation of larger-scale phenomena.

The full extent of the molecular gas distribution is most clearly revealed in emission line observations of carbon monoxide. The general observational situation in the innermost regions is shown in Figures 1 and 2, position-velocity diagrams made parallel and perpendicular to the galactic equator through the position of Sgr A (West) (Liszt and Burton 1978). One difficulty for most of the previously proposed models of the expanding features is evident in that the assumed front and back portions of the gas distributions are not contiguously distributed. The positive velocity portion extends between $-0.85° \lesssim \ell \lesssim 2.3°$, or more than 400 pc from the center. Figure 2 shows, however, that the displacement of the original ring feature to slightly negative latitudes is mirrored in the positive velocity gas, and that the tilt inferred from the original observations persists from front to back. A second general property of the expanding molecular features is traced in the maps of Liszt and Burton (1978). At negative longitudes, the emission occurs predominantly above $b \sim 0°$, and at positive longitudes, below. This latter property was recognized by Kerr (1967) as common to (1) the disposition of 20-cm continuum radiation observed near Sgr A; (2) the disposition of permitted-velocity HI at longitudes removed 7°-12° from the galactic center; (3) the disposition of many HI "packets" observed at high galactic latitudes $|b| \gtrsim 1.5°$ to have large, non-circular motions and therefore presumed to have been ejected from the galactic nucleus. That this situation occurs in the molecular gas as well indicates that its distribution is not necessarily anomalous. Below we show that the tilt in Figure 2 is observable in HI; a coherent and unified description of both the atomic and molecular gas components may be possible if the unusual inner-galaxy geometry is explicitly considered.

The most intense emission in Figure 2 arises from gas at velocities permitted by pure rotation, extending from $(v,\ell) \sim -200$ km s^{-1}, $-1.5°$ to -100 km s^{-1}, $-0.5°$; 0 km s^{-1}, $-0.15°$; 90 km s^{-1}, 0.5°. Beyond +0.5° from the galactic center the velocity no longer increases. For $\ell \lesssim 0.5°$ the properties of this emission are consistent with a ring

