HI IN THE INNER FEW KILOPARSECS OF THE GALAXY

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After reviewing the available observational material, we describe here a simple model of the distribution and kinematics of HI gas within 1.5 kpc of the galactic center. According to this model, most of the inner-Galaxy gas is smoothly distributed in a tilted disk, within which the perceived kinematics are consistent with axisymmetric rotation and expansion of approximately equal magnitude. The model subsumes in a coherent way many observed spectral features which were previously studied separately, without requiring important density enhancements or anisotropic ejection from the nucleus.

PERSPECTIVE AND EARLIER WORK

The evidence for peculiar kinematics in the inner regions of our Galaxy and of other nearby spiral galaxies is well established. The disturbances extend to z-distances of at least several hundred parsecs, to radii of several kiloparsecs, and involve non-rotational velocity components of substantially more than 100 km s^{-1}. Most earlier papers interpreting the wide variety of anomalous-velocity, non-planar phenomena observed toward the central region of the Galaxy have considered them as ejecta produced by violent activity in the nucleus (see Oort's 1977 review). Here we suggest an alternative interpretation of these features which acknowledges little evidence of anisotropic ejection from the nucleus.

For the case of our own Galaxy, the most definite and extensive observational data come from radio observations at λ21 cm of atomic hydrogen. The Galaxy is to a large extent transparent to this radiation, allowing access to the nuclear region, and the emission is intense, allowing more extensive sampling than in the much weaker molecular lines.

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In Table 1 we have compiled the observational parameters of the most recent 21-cm surveys of the general region of the galactic center. Each body of data represented in the table is unique in terms of at least one of its observational parameters and satisfies at least in part the requirements for a general investigation of the nuclear phenomena: extensive angular and velocity coverage and high sensitivity. Additional material, suitable for special-purpose investigations, is tabulated by Simonson (1974) and by Heiles and Wrixon (1976).

Table 1. Still-current general HI line surveys of the galactic center

Reference	Telescope	ℓ-coverage (degrees)	b-coverage (degrees)	v-coverage (km s^{-1})	Sensitivity (K)	Form of Display
Burton et al. 1977	43 m	349 to 12, $\Delta\ell = 1$	-10 to 10, $\Delta b = 1$	-500 to 500, $\Delta v = 5.5$	0.2	$(b,v)\vert_\ell$ maps
Burton and Liszt 1978	43 m	349 to 13, $\Delta\ell = 1$	-10 to 10, $\Delta b = 0.5$	-320 to 320, $\Delta v = 5.5$	0.1	$(\ell,v)\vert_b$ & $(b,v)\vert_\ell$
Cohen 1975	30 m	355 to 10, $\Delta\ell = 1$	5 to 5, $\Delta b = 0.25$	-300 to 300, $\Delta v = 7.3$	0.3	$(b,v)\vert_\ell$ maps
Kerr 1969	64 m	300 to 60, $\Delta\ell = 1$	-2 to 2, $\Delta b = 0.2$	-250 to 120, $\Delta v = 7$	2.0	$(b,v)\vert_\ell$ maps
Lindblad 1974	43 m	339 to 12, $\Delta\ell = 3$	-10 to 15, $\Delta b = 0.3$	-120 to 120, $\Delta v = 1$	(2.0)	$(b,v)\vert_\ell$ maps
Mirabel 1976	30 m	355 to 5, $\Delta\ell = 1$	-5 to 5, $\Delta b = 1$	-1000 to -300, $\Delta v = 25$	0.3	none
Sanders and Wrixon 1972a and Sanders et al. 1972	6 m	350 to 12, $\Delta\ell = 2$	-10 to 0, $\Delta b = 2$	-340 to -40, $\Delta v = 16$	0.1	special purpose
Sanders and Wrixon 1972b	6 m	355 to 5, $\Delta\ell = 2$	-5 to 5, $\Delta b = 2$	-300 to 300, $\Delta v = 16$	0.1	special purpose
Sanders et al. 1977	100 m	357 to 3, $\Delta\ell = 0.1$	0	-300 to 300, $\Delta v = 3$	0.5	$(\ell,v)_b$ maps
Simonson and Sancisi 1973	25 m	356 to 2, $\Delta\ell = 0.5$	0 to 5, $\Delta b = 0.5$	-120 to 120, $\Delta v = 3.4$	2.0	$(\ell,v)\vert_b$ & $(b,v)\vert_b$
Sinha 1978	43 m	339 to 11, $\Delta\ell = 0.5$	-2 to 2, $\Delta b = 0.25$	-260 to 300, $\Delta v = 4$	0.1	$(\ell,v)\vert_b$ maps
Wrixon and Sanders 1973	43 m	357 to 3, $\Delta\ell = 0.3$	-3 to 3, $\Delta b = 1$	-300 to 300, $\Delta v = 5.5$	0.2	$(\ell,v)\vert_b$ maps

