MOTIONS AND DEFORMATIONS OF THE INNER-GALAXY NEUTRAL GAS LAYER

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Abstract.
Neutral gas in the inner few kpc of the Milky Way is notable for showing strong non-circular motions, large excursions from the nominal galactic plane, and an overwhelming preponderance of molecular (rather than atomic) neutral gas. Here, we discuss the coherent nature of the kpc-scale tilts seen in H I and CO emission and demonstrate the congruence of the inner-Galaxy atomic and molecular gas distributions, out more than 1 kpc in radius and 300 pc vertically from the center. We point out that features in inner-Galaxy spectra can usually not be identified with discrete, underlying material entities, but instead arise solely as the result of kinematic projection effects.

1. Introduction

In 1977, Jan Oort published a long review ('The Galactic Center'), mostly concerned with interpretation of atomic and molecular gas in the inner few kpc of the Galaxy. At that time, the first H I maps were twenty years old and molecular (OH) absorption profiles had been known for more than 10. An important result of this interpretational effort, presented in Table 1 on

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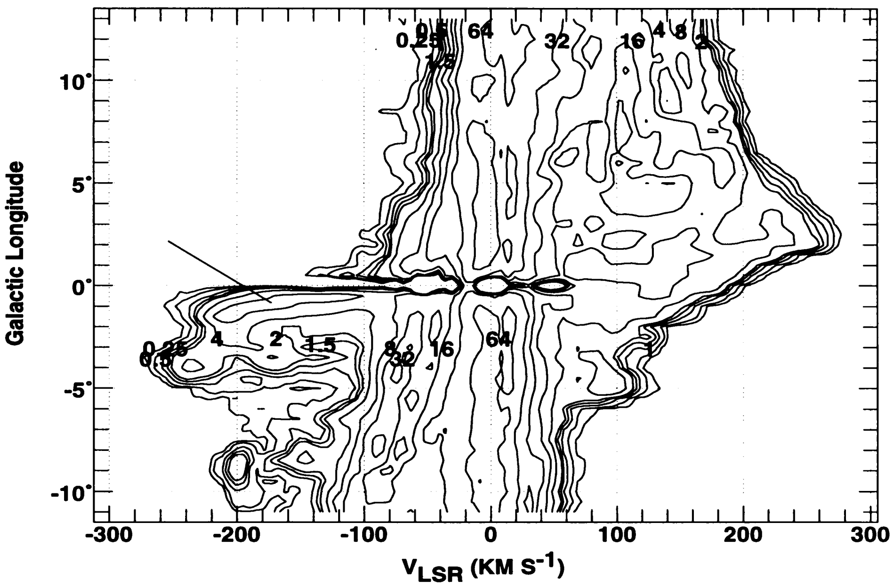

Figure 1. H I emission at b = 0° from the 21′-resolution, 0.5°-spacing survey observations of Burton and Liszt (1983). The nuclear disk of Rougoor and Oort (1960) is marked by a line.

the first page of the article, was derivation of the galactic rotation curve and mass distribution at galactocentric radii 50 pc $\leq$ R $\leq$ 1000 pc from H I data, continued inward using the $\lambda 2\mu$ intensity distribution of Becklin and Neugebauer (1968).

In Oort's summary, there are sharply-etched distinctions between H I gas seen in and out of the galactic plane and between gas seen at so-called 'permitted' and 'forbidden' velocities (*i.e.* consistent or inconsistent with direct circular motion about the center). The gas seen out of the plane was not just the expected plane-parallel stratified continuation of lower-latitude material, but was often remarked to have large (> 100 km s^{-1}) forbidden velocities directed away from the nucleus. This out-of-plane gas had a preferred axis such that it appeared in the two opposed quadrants with b < 0°, l > 0° and b > 0°, l < 0°, and at b < 0° (b > 0°) on the near (far) side of the center (van der Kruit 1970, Cohen and Davies 1976). The preferred explanation for this material, which in the aggregate is quite massive, was ejection from the nucleus as in classical radio galaxies. The gravitational potential of the inner galactic regions could not possibly have been as tipped as the apparent pole of the ejected gas.

In the galactic plane, a welter of features rendered generalization difficult but one feature at permitted velocities and negative longitudes was

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singled out for special attention. The 'rotating nuclear disk' of Rougoor and Oort (1960), shown in Figure 1, was the source of the all-important gravitational potential in Oort's Table 1. There clearly is much gas at $b = 0°$ which does not accord with simple rotation, for which various dynamical interpretations might be invoked (ejection, spiral arms, a bar, resonance orbits to name a few); the rotating nuclear disk is *invisible* at $l > 0°$. Nonetheless, Oort (and many others) felt that the appearance of a feature having behaviour consistent with pure rotation provided one case where a simple interpretation was both fully justified and amply rewarded.

