THE ASTROPHYSICAL JOURNAL, 436:L173–L176, 1994 December 1

DETECTION OF A THICK MOLECULAR DISK IN THE GALAXY

T. M. DAME AND P. THADDEUS[1]

Received 1994 February 8; accepted 1994 September 15

ABSTRACT

The 1.2 m telescope at the Center for Astrophysics was used to conduct the first sensitive and systematic search for molecular gas in the inner Galaxy more than 100 pc from the Galactic plane. With an rms sensitivity per spectrum of 0.1 K at $\Delta v = 1.3$ km s^{-1} and a sampling interval of 3'.75 (0.43 beamwidth), the survey is 3–10 times more sensitive per unit solid angle than existing CO surveys of the plane, and 16 times more sensitive than the only previous extensive wide-latitude survey. Three selected regions centered on the plane were mapped, each $\sim 1°$ wide in l and $\sim 8°$ wide in b, at Galactic longitudes 30°, 40°, and 50°; in all three there is CO emission near the terminal velocity extending up to 3° from the plane. This CO is evidence for a faint, thick molecular disk in the inner Galaxy ~ 3 times as wide as that of the dense central CO layer, and comparable in width to the central H I layer. In the inner Galaxy regions surveyed, $\sim 5\%$ of the total emission, and possibly a comparable fraction of the H_2 mass, lies above the previously studied thin molecular disk.

Subject headings: Galaxy: halo — Galaxy: structure — ISM: molecules — ISM: structure

1. INTRODUCTION

Sensitive 21 cm surveys of the Milky Way over the past 2 decades have revealed a very complicated vertical (z) structure of atomic gas, with large sheets, filaments, and shells extending more than 1 kpc above the Galactic plane (e.g., Heiles 1984; Lockman 1984). Although molecular gas associated with the infrared "cirrus" is observed to high latitudes, most of this material is probably quite local—it may lie entirely within the thin molecular disk (~ 120 pc FWHM) established by the in-plane CO surveys (e.g., Bronfman et al. 1988). Prior to the work presented here no CO surveys had the combination of high sensitivity and latitude coverage required to detect a molecular counterpart to the high-z H I.

Since 1991 October, we have been using the 1.2 m telescope at the Harvard-Smithsonian Center for Astrophyics (CfA) to carry out the first sensitive and systematic search for molecular gas in the inner Galaxy more than 100 pc from the plane. To date, ~ 45 deg^2 of the first quadrant have been surveyed in the $J = 1 \rightarrow 0$ line of CO with a sensitivity per unit area 3–10 times higher than existing CO surveys of the plane, and 16 times higher than the only previous extensive wide-latitude survey (Dame et al. 1987). Here we will discuss only the three largest regions surveyed—1° wide vertical strips centered on the Galactic plane at $l = 30°$, 40°, and 50° (Table 1). All of these regions show weak, clumpy CO emission extending to heights of 200–300 pc.

2. OBSERVATIONS

The observations described here were obtained during two 8 month periods (October–May) in 1991–1992 and 1992–1993. The weather was acceptable for the very sensitive observations at 115 GHz demanded by the survey during approximately half the days in the observing periods, when it was possible to observe ~ 6 hours per day. Within the regions listed in Table 1, spectra were obtained every 3'.75 (slightly less than half the 8'.7 beam of the CfA telescope) with an rms sensitivity of 0.1 K at $\Delta v = 1.3$ km s^{-1}. The telescope is equipped with an extremely sensitive SIS receiver (65 K SSB) and two 256 channel filter-bank spectrometers with velocity resolutions of 0.65 and 1.3 km s^{-1} at 115 GHz. The two spectrometers were run simultaneously and centered on the same frequency, the wider one being used primarily to provide emission-free channels for baseline subtraction.

Observations were switched every 15 s between the source position and two emission-free reference (OFF) positions chosen to straddle the source in elevation. By adjusting the time spent on each OFF, ON-OFF residual powers were generally held below 1 K. This residual was removed by fitting a baseline to channels with little or no CO emission, beyond the terminal velocity and at large negative velocities. In addition to the three regions discussed here (Table 1), we have surveyed a comparable region at $l = 25°$, but so far only at positive latitude, and two narrower vertical strips near $l = 37°$ and 44° which were surveyed previously in H I with the Arecibo telescope (Bania & Lockman 1984), plus a horizontal strip $\sim 0°.5$ wide at $b = -2°$ extending from $l = 26°$ to 50°. All of these observations, as well as some in ^{13}CO, will be discussed in a subsequent paper.