Note: The sensitivity refers to the lowest-level contour plotted or to the quoted 3σ value, in the temperature units of the survey rounded to one decimal. The velocity coverage refers to the published data, if any.

The observations show many apparently isolated HI features with anomalous velocities. To account for these features, separate, highly directional nuclear events have been invoked, with the epoch and imparted initial velocity of each event being tailored in accordance with the individual feature's observed properties. It has been recognized for some time that the anomalous material occurs mainly in the two opposed quadrants $\ell > 0^\circ$, $b < 0^\circ$ and $\ell < 0^\circ$, $b > 0$. This has been shown by Kerr (1967), van der Kruit (1970), Cohen (1975), and others using maps of the HI integrated-intensity first moment. Kerr and Sinclair (1966) have shown that perturbations in the distribution of the non-thermal continuum radiation at λ20 cm also occur in these opposed quadrants. Figure 1 shows two examples of HI moment maps; by suitable choice of the range of integration, the inner-Galaxy material may be separated to a large degree from other line-of-sight material. The obvious preference for two quadrants has been taken as evidence of a favored collimation axis for the violent events. Such explanations are unsatisfying because of the number of unrelated events which they require and because they address directly neither the nature of the ejection mechanism nor the focussing. Also puzzling are the general lack of disruption of the nuclear-region gas, which remains predominantly neutral and conducive to molecule formation, and the confinement of the anomalous-velocity features within a well-defined velocity envelope.

We suggest here (see also Burton and Liszt, 1978, and Liszt and

Burton, 1978) an alternative model of the distribution and kinematics of the gas within 1.5 kpc of the galactic center which accounts in a simple way for many of the phenomena observed. Lacking a dynamical foundation, the principal use of the model is the constraint of other interpretations of the inner-Galaxy gas.