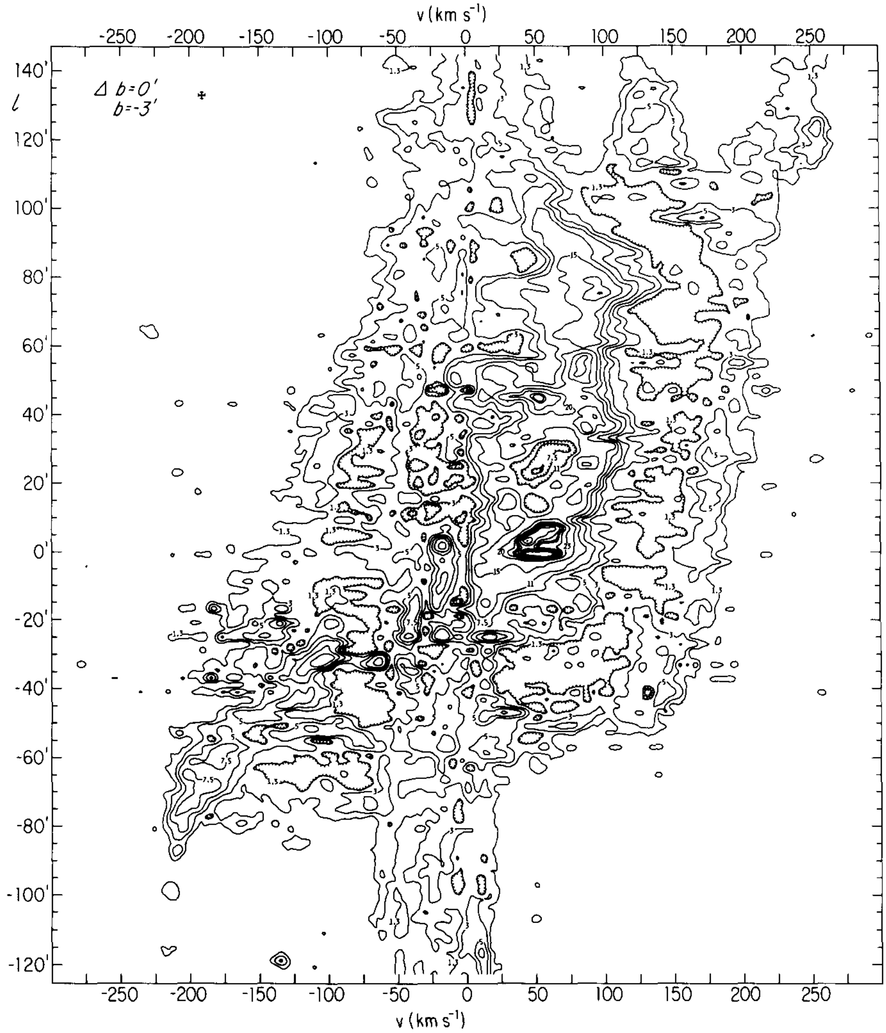

FIGURE 1: Longitude-velocity arrangement of ^{12}CO emission at b = -3' (from Liszt and Burton 1978).

of material in pure rotation at a distance ≲ 200 pc from the galactic center (Liszt et al. 1977). This emission is the true molecular counterpart of the well-known HI nuclear disk of Rougour and Oort (1960) and displays some of its less-understood properties. The HI nuclear disk also does not attain high positive velocities and exists as an observable feature only at negative longitudes. One possible connection of the intense molecular emission with the systematics of the "expanding" gas is pointed out by Liszt and Burton (1978): the Sgr B cloud is identically distributed in galactic latitude with the high positive velocity gas seen in its direction. The properties of this intense emission remains to be more completely studied observationally. Although many of the larger scale features of the nuclear gas distribu-

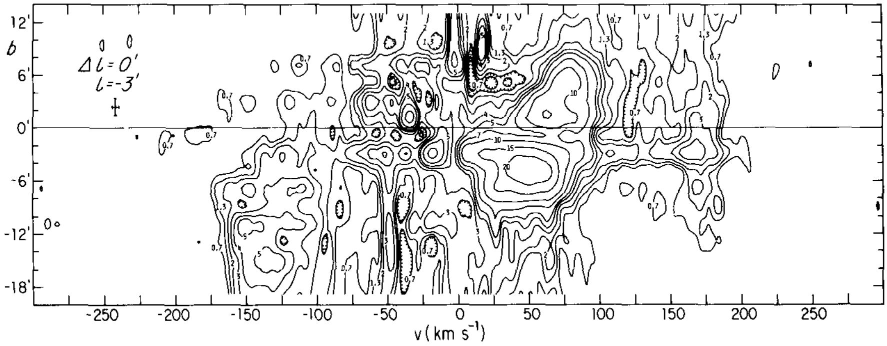

FIGURE 2: Latitude-velocity arrangement of ^{12}CO emission at ℓ = -3' (from Liszt and Burton 1978).

tion can be coherently accounted for in the work described below, this intense permitted-velocity molecular emission has not been satisfactorily interpreted.

OBSERVATIONS OF HI

The properties of HI in the galactic nucleus have been reviewed often and, in this context, the reader is referred to van der Kruit (1970) or Cohen (1975) for detailed description of the many features which may be discussed; to Kerr (1967), Sanders and Wrixon (1974b), Simonson (1974), and Oort (1977) for exposition of various models or general morphological characteristics; to Simonson (1974), Burton and Liszt (1978) and Sinha (1979) for catalogs of available HI surveys. The papers of Rougoor (1964) and of Rougoor and Oort (1960), in which this gas distribution was first mapped, remain a stimulating introduction to the observational complexities encountered in this region. The discussion here is an attempt at synthesis of the most general properties of the inner galaxy gas. It is based on recognition of the non-coplanar geometry of this region and of the presence of a pervasive field of non-circular velocities there. Both are fairly radical conceptions for such a "normal" galaxy as our own. While controversial, they yield a powerful and coherent description of the overall morphology and kinematics.