If we associate the permitted terminal-velocity edge of the H I emission with the circular rotation speed at each projected sub-central point, which is the usual manner of derivation in the disk of the Milky Way, a peculiarly-shaped rotation curve results (Figure 2). The inner peak requires a separate, concentrated mass component or other contrivance but is easily accounted for if the potential is strongly non-circular (*i.e.* barred, see Gerhard and Vietri 1986). In fact the usual assumptions for deriving the rotation curve from the terminal velocity are *not* met in the central region and the appearance of the rotating nuclear disk feature is heavily modulated by absorption against the Sagittarius radiocontinum source complex (Burton and Liszt 1993). Roughly speaking, the difference in Figure 2 between the odd galactic rotation curve and the $R^{0.1}$ behaviour is probably ascribable to non-circular motion out to at least $R = 2$ kpc. The H I terminal velocity may be determined by equilibrium gravitational forces, but the motions are non-circular nonetheless.

So studies of the atomic and molecular neutral gas have provided early and continuing indications that the Galaxy is barred, as discussed at length elsewhere in this volume and dating to the earliest attempts to understand such features as the 3-kpc arm *cf.* Peters (1975). However, the makeup of the bar is uncertain (where is co-rotation? where does the bar point?) and attempts to reproduce observed velocity patterns in the Galaxy, even with barred potentials, have generally shown that success in the disk precludes agreement in the center and *vice-versa* (see Mulder and Liem 1986 and Burton and Liszt 1993).

The present discussion concerns some of the clearest and yet most puzzling aspects of the inner-Galaxy neutral gas distribution. The distribution is strongly inclined with respect to the galactic plane, so that the tilts seen earlier and ascribed to the ejected H I are a general feature of all the gas, both atomic and molecular, over the entire central region. The inner-Galaxy is filled with both H I and CO, but the distribution is *extraordinarily* molecular in nature, with the CO and H I emission patterns coinciding in space, velocity, and *intensity* over the inner 20° of longitude: less than 1% of the gas is atomic.

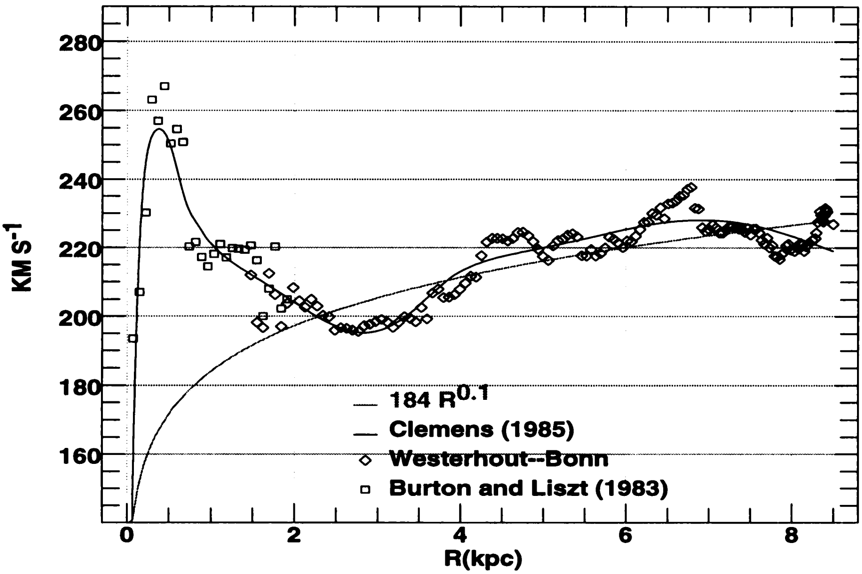

Figure 2. The Galactic rotation curve of Clemens (1985), superposed on H I terminal velocities as noted. The gray curve represents the circular velocity corresponding to a galactic density distribution which varies as $R^{-1.8}$ (see Burton and Liszt 1993).