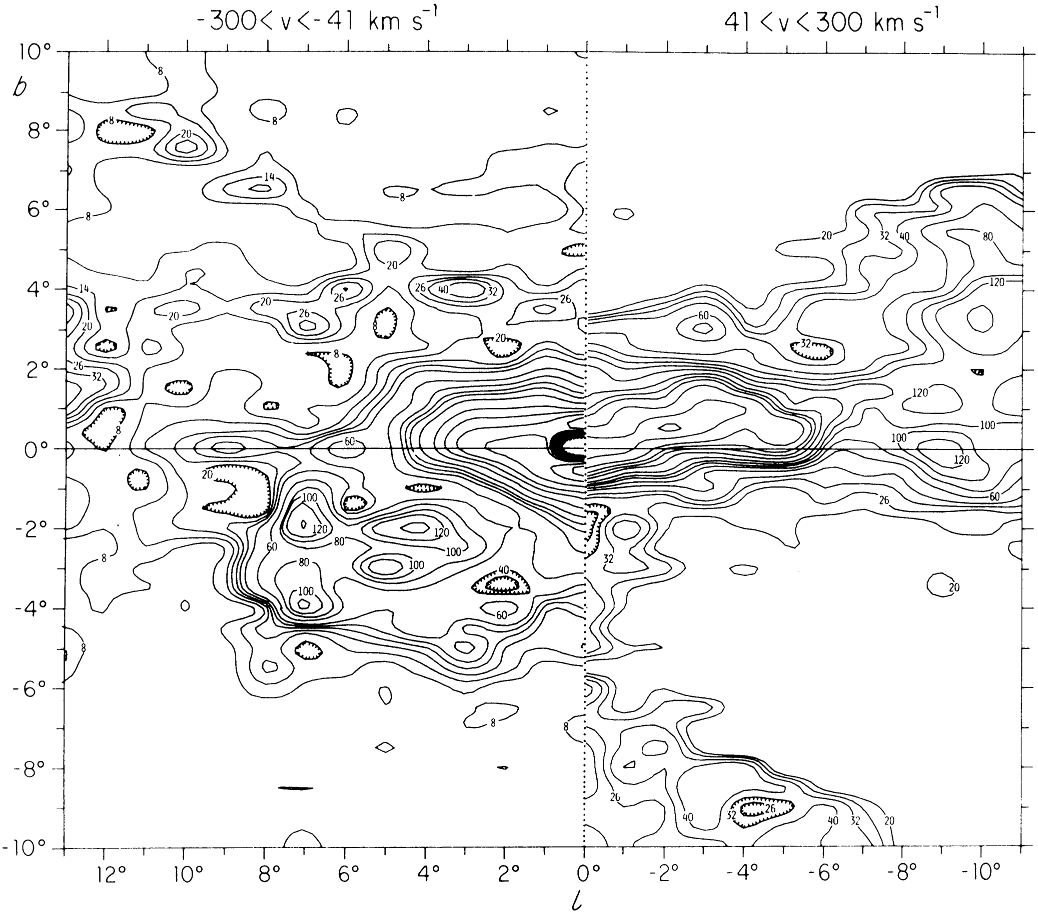

Figure 1. Contours of observed T_A integrated over the velocity ranges $-300 < v < -41$ km s^{-1} (left) and $+41 < v < +300$ km s^{-1} (right). The choice of the velocity intervals excludes most of the emission from the Galaxy at large.

TILTED-DISK MODEL OF THE INNER-GALAXY GAS DISTRIBUTION

The model which we suggest (see Figure 2) confines the gas in a layer of 0.1 kpc scale height to a disk of 3 kpc diameter. This disk is tilted α = 22° with respect to the plane b = 0° and i = 78° with respect to the plane of the sky; it is the plane of this disk, not the plane b = 0°, which is fundamental to the gas distribution in the inner Galaxy. Within this disk the kinematics are axisymmetric and density varies only with distance from the equatorial plane.

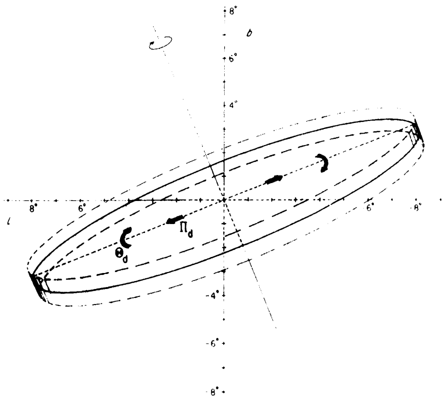

Figure 2. Appearance of the model tilted gas distribution as projected onto the plane of the sky. The solid-line approximate ellipse represents the equatorial plane of a disk of radius 1.5 kpc tilted through the angles $\alpha = 22°$, $i = 78°$. The vectors indicate schematically the model rotation and expansion functions.

The free parameters of the model are specified--and the success of the model judged--by requiring agreement of synthetic with observed spectra. The synthetic spectra are generated in a way which includes the consequences of the radiative transfer inherent in the model velocity field and density distribution. In practice, the choice of parameters defining the model required iterative comparison between observed and simulated profiles.

We specify perpendicular distance from the disk axis by ϖ_d, velocities in the ϖ_d-direction by Π_d, perpendicular distance from the central plane of the disk by z_d, and rotation velocities orthogonal to both the ϖ_d- and z_d-directions by Θ_d. The disk has azimuthal symmetry, so that Π_d and Θ_d depend only on the radius ϖ_d. Necessary for the generation of synthetic data is the velocity measured with respect to the local standard of rest at a point at distance r from the Sun on a line of sight in the direction (ℓ,b):

$$v_d = \Pi_d(\varpi_d) \cdot \{\varpi_d^2 - \varpi_o \cdot (\varpi_o - r \cdot \cos b \cdot \cos \ell - z_d$$

$$\cdot \cos i)\} \cdot (\varpi_d \cdot r)^{-1} - \Theta_d(\varpi_d) \cdot \varpi_o \cdot \sin i \cdot (\sin b \cdot \sin \alpha -$$

$$\cos b \cdot \sin \ell \cdot \cos \alpha)/\varpi_d - \Theta_o \cdot \sin \ell \cdot \cos b. \qquad (1)$$