The connection between the geometries of the outward-moving molecular gas and that of several other emission components was outlined above. The molecular emission, with its prominent non-circular velocities, most clearly shows the tilt of the inner-galaxy axis toward the Sun (Figure 2); in HI a tilt orthogonal to this is more easily demonstrated and was therefore noticed earlier. In Figure 3 we show two maps of HI intensity integrated over the highest velocities observed in the galactic center (these maps are taken from Liszt and Burton 1979 but both Cohen and Davies 1979 and Sinha 1979 present nearly identical data). All such emission is consistent with pure rotation in its sign, but the contours depart markedly from the galactic equator. The better-defined symmetry axis in the lower panel is the line $b = -\ell \tan \alpha$, where $\alpha \sim 22°$; this value is found by

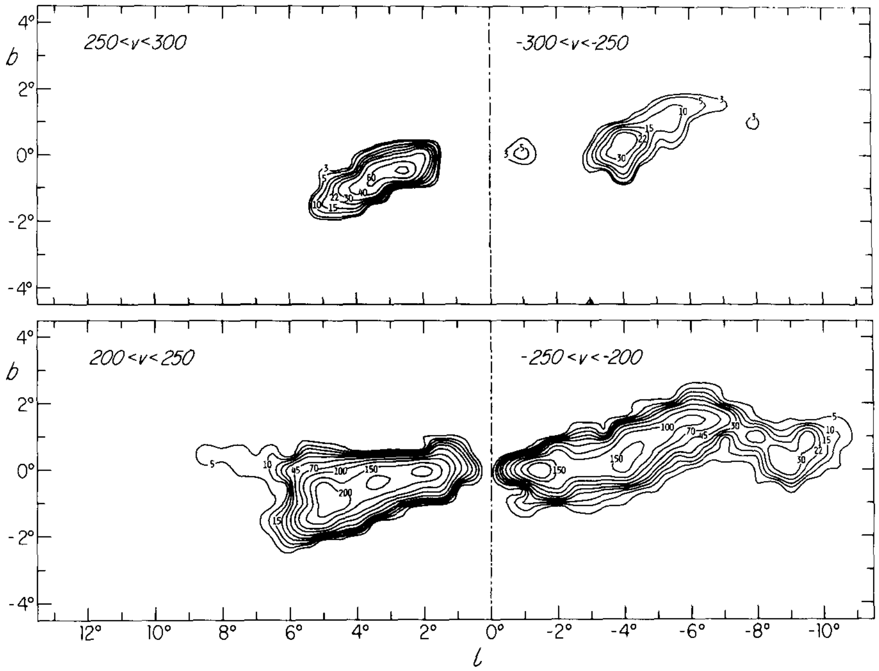

FIGURE 3: Spatial maps of HI intensity integrated over several velocity intervals. All such emission is "permitted" by pure rotation but notice the marked coherent departures from the galactic equator (Liszt and Burton 1979).

Burton and Liszt (1978), Sinha (1979), and Liszt and Burton (1979), but Cohen and Davies (1979) quote a lower value 4°. That the observed emission lies above and below this axis, rather than along it, indicates both the substantial contribution of noncircular motions to these "permitted" velocities and of the tilt suggested in Figure 2. This inclined locus has the additional virtue that the kinematics observed along it (Burton and Liszt 1978, Sinha 1979, Liszt and Burton 1979) display symmetries whose absence in the galactic equator are troubling; these asymmetries include the lack of a positive-longitude and velocity nuclear disk feature (see Sanders, Wrixon, and Mebold 1977). This inclined locus is the true spatial and kinematic symmetry axis of the inner galaxy HI distribution.

The distribution of the negative velocity gas in the range -300 km s^{-1} $\le$ v $\le$ -100 km s^{-1} is shown in Figure 4. It crosses the plane ℓ = 0° smoothly, at negative latitudes, and is essentially bounded above by the symmetry axis of the general distribution. This emission, which cannot arise from a purely rotating gas at positive longitudes, is clearly tilted in the same manner and to the same degree as that at the highest "permitted" velocities. Such similarities enhance the validity of a general decomposition of the observed velocities into circular and non-circular components.