In Section 2 of this work, we show how the tilt of the forbidden-velocity ejected H I gas came to be seen as a general property of inner-Galaxy gas, how recognition of this tilt leads to the introduction of non-circular motion into the kinematics of the low-latitude permitted-velocity features (including the rotating nuclear disk), and how the permitted and forbidden-velocity H I emission can be unified into a large-scale, coherent, pattern. As satisfying as this demonstration of consistency may be, it begs the question of why such an unusual distribution persists in the center.

In Section 3, we show that the large-scale CO and H I distributions are identical, with the inner-Galaxy filled by both gases out to (at least) 1 kpc from the nucleus and 300 pc from the galactic equator. We discuss the *apparent* differences between the atomic and molecular gases (see Oort's Figure 22, due to Bolton, meant to highlight these differences) and the origin of a chimerical feature known as the 'expanding molecular ring'.

2. The Tilted Inner-Galaxy H I layer

Oort's discussion included Figure 15 due to Kerr (1968) which was recreated later to great effect by Burton and Liszt (1978), Sinha (1978), and Liszt and Burton (1980). If we follow the terminal-velocity H I ridge–the gas from

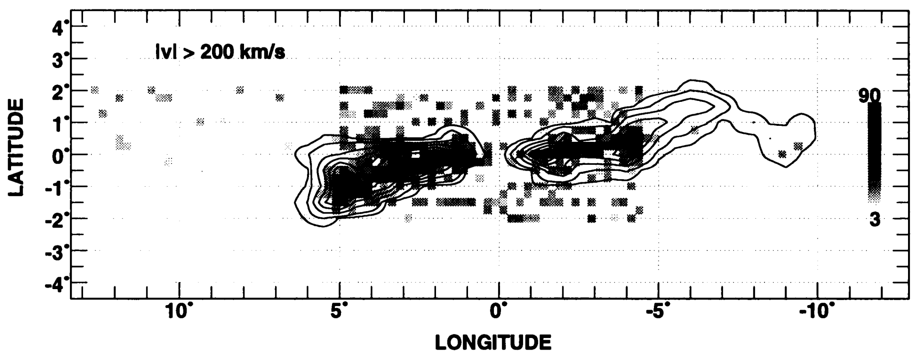

Figure 3. Contours of integrated, permitted-velocity H I emission seen at $|v| > 200$ $km\,s^{-1}$ (levels are 20, 40, 80 ... K $km\,s^{-1}$), with a superposed gray-scale of the analogous CO emission from the survey of Bitran (1986).

which the circular velocity was supposedly derivable–something like our Figure 3 results. But Figure 3 shows precisely the out-of-plane behaviour and orientation ascribed to the isolated and supposed ejected H I features, with several immediate implications. The low-latitude permitted-velocity gas is neither purely rotating nor aligned with the larger galactic disk; the high-latitude forbidden velocity gas has more in common with the 'normal' emission than can be accomodated by the ejection hypothesis.

The disposition of the H I is shown in Figure 4 as a series of latitude-velocity cuts across the H I survey of Burton and Liszt (1983). For a galacto-centric distance of 8.5 kpc, 1° corresponds to 150 pc, so that the outermost of these diagrams, at $|l| = 7°$, come no closer than 1 kpc to the nucleus. In the oral presentation it was easier to 'walk' the audience across several aspects of the distribution. Here only a self-guided tour can be suggested.

2.1. THE SELF-GUIDED TOUR OF FIGURE 4

To begin, follow the permitted terminal-velocity ridge from $l = 7°$, b = -1°, v = 160 $km\,s^{-1}$ inward toward $l = 0°$, noting two things: the velocity increases toward the center, at least into $l = 3°$, while the mean latitude moves closer to 0°. At $l = 0°$, pretend that the gas is purely rotating and cross over to $l = -1°$, v = -200 $km\,s^{-1}$. Continue to follow the outer negative-velocity gas as it moves out in velocity and up in latitude to $l = -7°$, b = 1°. The gas is noticeably weaker at $l < 0°$. The slope indicated by this behaviour is perhaps 1/7, for a tilt of 8°, but see below; the tilt cannot be derived with recourse to the permitted velocity gas alone.