Kinematics, rather than the gas density or temperature distributions, dominate the appearance of long-line-of-sight spectra of ubiquitous galactic tracers like HI or CO. The kinematic functions which follow from the model/observation comparison, utilizing in addition to the HI the CO data described by Liszt and Burton (1978), are

$$\Pi_d(\varpi_d) = 170\ (1\text{-exp}\ (-\varpi_d/0.07))\ \text{km s}^{-1}, \qquad (2)$$

and

$$\Theta_d(\varpi_d) = 180\ (1\text{-exp}\ (-\varpi_d/0.20))\ \text{km s}^{-1} \quad \text{if } \varpi_d \leq 0.85 \text{ kpc}$$

$$= 180\ (1\text{-exp}\ (-(1.7 - \varpi_d)/0.20\ \text{km s}^{-1} \quad \text{if } \varpi_d > 0.85 \text{ kpc} \quad (3)$$

COMPARISONS OF OBSERVED AND MODELLED SPECTRA

Integrated-intensity moment maps are convenient at the beginning of the modelling process because they reflect directly the size and orientation of the disk. Figure 3 shows the arrangement on the plane of the sky of intensities integrated in synthetic spectra over the indicated velocity ranges. The model moment maps show the same general trends as those observed and plotted in Figure 1, including the zero-longitude crossing at $b \neq 0°$ as well as the tilted nature and extent of the moment distributions.

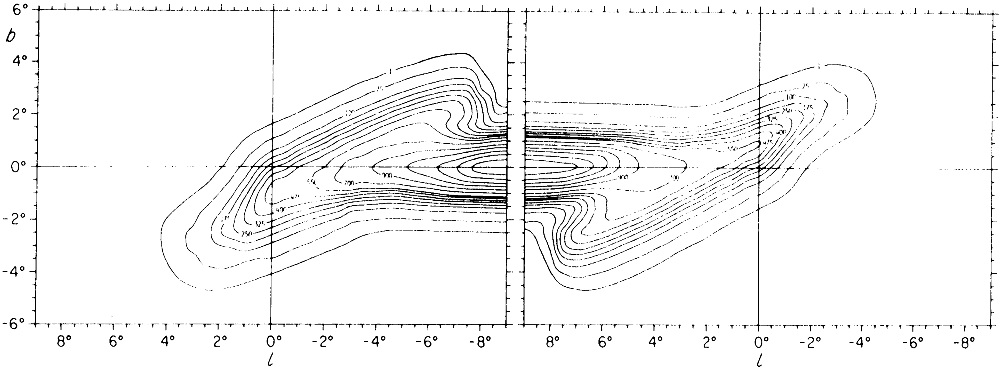

Figure 3. Arrangement on the plane of the sky of intensities integrated over the indicated velocity ranges in synthetic spectra representing HI in the modelled inner-Galaxy distribution. Some emission from the Galaxy at large also enters.

The principal disadvantage of the moment maps is their insensitivity to the available kinematic information which position, velocity maps do not suppress. Spectral data from the central region of our Galaxy are usually displayed in ℓ,v maps taken parallel to the plane $b = 0°$ or in b,v maps taken parallel to $\ell = 0°$. For gas distributed as in Figure 2, such cuts are not the most revealing. The tilted disk projects approximately to an ellipse whose major axis lies approximately on the line $b = -\ell \tan \alpha$. A position, velocity map constructed along this line should, according to the model, show a high degree of kinematic symmetry (because the projections of the functions Π_d and Θ_d onto the line of sight are very nearly antisymmetric about $\ell = b = 0°$, $v = 0$ km s^{-1}) and so should yield straightforward information about these functions in the inner Galaxy. Such a map should also reveal the maximum extent of the tilted distribution.