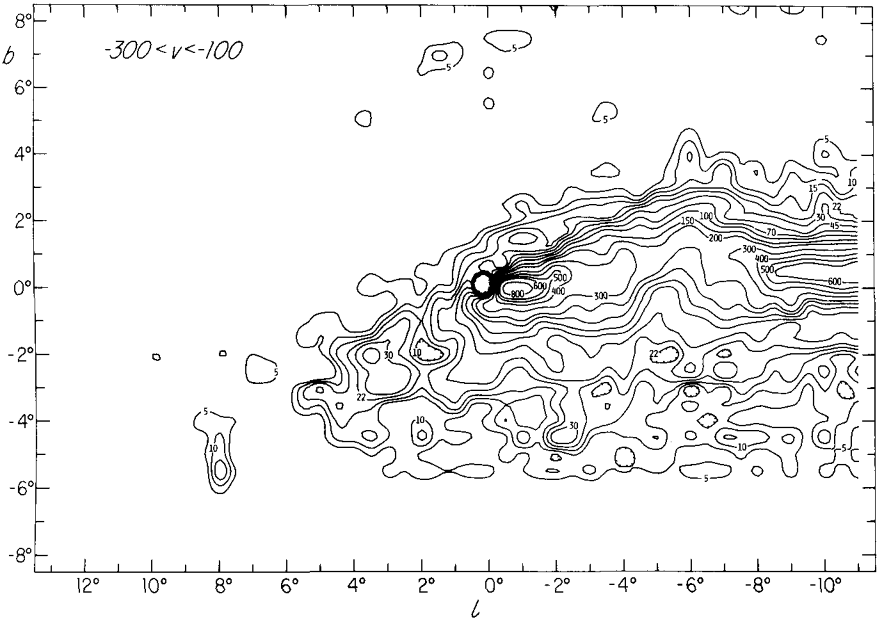

FIGURE 4: A spatial map of HI intensity integrated over velocities less than -100 km s^{-1}. The gas sampled here is clearly tilted with respect to the galactic equator and lies below the symmetry axis of the gas distribution in Figure 3 (Liszt and Burton 1979).

Models of the inner-galaxy gas incorporating both the observed tilts and ubiquitous non-circular motions may take a variety of forms, exposition of which is only now beginning. The simplest kinematic decomposition, involving superposed rotation and expansion within a thin, tilted circular disk was explored in great detail by Burton and Liszt (1978). Their model, inclined a total of 25° to the rotation axis of the outer galactic regions, was characterized by slowly varying expansion and rotation velocities of comparable magnitude $\sim$175 km s^{-1}, a radius of 1.5 kpc and perpendicular dispersion 100 pc, and otherwise uniform density. When computer-generated line profiles from this model are presented in the usual observation format, a remarkably diverse assortment of behaviour is seen to result. As discussed by Burton and Liszt (1978), this relatively simple model can account *in detail* for essentially all of the HI ejecta observed at high latitudes, and for the presence of a nuclear disk-like feature in intensity maps shown here. It accounts for the presence of the molecular expanding features and for their partially-overlapping spatial disposition about $\ell \sim 0°$ (Liszt and Burton 1978) as the consequences of velocity and spatial projection effects in an optically thick gas, without requiring material condensations to produce spectral features. Approximately a dozen individually described "features" and many general trends are found in a model of essentially constant density. Although quite clearly and awkwardly lacking a dynamical foundation (what theoretical basis exists at all at this moment for consideration of such a large-scale but inclined feature?) this kinematic model is useful as a descriptive guide to a wide range of observable phenomena.

It has of course been pointed out fairly often that one need not have an actual net outward flow of material to produce perceived expansion velocities; recent examples of such models are the elliptical streamline (bar-like?) models of Peters (1975) and the dispersion rings of Simonson and Mader (1973) or Bania (1977), all of which were constructed to account for the 3-kpc arm and "135 km s^{-1} expanding arm" features which occur at low galactic latitudes. Sinha (1979) mentions the possibility of invoking a triaxial central system such as is described in a separate contribution by Schwarzschild. Cohen and Davies (1979) sketch an association of arm and arc-like features elongated in the direction of a possible central bar and Kerr (1967) also sketched a central bar connecting two centrally located spiral arms. The detailed kinematic consequences of a central tilted distribution based on elliptical streaming in a thin disk were examined by Liszt and Burton (1979), who demonstrated that such models are at least equivalent to their expanding disk in descriptive ability.