Next, proceed as before to follow the positive-velocity gas inward and upward from $l = 7°$, but do not cross over to negative velocity at the

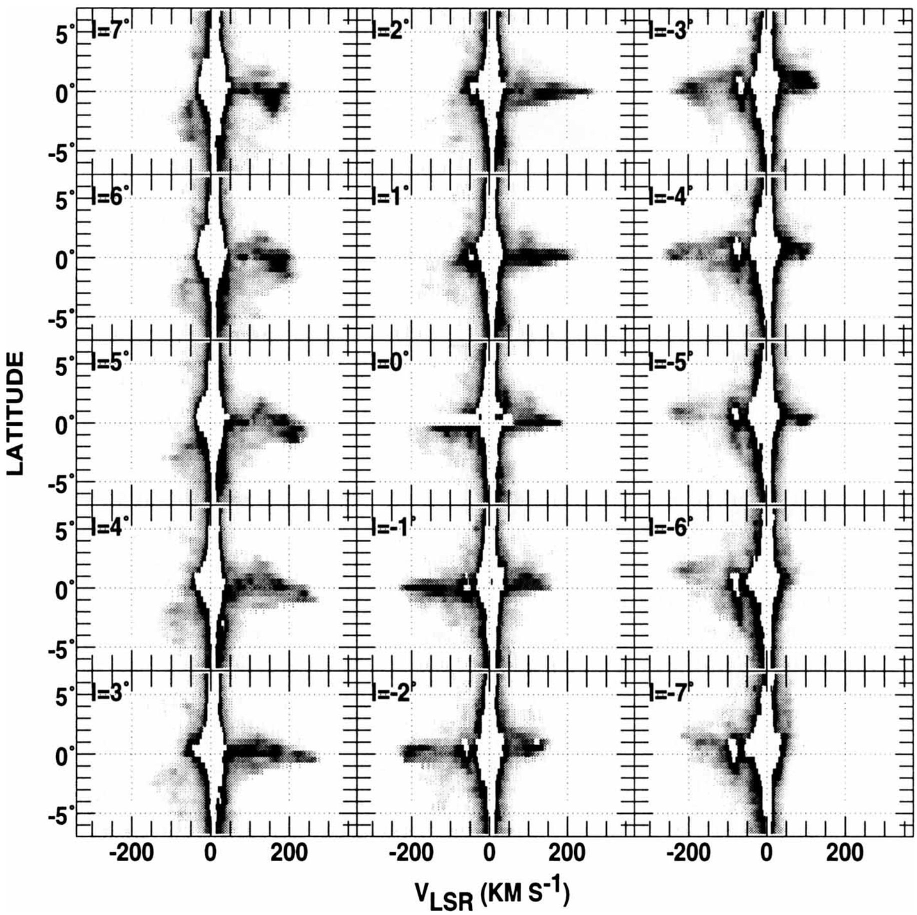

Figure 4. Latitude-velocity diagrams of H I emission at l = 7°,6°... -7°. Antenna temperatures above 20 K have been blanked. Note the unusual distribution of the 3 kpc arm gas, although this lies outside the region of interest here. See Section 2.1 of the text for a description of the other behaviour shown here.

galactic divide ($l = 0°$); follow the outermost positive-velocity contours at each longitude. See how this gas is continuous across $l = 0°$, in both velocity (see Figure 1) and space, moving gradually upward in latitude at more negative longitudes. Although difficult to see in the Figure, the forbidden-velocity gas at $l = -3°$ extends up to b = 3.5° in a feature once known as J2 (Jodrell 2). J2 appeared in Oort's (1977) Figure 13 demonstrating the tilted pole of the H I ejection, along with Feature VII which is the stronger

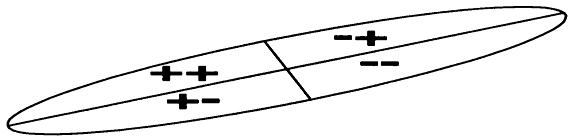

Figure 5. Schematic projection of circular and non-circular motions in an inclined disk. The left-hand and right-hand signs in each quadrant describe the sense of projection of rotation and outward-directed non-circular motion, respectively. Velocities inconsistent in sign with rotation (the so-called 'forbidden velocities') can only occur where the signs are opposite, and so appear to be more highly inclined with respect to the horizontal.

forbidden-velocity ridge at $l = -3°$, b = 1°, v = 100 km s^{-1}. If the reader *can* see J2 in Figure 4, it is apparent that it is the positive-velocity tip of a finger of H I emission extending continuously (at $l = -3°$) to b = 0.5°, v = -200 km s^{-1}. This behaviour is shown in more detail in Figure 8.