3. ANALYSIS AND RESULTS

To exhibit the molecular gas at high z, the survey windows are best summarized as latitude-velocity maps integrated over longitude. That at $l = 30°$ is shown in Figure 1*a*, with superposed contours of z, computed on the assumption that all emission is from the near kinematic distance. While this assumption may be somewhat poor very close to the plane, at points more than $\sim 1°$ away the far-side emission is negligible; its effect in any case is to reduce, not increase, the apparent thickness of the molecular disk.

The contours in Figure 1*a* are linearly spaced, but to accommodate the large dynamic range in the data, the contour interval in the high-intensity regions shown without shading is 30 times higher than elsewhere. It is only these high-intensity regions that were detectable by the first generation of Galactic plane surveys (e.g., Cohen, Dame, & Thaddeus 1986; Sanders et al. 1986). It is evident that the latitude limits of those surveys ($\pm 1°$ in b) were fairly well chosen, since at their sensitivity little high-z CO would have been detected at higher latitudes. The order of magnitude improvement in sensitivity of the present

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

TABLE 1

COMPLETED SURVEY REGIONS

				THIN DISK			THICK DISK		
l_{min}	l_{max}	b_{min}	b_{max}	n_0	z_0	FWHM	n_0	FWHM	THICK/THIN
29°50	30°50	−4°	4°	2.1	−13	85 ± 1	0.23	266 ± 16	3.1 ± 0.2
39.50	40.50	−4	3	0.9	−28	54 ± 2	0.13	142 ± 23	2.6 ± 0.4
49.25	50.25	−4	4	1.0	−18	62 ± 3	0.22	207 ± 21	3.3 ± 0.4

NOTE.—Thin and thick disk parameters were derived from double Gaussian fits to the density profiles in Fig. 3, assigning Poisson weights to assure a good fit in the wings of the profiles; the thick disk was constrained to be centered on the thin disk. n_0 = central H_2 density (cm^{-3}); z_0 = displacement of the midplane (pc); FWHM = thickness of the layer (pc); thick/thin = ratio of the layer thicknesses. Thick disk parameters derived from data not cleaned of sidelobe contamination are 5%–18% larger.

survey, however, reveals weak CO emission extending to at least 250 pc above and below the plane.

Although at $l = 30°$ the emission more than 150 pc from the plane is weak, the cutoff at the terminal velocity ($v \sim 105$ km s^{-1}) and at negative velocities demonstrates that it is real and well above the instrumental noise; the signal-to-noise ratio in some of the stronger broad emission lines at high z, such as the one shown in Figure 2, is greater than 10:1. Further evidence that the high-z emission is real, rather than of instrumental origin (e.g., baselines or sidelobes), is provided by the rough alignment of the low CO contours in Figure 1 with contours of constant z, as expected for an extended layer of constant thickness, and the general similarity to the 21 cm distribution in the same region (Fig. 1*b*).

Sidelobe contamination is potentially a serious concern in a study like this, where faint emission is being observed near a strong, extended source, that is, the Galactic plane. To calculate the sidelobe contamination we made an exhaustive study of our antenna pattern, comparing a 6° × 6° map of the solar continuum emission to a calculation from scalar diffraction