Bar-like configurations are probably the preferable model at the present time for they are known to exist in the centers of galaxies and may obviate the need for a large flux of mass out of the central regions of our own galactic system. Invocation of a triaxial system to account for the central tilted distribution is somewhat paradoxial, as these have been proposed to account for the isophotal twists seen in other galaxies without requiring actual tilts in the mass distribution (Stark 1977). The extent to which bars and triaxial configurations may be related, or to which bars may be three rather than two-dimensional, has not been discussed theoretically. At the present time the dynamics of untilted bar-like configurations are sufficiently uncertain that it is not possible to constrain kinematic models of them too significantly. Rather, the axial ratios and other parameters of descriptive models, to the extent that they may be separately inferred (Liszt and Burton 1979), may provide basic information for the construction of satisfactory dynamical models. As discussed by Liszt and Burton (1979) the total tilt of the inner galaxy gas is probably the best determined of all parameters at 23°-25°, and it also appears to be required of streaming models that the flow becomes more circular nearer the center. The necessity to preserve a coherent inclined structure over as much as 3-4 kpc of the inner galaxy will undoubtedly place significant constraints on the total mass distribution.

Estimates of the total gaseous mass in the galactic center region are not strongly dependent on the tilted geometry or kinematic decomposition of perceived velocities, particularly for the optically thin HI. For the atomic gas constituent, masses $\sim 2\times10^7$ $M_\odot$ are obtained, and even the largest mass flux out of the central region would be ~ 3 $M_\odot$ yr^{-1} (Oort 1977, Burton and Liszt 1978). For the molecular gas, estimates are much larger, ranging previously from 10^8 $M_\odot$ for the molecular ring alone, to 5×10^8 $M_\odot$ in the inner 1.5

kpc at relatively low latitudes (Bania 1977); larger values were quoted by Liszt and Burton (1978) as the result of a more widespread inferred distribution. They argued that velocity projection effects determined the observability of carbon monoxide and showed that the HI and molecular distributions are coincident within the sensitivity limits imposed by currently available mm-wave receivers. If this is the case, the minimum average space density of hydrogen molecules necessary to account for the observed molecular intensities, 100 cm^{-3}, leads to masses $\sim 5x10^9$ $M_\odot$ within 2 kpc of the galactic center. This mass might be brought down somewhat by assuming a large carbon monoxide abundance relative to hydrogen, but such a procedure would not alter the disparity with the extragalactic observations if applied uniformly. The surface density of hydrogen molecules in our own Galaxy appears to be much larger than observed elsewhere, with the possible and very tentative exception of NGC 1068 as discussed above. We note, however, that our galactic nucleus appears to be rich in HI and that the ratio of molecular to atomic gas densities is quite large in other nuclei. If the larger mass quoted above were spread uniformly over the inner 8 kpc of the Galaxy (to fill the hole which presently is thought to exist there), the gas surface density would be only slightly above the value presently observed at slightly larger galactocentric radii.

NON-COPLANAR PHENOMENA OBSERVED IN THE INNER GALAXY

Although the tilt discussed above is large and very widespread, it is but one of many out-of-plane phenomena in the inner regions. The "135 km s^{-1} expanding arm" is located some 150 pc or more above the galactic equator over 18° of longitude (see the discussion of Peters 1975). The 3-kpc arm is corrugated (Kerr 1970); over the inner 15° of longitude its centroid moves smoothly from a location above the galactic equator at $\ell \sim -12°$ to one below at $\ell = \sim +5°$. As cited above, the centroid of HI emission observed near the terminal velocity lies slightly above b = 0° at $\ell = -12°$ and below at $\ell = 7°$, indicating a tilt of order 5°. Lastly, the kinematic axis of the NeII distribution described in this Joint Discussion by Lacy makes a very large angle, 60°, with the rotation axis of the outer regions. In the galactic nucleus it is co-planarity, rather than misalignment, which is rare. As it presently appears to be constituted, the inner galaxy is a superposition of several non-aligned dynamical subsystems. Their differing orientations, their interaction and interrelation to each other and their effect on the galactic disk remain to be explored.

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