2.2. THE TILT

The demonstration by Burton and Liszt (1978) that high-latitude 'ejected' H I features had nearby, permitted-velocity extensions/counterparts played a large role in showing that they could be understood in terms of a coherent geometrical and kinematic pattern valid across the entire center region. The ejection hypothesis fell into disuse once this was noted, and it is no longer the case, as was once common, that individual forbidden-velocity H I features are invested with much importance. In Section 2.1, our purpose was to show that the same continuities apply as well to lower-latitude material which is often seen as the strong permitted-velocity gas. But a tilt clearly applies to *all* the gas and it is not a subtle effect; it is pronounced and very consistent across the region.

If the tilt angle is estimated from the permitted-velocity terminal velocity gas alone, the slope is 1/7; Oort (1977) cited a communication from R. Davies estimating a tilt of 6°. However, the forbidden velocity material is more strongly tilted (Cohen and Davies 1976) and a complete explanation melding the two will necessarily have a larger tilt than 6°. There is a simple geometrical explanation for this. As is well known from extragalactic studies, the circular component of the perceived velocity changes sign across the apparent minor axis of the gas and is of one sign on either side. Any non-circular component of the motion changes sign across the apparent major axis, however, so that the kinematics are split into four distinct quadrants. In two of these, appearing on opposite sides of both the minor and major axes, the circular and non-circular components have the same sign and

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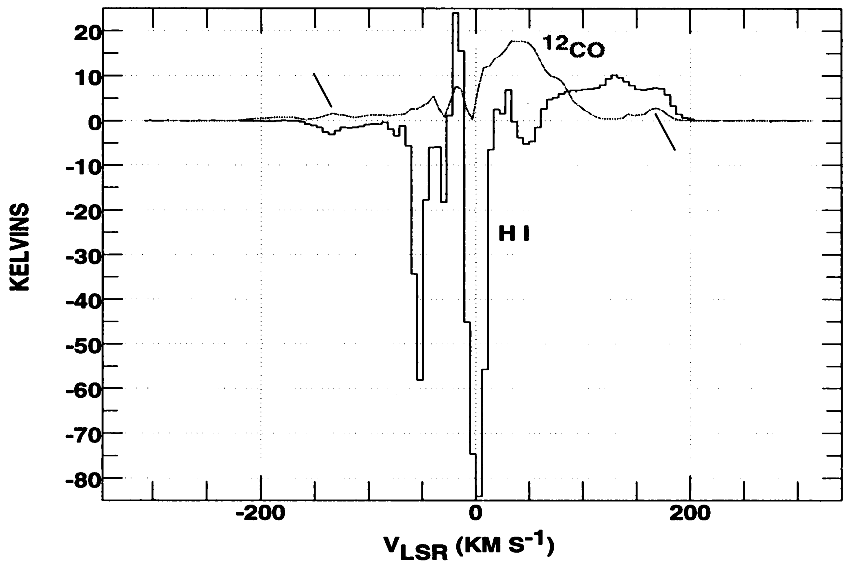

Figure 6. H I and CO spectra observed toward Sgr A* with 21′ and 1′ resolution, respectively. The so-called expanding molecular ring emission is marked by lines in the CO spectrum.

permitted velocities are augmented. In the other two, the components have opposite signs and forbidden velocities may appear. The situation relevant to the Milky Way is shown in Figure 5. For the case of apparent outward non-circular motion (the old ejection idea), the net result is that forbidden velocities appear to be more highly tilted while permitted velocities appear closer to the galactic plane (albeit with larger |v|). The kinematic models made by Burton and Liszt (1978) and Liszt and Burton (1980) typically needed total tilts of 20° to mimic the observations.

3. Congruence of the Large-Scale Atomic and Molecular Gas Distributions

Another distinction sharply drawn in Oort (1977), and one which continues to exert a strong hold on the popular imagination, concerned profound differences in the distributions of the atomic and molecular gases. Emission-line mapping of CO, which was very new in 1977, could probe the inner parts of the gas distribution with exquisitely high 1′ (2.5pc) resolution, or some 2–3 orders of magnitude smaller beam area than was used for H I . CO also was free of the absorption which bedeviled H I in the inner degree of longitude. Spectra of H I and CO taken toward Sgr A are presented in