Figure 4 shows an observational ℓ,v map on the line $b = -\ell \tan 22°$. To avoid distortion of the contours caused by absorption at the position of the galactic center, we have replaced the spectrum at that point by the average of those at $\ell,b = +0\overset{\circ}{.}0, +0\overset{\circ}{.}0$, and $0\overset{\circ}{.}0, -0\overset{\circ}{.}5$. As predicted, and in great contrast to the ℓ,v arrangement taken at $b = 0°$, the observations show a high degree of kinematic symmetry about the map origin. That the envelope of the emission is not pinched toward $v = 0$ km s^{-1} at $\ell = 0°$ indicates radial motion; that the pattern is skew indicates

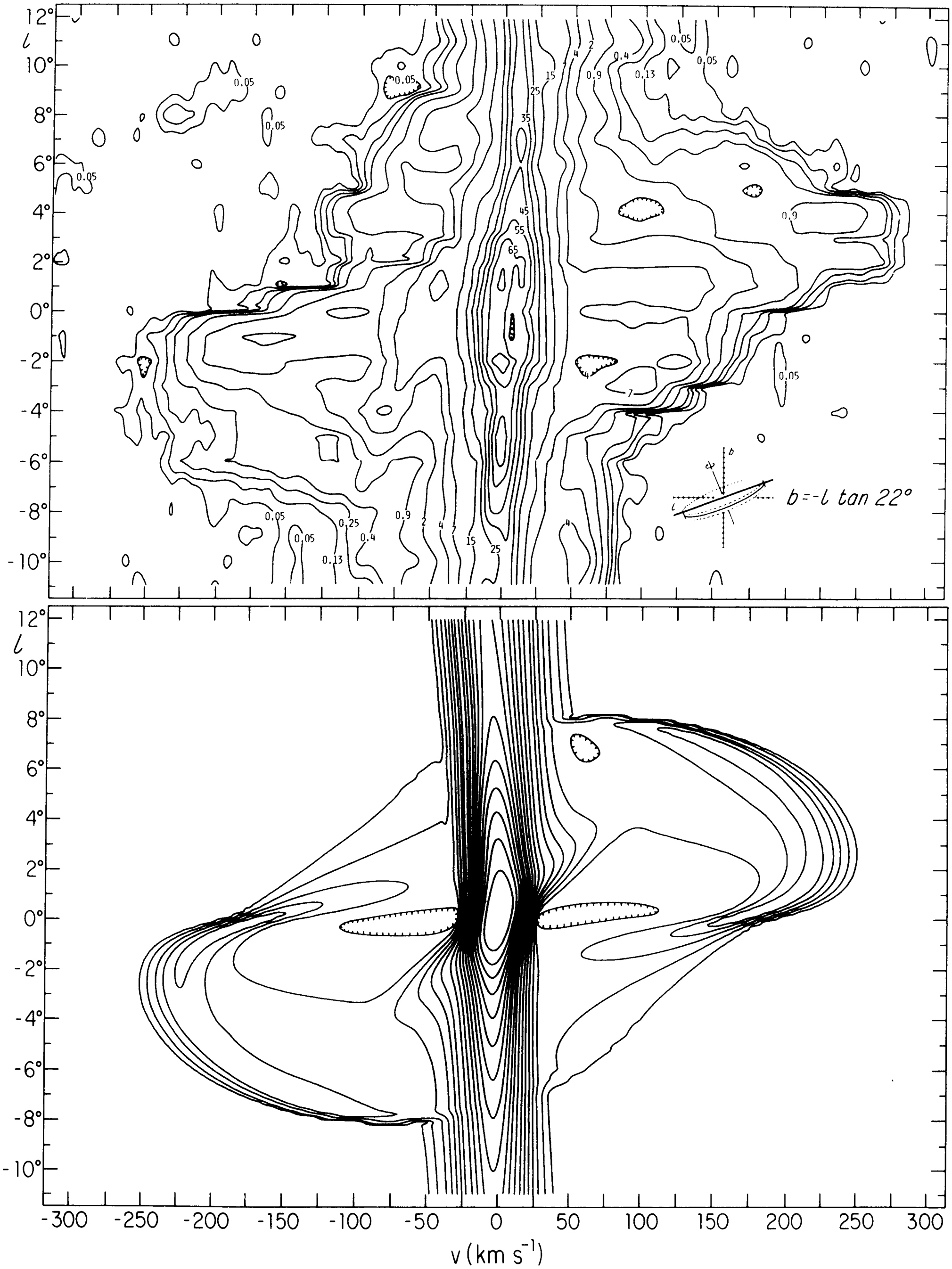

Figure 4. Longitude, velocity arrangement of emission from directions with b = − ℓ tan 22°. This cut through the inner-Galaxy reveals the approximate extent of the tilted fundamental distribution of gas, and shows its kinematic symmetry. (top) Observed profiles. (bottom) Synthetic profiles.