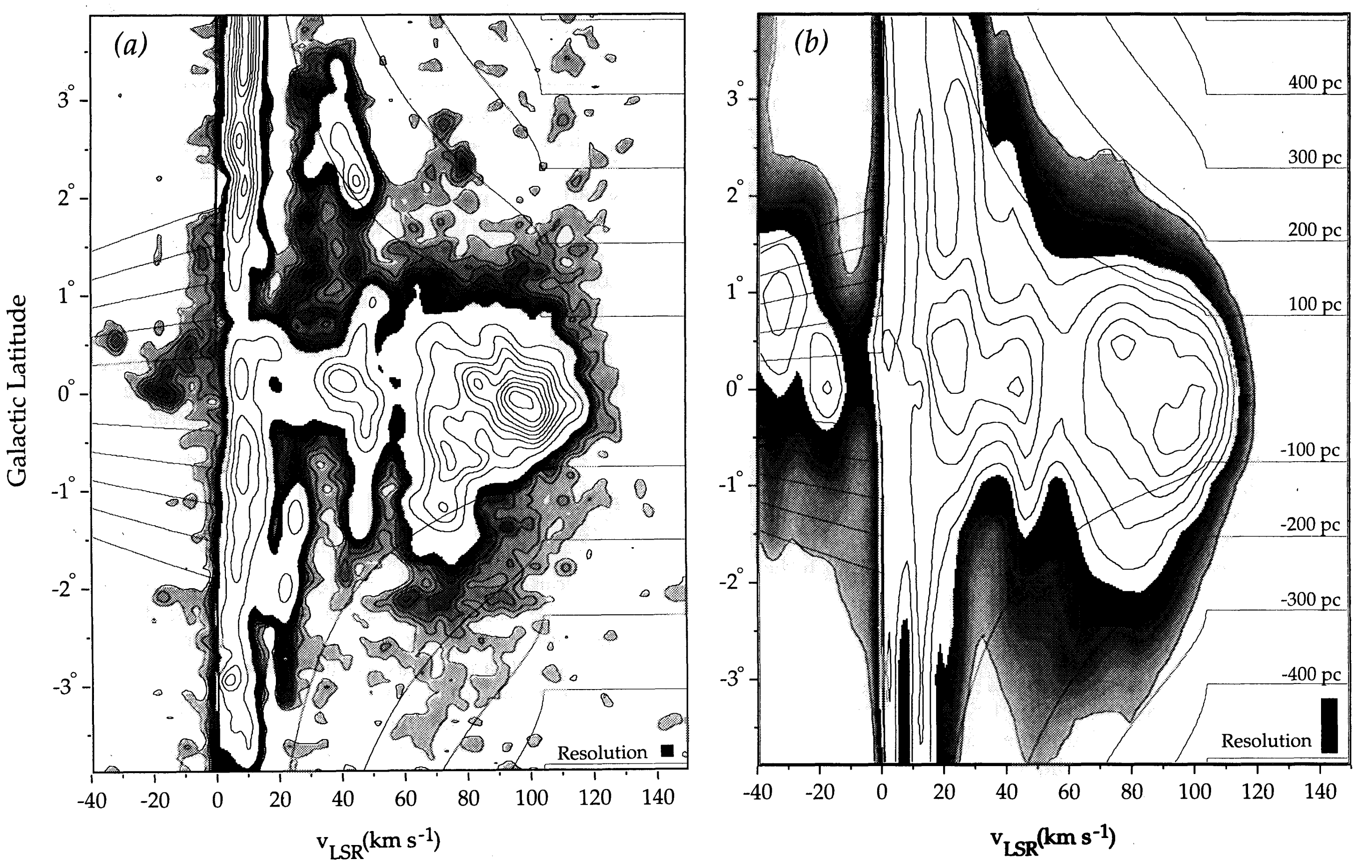

FIG. 1.—(*a*) Latitude-velocity map of Galactic CO emission integrated from 29°5 to 30°5 in longitude. The emission has been smoothed to a resolution of 10′ by 5 km s^{-1}. In the shaded region contours are spaced at 0.015 K deg_l, (i.e., K times degrees of Galactic longitude) starting at 0.015 K deg_l (~2 σ noise level); in the unshaded region, contours are spaced at 0.45 K deg_l, starting at 0.45 K deg_l. The smooth contours indicate distance from the Galactic plane (z) assuming all emission arises from the near kinematic distance; the same contours are labeled in (*b*). (*b*) Latitude-velocity map of Galactic H I emission (Weaver & Williams 1973) integrated over the same longitude range as (*a*). For the sake of comparison, the low-intensity emission which roughly coincides with the high-z CO in (*a*) has been similarly shaded. The lowest contour is at 17.5 K deg_l and the contour interval is 25 K deg_l.

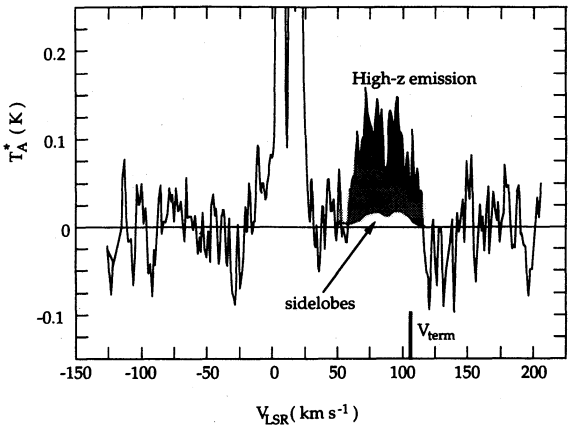

FIG. 2.—An average of the five spectra observed within a half beamwidth of $l = 30^\circ.1875$, $b = -1^\circ.875$, smoothed to a velocity resolution of 2 km s^{-1}. The dotted curve indicates the level of the expected sidelobe contamination. Emission near 105 km s^{-1}, the terminal velocity in this direction, lies ~240 pc below the plane.