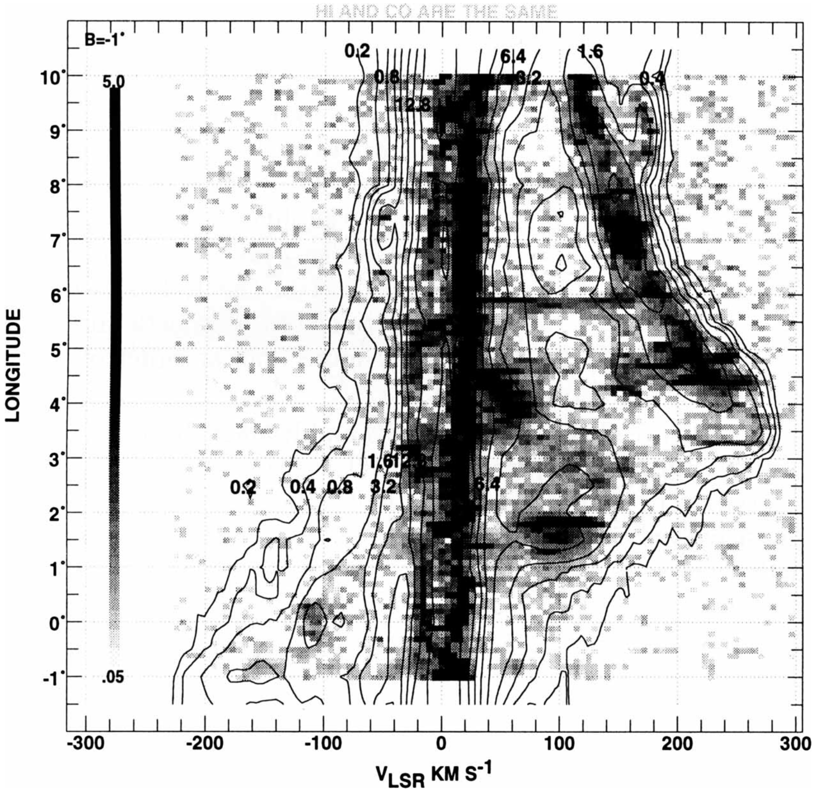

Figure 7. Contours of H I emission at b = -1°, with superposed CO emission gray-scale. The 1′ resolution CO spectra are spaced by 6′.

Figure 6; are they similar or dissimilar?

But the differences were seemingly more basic than mere questions of resolution, or the presence or absence of absorption, because crucial features of the H I distribution–the nuclear disk!–were just not dominant in any molecular species. Conversely, some important molecular features (the so-called 'expanding molecular ring') had been previously ignored in H I (although they are certainly present; see Figure 6 here). Oort's Figure 22, due to Bolton, Gardner, McGee, and Robinson (1964) compared H I and OH absorption. The former showed strong features only at -53 and 0 km s^{-1}(as in our Figure 6), while the OH was strongest at -135 km s^{-1} and 50 km s^{-1} (which are weak in H I). Strikingly, the OH absorption profile extended to significantly more negative and positive velocities.

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3.1. LARGE-SCALE CONGRUENCE OF H I AND CO EMISSION

In Figure 3 we showed contours of the highest permitted-velocity H I to illustrate the pervasive nature of the tilt. Overlaid on those contours is a gray-scale representation of the large-scale CO J=1-0 distribution from the work of Bitran (1986); some of the most extreme negative longitude and velocity emission was not covered in the CO. Perhaps surprisingly, given the prevailing view that CO and H I are so different, the CO fills the H I contours out even to $l = 5^\circ$, b = -1°. The peak integrated intensity of the CO is about 100 K km s^{-1}, while that of the H I is twice greater. But this can be compared with observations of the galactic disk, in which the integrated H I intensity is typically more than an order of magnitude greater (Burton and Gordon 1978).

This congruence of the large-scale CO and H I distributions is illustrated further in Figure 7. There, we compare H I with CO data taken with a 1′ beam spaced every 6′ over a large swath of the inner Galaxy at b = -1°. The strong positive-velocity, positive-longitude ridge with $dv/dl < 0$, mimicking the peculiar shape of the rotation curve in Figure 2, has been called the H I 'connecting arm' between the galactic center and disk.

The H I features in Figure 7 are galactic in scale, extended over several degrees. Their appearance in CO, observed with a 400 times smaller beam (continuously and in detail) implies that the inner few kpc of the Milky Way are filled with molecular material. There is another striking aspect of this congruence, namely the similarity of the CO and H I *brightnesses* in the inner-Galaxy material; the 2–3 K CO signals appear nested within H I contours of similar value. This could be an accident, but a more straightforward explanation is that the H I emission originates in an atomic residue within a molecular gas, and that the H I is fairly cold.