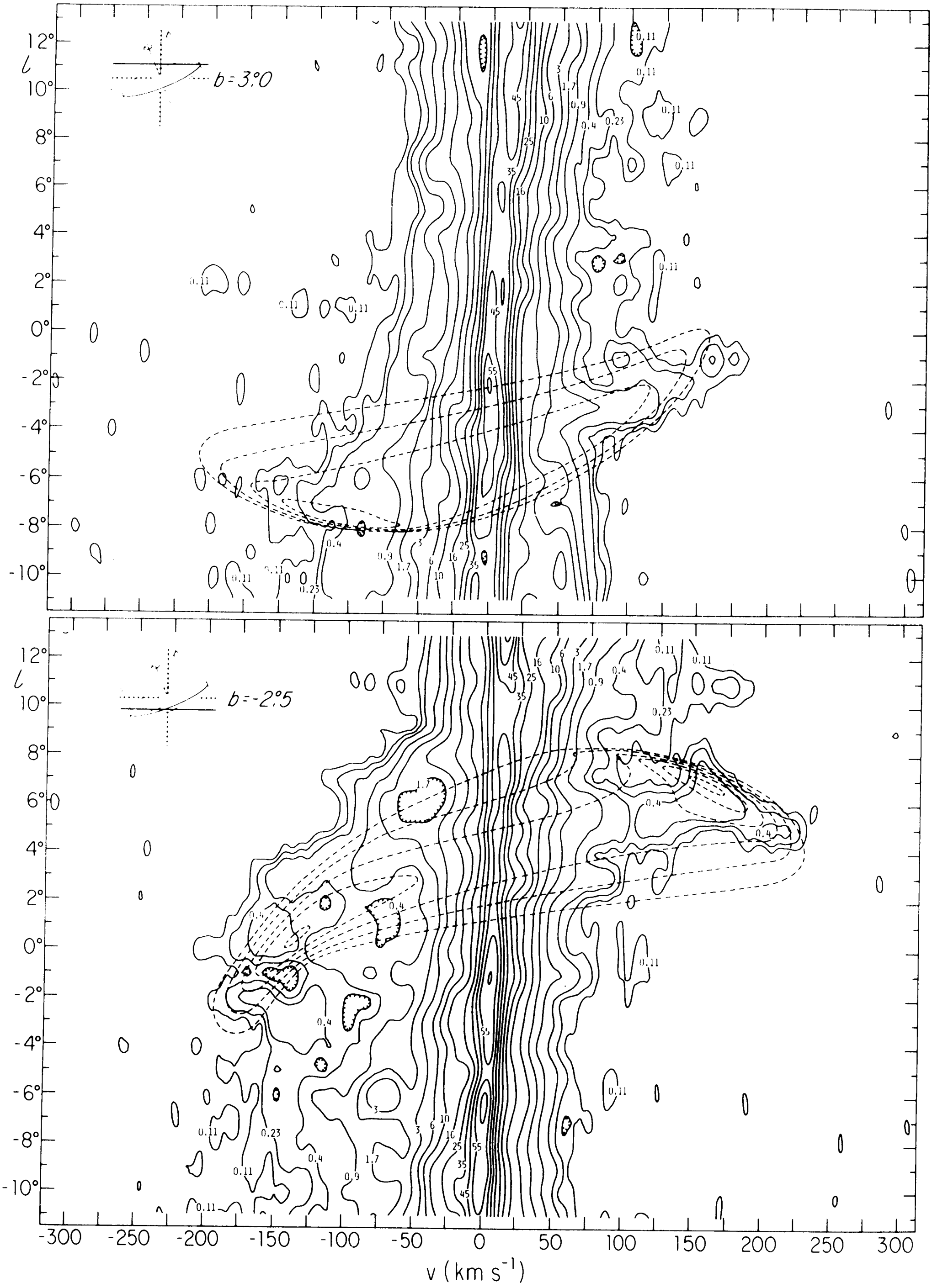

Figure 5. Emission in the ℓ,v planes at the indicated latitudes. The dashed contours represent synthetic emission from the modelled disk;

the Galaxy at large does not enter these spectra. As these sample comparisons show, the model accounts for a number of apparently isolated features.

rotation. The negative-velocity HI absorption (see Figure 1) against the Sagittarius continuum sources shows directly that the radial motion is expansion. Detailed specification of the Π_d- and Θ_d-functions in accordance with the observational material is described by Burton and Liszt (1978).