theory, finding agreement to 1.3 dB over the crucial region 1°–3° from the main beam. All of the data presented and analyzed here have been cleaned of sidelobe contamination. As Figure 2 shows, the sidelobe correction to the stronger high-z CO lines is small, but it is not insignificant for the determination of the *average* space density of H_2 (see Table 1).

Compared with the other regions surveyed, the emission at negative latitudes toward $l = 30^\circ$ is unusually strong and extends especially far from the plane, perhaps because of an H I "chimney" or "worm" in this direction (Koo, Heiles, & Reach 1992); the emission at positive latitudes, however, is quite typical of that observed in the other windows. To demonstrate this quantitatively, we have computed molecular density as a function of z for the three survey regions, again on the conservative assumption that all emission arises from the near kinematic distance.

The resulting density profiles are shown in Figure 3, with both single Gaussian (solid curve) and double Gaussian (dotted curve) fits superposed. It is evident that the previously made assumption of a single Gaussian distribution of molecular gas breaks down badly in the wings at high z, but that the high-z gas is fairly well represented by a second Gaussian distribution with a width ~3 times greater than the first. To demonstrate why the thick molecular disk escaped previous detection, Figure 3 indicates the typical uncertainty in n_{H_2} derived from the only previous extensive wide-latitude CO survey (Dame et al. 1987). It is also evident that in the three windows observed the present latitude coverage was adequate to reach the outer edge of the thick molecular disk.

The density profiles in Figure 3 are qualitatively similar to those found by Lockman (1984) for H I in the inner Galaxy, with a dense central disk immersed in a much lower density disk several times as wide. Both the thin and thick molecular disks, however, are about half as wide as the corresponding H I disks. The width of the *thick* H_2 disk, ~230 pc, is approximately equal to that of the *thin* H I disk (all quantities based on $R_\odot = 8.5$ kpc)—perhaps not an entirely accidental agreement, as discussed below. The widths of the thin disk derived from our double Gaussian fits are somewhat less than those determined by Bronfman et al. (1988) in the same longitude range because in that study fluctuations in the location of the midplane, in part due to individual large complexes, are averaged out.