If 1 K km s^{-1} of integrated H I intensity represents 1.8×10^{18} H-nuclei cm^{-2}, while the same conversion for ^{12}CO is $2 - 3 \times 10^{20}$ H_2 cm^{-2}, less than 1% of the gas is atomic. Viewed another way, there is about as much molecular material represented in the 1′ CO beam as atomic material within the 21′ H I beam. The molecular distribution can easily be followed several hundred pc from the nominal galactic plane in Figure 8, where CO and H I are again overlapped in a latitude-velocity cut at $l = -3^\circ$ (compare with the panel in Figure 4). The J2 feature discussed previously is easily seen above b = 2.5° but the CO observations do not extend this far. However, the old H I feature VII at v = 100 km s^{-1}, mentioned above, is also well populated with forbidden-velocity molecular emission.

If the high mass of anomalous H I features was problematical for the ejection hypothesis two decades ago (Oort 1977), it pales in comparison with their presence in CO. Figure 8 is perhaps the first time that the presence

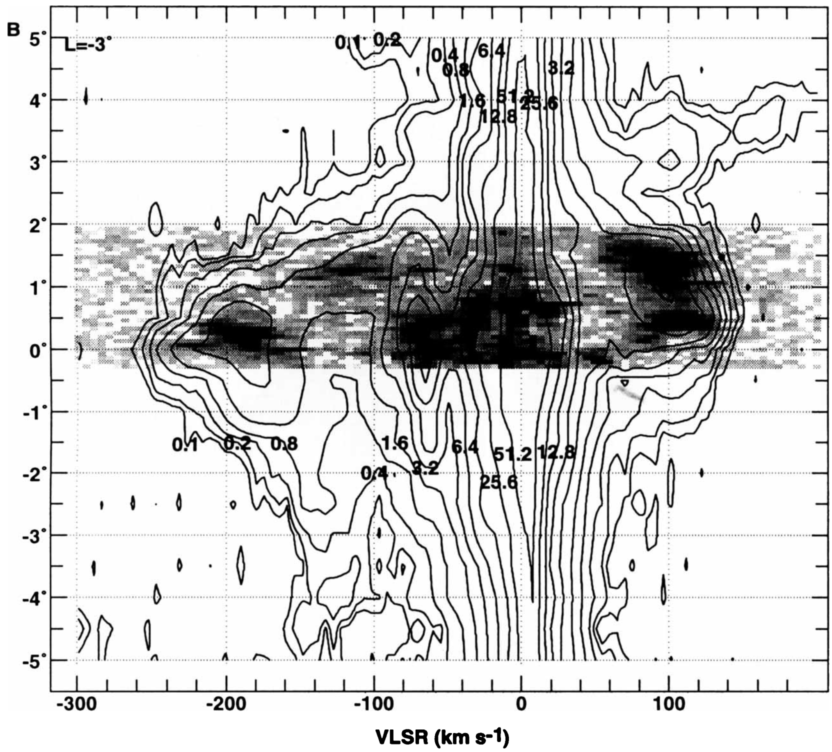

Figure 8. Contours of H I emission at l = -3°, with superposed CO emission gray-scale. The feature at v $\geq$ 100 km s^{-1}, b $\geq$ 2.5° is known as J2 (Jodrell 2); CO was not observed there. The emission just below J2 was another example of H I ejecta, feature VII. VII is clearly full of CO which, due to the inner-Galaxy tilt, is carried well above the local 0-velocity CO emission.

of molecular gas in the old H I ejecta has been explicitly noted. Note how the tilt of the inner-Galaxy CO distribution carries it above the local (0-velocity) gas in latitude (2°, corresponding to 300 pc). A derivation of the vertical thickness of the molecular material which ignored the tilt would ascribe to the gas an inordinately large scale-height.

3.2. THE EXPANDING MOLECULAR RING

Demonstration of the large-scale congruence of the atomic and molecular gas is as direct as making and overlaying the maps. How then does it occur that they have been widely supposed to be so disparate?