A synthetic map generated along the line $b = -\ell \tan 22°$ is also shown in Figure 4. The basic agreement of the outer envelopes of the observed and modelled distributions indicates that the kinematics are successfully modelled. Obviously the presence of large general expansion velocities forces our rotation function to be much smaller in magnitude than those derived on the basis of pure rotation.

The data displays which most usefully show the previously studied and apparently isolated anomalous features are ℓ,v intensity-contour maps. Figure 5 shows two examples of these, drawn at $b = 3\overset{\circ}{.}0$ and at $b = -2\overset{\circ}{.}5$. Superimposed on the observed material are dashed contours representing synthetic spectra. The model profiles exclude the Galaxy at large, which, in the observations, contributes the broad band of emission at $|v| \lesssim 50$ km s^{-1}. In both ℓ,v maps, the characteristic signature of the disk encompasses the principal perturbations observed. Thus, at $b = 3\overset{\circ}{.}0$, the model subsumes Cohen's (1975) feature J2 at high positive velocities near $\ell = -1°$ as well as the feature near $\ell = -3°$, $v = 100$ km s^{-1}, discussed by Sanders and Wrixon (1972b). At $b = -2\overset{\circ}{.}5$, the positive-velocity pattern near $\ell = 6°$ is Cohen's feature J4. The negative-velocity portion of the observed ℓ,v plane shows the combined emission from features X and XII of van der Kruit (1970) and from feature E of Sanders et al. (1972).

Other model/observation comparisons show that many of the apparently isolated observed spectral features occur along the position, velocity loci predicted by the model. Because the density of gas in the model varies smoothly, and because the velocity fields are axially symmetric and simply described, we see no compelling evidence for important density enhancements or kinematic perturbations associated with particular observational features. In this respect the model avoids some of the most troubling aspects of earlier interpretations of the emission from the inner Galaxy. Like them, however, it lacks a dynamical foundation.

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DISCUSSION

Contopoulos: About two years ago Mr. Sinha (University of Maryland) sent me a letter, suggesting a tilted disk near the center of our Galaxy, and asked me if I could provide a dynamical explanation. Well, I have no ready-made dynamical explanation, thus I would like first to have a feeling how certain is the kinematical model provided. May I ask, therefore, whether you exclude a model without expansion and for what reasons?

Burton: Although our kinematic model cannot be defended dynamically, we do believe that any dynamically consistent model must provide line-of-sight motions which are not very different from those given by the combined effects of our Θ_d and Π_d functions. No pure-rotation situation would do that. However, motions in elliptical streamlines might suffice. Liszt and I are testing this now. If such a solution could be found, it would avoid the problem of net outward mass flux implied by our Π_d function.

Sanders: Have you produced moment maps of the neutral hydrogen surface density distribution at very high velocities--say $|v| > 200$ km s^{-1}, where the contribution from transgalactic hydrogen is certainly excluded? Do you see the tilt in such moment maps?

It seems to me that the tilt does not show up in other conspicuous tracers of the gas density distribution, such as the extended non-thermal continuum source and the extended far-infrared emission. Concerning the far-infrared, this is almost certainly thermal radiation of star light by dust in the inner 100-200 pc and thus should be a tracer of the gas density in the inner region. Can you comment on this?

Burton: We have produced moment maps over a large number of velocity ranges, and find in all cases the tilted distribution in all the inner-galaxy material, whether at permitted or forbidden velocity. Regarding the highest velocities, it is an important fact that the gas is confined within very definite kinematic boundaries. Very high velocities, which might be expected (Oort 1977) for ejection from the nucleus, are not found (Mirabel 1976, Burton et al. 1977).

In two respects the non-thermal continuum and infrared data are not well suited for a search for the tilted distribution: the observed angular extent (especially in b) is small, and the measurement technique is a differential one, making the results rather insensitive to a weak, extended background. In addition, because kinematic isolation of the inner-galaxy gas is not possible, one must somehow separate the contribution from a ∿500 pc intersection of the tilted disk from the ∿30 kpc intersection of the general galactic layer.

Davies: In contrast to Dr. Sanders, R. J. Cohen and I found in our 1976 paper that the locus of the moments of the HI distribution in fixed velocity ranges made an inclined line to the plane; the distribution at each velocity was also inclined. The distributed ionized hydrogen over a scale of 10° shows no evidence for the inclined disk. This is not in contradiction to the HI result because this ionized gas, as measured by the 166α recombination line, is near zero velocity and is evidently foreground material.

I have a comment about the distribution within the inclined disk. R. J. Cohen and I found a number of features within the central region--too many to be explained by velocity crowding in a uniform disk.

A study by K. Grape of the observed terminal-velocity hydrogen has shown that the inner region of the Galaxy has a distributed HI component with a density of about 0.1 atoms cm^{-3}.

Sinha: The area under the profile integrated up to 100 km s^{-1} from the permitted-velocity edge shows the inclined feature very clearly.

Ostriker: Have you made any progress in assessing the suggestion that there is neither explosion or even expansion but that, rather, the apparent expansion is caused by motions along elliptical streamlines. Even if the gravitational field were approximately axisymmetric so that $j = rv_{\perp}$ were constant along a streamline, it would appear from a superficial examination of your results that a good fit to observations would be possible and the large rates of mass and energy outflow (implied by your present model) could be avoided.

Burton: Liszt and I are pursuing this, motivated by the desire to find a dynamically plausible model. Our kinematic model shows the sort of restraints which an elliptical-streamline model will have to satisfy.

Oort: It is hard to imagine how a smooth expansion and rotation could exist simultaneously throughout your tilted disk. In a physically possible model one should either have distinct expanding features, or a bar-like structure strongly differing from azimuthal symmetry. However, I understand and appreciate that your model was based on the wish to have as simple a model as possible.

Menon: Your model implies that the disc is transient. What is the time scale for its appearance and disappearance?

Burton: Such a time scale is implied by the parameters of the kinematic model, but probably does not merit much discussion until a dynamically satisfying model can be found.

Tinsley: What mass outflow rate would be predicted by your expansion model?

Burton: The expansion flux across the outer boundary of the tilted disk is 4 $M_\odot$ per year. Because this refers only to HI, the total flux would be much greater. This is of course uncomfortably large, and provides one of our motivations for searching for a closed-streamline elliptical model which can still satisfy the restraints indicated by our kinematic model.

de Vaucouleurs: Your schematic map of the nuclear region agrees well with what should be expected in a barred spiral having its bar in the position angle suggested by the major axis of the inner ring of the Simonson map and the Georgelins' map of the spiral pattern. Models with pure circular symmetry are not likely to lead to realistic pictures of the gas distribution.

Burton: I am bothered by the insistence that the evidence indicates important high-density features in the central region. Our model shows that a smooth, axisymmetric distribution of density and velocity results nevertheless in intensity concentrations in position, velocity maps. These concentrations occur at the locations of features E, J2, J4, J5, VII, X, and XII, as well as at other locations. Among these other features which we believe adequately accounted for in these terms is the "connecting arm" feature of Rougoor, also identified by van der Kruit (feature III) and by Cohen (feature IIIa). It plays an important role in the interpretations of Rougoor, Kerr, and Cohen and Davies, where it is identified as a steeply inclined arm, or bar-like feature. Would you care to comment on this identification in view of our opinion that it is adequately accounted for by the vagaries of radiation transport through a smooth density in a rotating disk?

Cohen: The velocity-longitude diagram, Figure 1 of my paper, indicates some large-scale symmetry in the velocity field of gas in the central region, since the outermost velocities at which emission is detected are symmetrical through $\ell = 0°$, $v = 0$ km s^{-1}. However the gas density distribution must be rather irregular. For example, the "connecting arm" you mentioned is a major feature in the map at positive longitudes, but it has no symmetric counterpart at negative longitudes. In general it is very hard to find symmetry in the ridge lines of emission, although the overall extent of the emission is symmetric. This is very difficult to understand in terms of your axisymmetric model. Another point is that for a given line of sight such kinematic models give rise to only a single emission peak as a rule, at the terminal velocity. The observations however show wavy peaks at lower velocities. Because of the concentration of molecules to these HI peaks we believe they represent real density enhancements.

Burton: Kinematic models can give rise to the multiple peaks; in addition, the subcentral point (terminal velocity) region is not necessarily favored in models which deviate from pure circular rotation. Furthermore, molecules--being kinematic tracers--respond to the velocity field in the same way HI does.