Part of the answer concerns the scales on which they have been observed. Large-scale surveys of CO are relatively recent and more attention (at mm-wavelengths) has been lavished on the inner few degrees of galactic

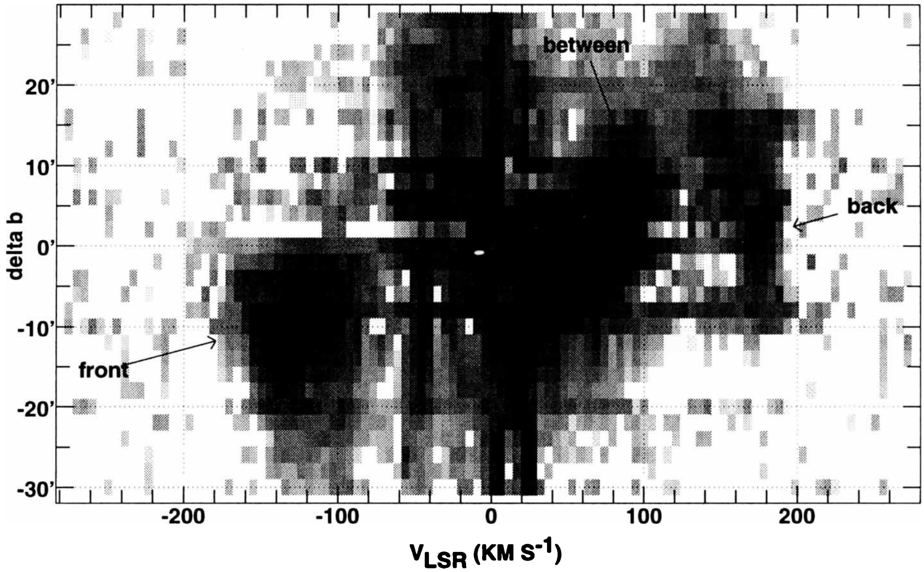

Figure 9. ^{12}CO emission in a cut across the galactic plane through Sgr A*. The vertical axis is galactic latitude measured with respect to Sgr A*. Note that the positive- and negative-velocity emission identified with the 'expanding molecular ring' has the up-down reflection symmetry originally discussed in H I.

longitude where star formation and strong molecular emission are concentrated. These inner regions are both difficult to resolve and distorted by absorption at cm-wavelengths. But even when looking at the Sagittarius source complex, it is impossible to avoid seeing features which are widely distributed. One of the most important and prominent of these is the 'expanding molecular ring'.

Although OH absorption at -135 $km\,s^{-1}$ against Sgr A had been known for some time, it remained for Scoville and Solomon (1973), while studying H_2CO, to trace a convincing pattern in the gas. They posited an expanding ring of (molecular) gas with a radius of about $75'$ (190 pc now), rotating at 50 $km\,s^{-1}$, with an outflow velocity of 140 $km\,s^{-1}$. Oort (1977) discussed this body in terms of the same ejective phenomena then used to characterize high-latitude H I. Because of the high molecular masses derived, and the weakness or absence of analogous behaviour in H I, this ring was supposed to be a genuinely new phenomenon prominent only in molecular material.

From absorption measurements alone the far side of the ring feature was not apparent, but an analogous band of CO emission was soon found crossing $l = 0^\circ$ at $+165$ $km\,s^{-1}$ by Sanders and Wrixon (1974; see Figure 6 here). Association of the two slightly asymmetric halves of the ring with each other was made by Bania (1977) and Liszt and Burton (1978): this was not entirely straightforward because the two have an unusual symmetry introduced by the tilt of the inner-Galaxy gas (see Figure 3 of Liszt and Burton 1978). The back-side emission clearly extends out to $l = 2.2^{\circ}$ near $b = 0^{\circ}$.

As the CO was mapped more fully, the true nature of the 'ring' became more apparent. Its negative- and positive-velocity portions quite obviously have the front-down, back-up reflection symmetry originally supposed to apply to the tilted H I ejecta and now known to apply generally (Figure 9). It should be clear from comparison of the H I and CO spectra in Figure 6 that the expanding molecular ring gas is nothing more than the molecular expression of the H I terminal velocity, and that this gas is broadly distributed over the center region as the inescapable consequence of geometry.

The continuity and coherence of the large-scale inner-Galaxy gas distribution are plainly on display in Figure 4 (Section 2). Despite this, we may note that the positive-velocity envelope of the gas has generally been given a different name and supposed to be a different body and phenomenon at each and every latitude at which we have shown it here. In Figure 7 at $b = -1^{\circ}$ it was the old H I 'connecting arm' (Section 3.1). In Figure 8 at $l = -3^{\circ}$ it was VII at $b = 1^{\circ}$ or J2 at $b > 2.5^{\circ}$. At $b = 0^{\circ}$ it is the back side of the expanding molecular ring. The appearance of each and every one of these is a simple consequence of the same tilted inner-Galaxy geometry and non-circular motion (Burton and Liszt 1978; Liszt and Burton 1980). None of is a material body having the properties originally ascribed to it in isolation from the others.

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