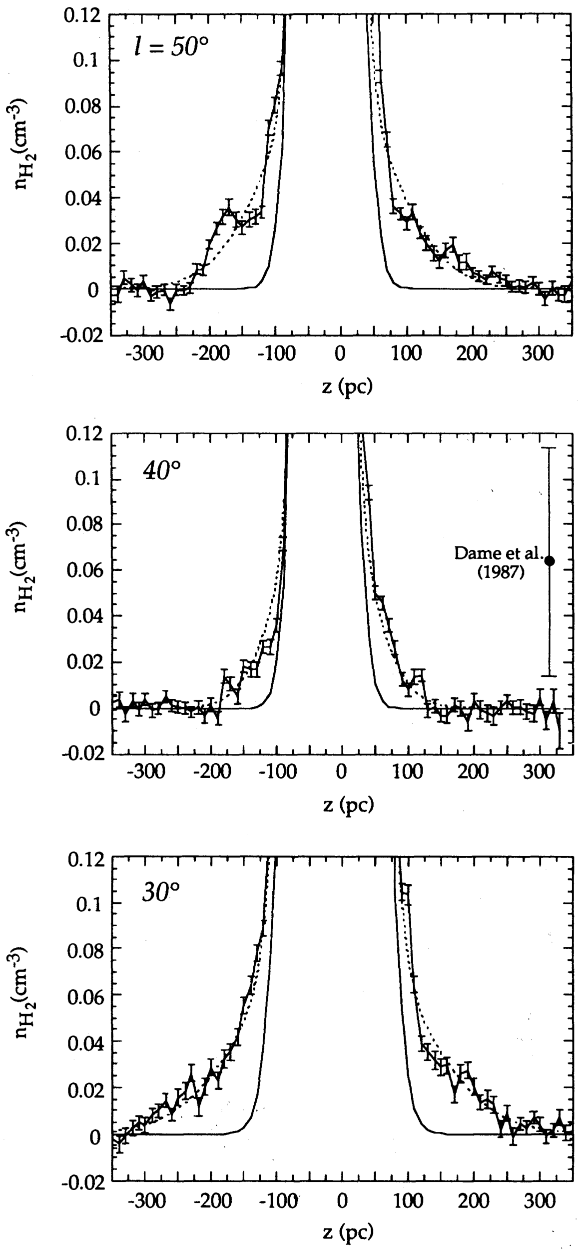

FIG. 3.—Molecular hydrogen number density as a function of distance from the Galactic plane, derived from the survey regions listed in Table 1 on the assumption that all emission arises from the near kinematic distance, and adopting a CO-to-mass conversion factor of 2.3×10^{20} cm^{-2} K^{-1} km^{-1} s (Strong et al. 1988). These profiles apply primarily to their respective subcentral regions, since it is only there that an adequate range of z is sampled. The profiles are shown with an expanded density scale to better display the low-density wings at high z. Single and double Gaussian fits are overlaid as solid and dotted lines, respectively. The large error bar corresponds to the only previous extensive wide-latitude CO survey of the Galaxy (Dame et al. 1987).

4. DISCUSSION

Although it is not yet possible to determine very accurately the distribution of high-z gas with Galactic radius and azimuth, the present narrow windows across the Galactic plane suggest rather strongly that the high-z gas may lie mainly above spiral arms. The thick H_2 disk is significantly wider and denser in the $l = 50^\circ$ and 30° regions, which have subcentral points in the Sagittarius and Scutum spiral arms, respectively, than in the 40° region, which has a subcentral point in a classic interarm region. It is evident even from Figure 1*a* that the high-*z* gas does not exist everywhere along the line of sight. For example, at negative latitudes in the velocity range 25–60 km s^{-1}, little CO is detected more than 100 pc from the plane, even though CO there would be easier to detect than the more distant gas detected at higher velocities.

In Figure 3, $\sim 5\%$ of the total emission lies beyond the wings of the thin Gaussian layer. However, if the high-*z* emission we have detected represents the wings of a new, distinct molecular component which also exists in the plane, the total emission in this component is quite significant, representing $\sim 15\%$ of the total. We already have some preliminary evidence that the high-*z* gas is a distinct component, at least in terms of its physical properties. As will be discussed in a subsequent paper, an analysis of the terminal velocity emission at $b = -2°$ suggests that the high-*z* gas has a higher velocity dispersion than gas in the plane, and ^{13}CO observations now in progress suggest that the high-*z* gas has a lower CO optical depth. Just such a distinct, lower optical depth molecular layer has been proposed by Polk et al. (1988) to explain the discrepancy between ^{12}CO/^{13}CO line intensity ratios in dense molecular clouds and those averaged over large areas of the Galactic plane.

At $l = 30°$, few well-defined clouds are apparent in the high-*z* molecular gas. The two most obvious lie near $v = 70$ km s^{-1}, $b = 2\overset{\circ}{.}5$ in Figure 1*a*, and these may also be present in the corresponding H I map (Fig. 1*b*). The lack of well-defined clouds is not surprising, however, since few clouds large enough for us to resolve would be expected to fall in our narrow window if the cloud mass spectrum is similar to that found near the plane. More structure is apparent at $l = 50°$, the window where the high-*z* CO we detect is closest; there the emission appears largely confined to a few clumps and filaments with a filling factor of approximately one-half.

A relationship between the high-*z* molecular gas that we observe in the inner Galaxy and the *IRAS* infrared "cirrus" observed locally at high latitudes would be interesting to establish, since little is currently known about the distance to the cirrus. Both seem filamentary in structure and relatively diffuse, and the CO optical depth in both is apparently low. Furthermore, the similarity in width of the thick H_2 disk to that of the central H I disk suggests that H_2 and H I are well mixed in the thick H_2 disk, as they appear to be in the cirrus.

Further study of the Galactic distribution and velocity dispersion of the high-*z* H_2 may help to distinguish among the various mechanisms that have been proposed to lift neutral gas well above the plane. If, as Lockman & Gehman (1991) propose for the H I, the high-*z* molecular layer is turbulently supported, driven by stellar winds and supernovae, its velocity dispersion must be ~ 3 times larger than that of the dense central layer, and thus ~ 15 km s^{-1}. The energy required to lift the gas to $z = 200$ pc is quite modest, amounting to only a few percent of that estimated by Abbott (1982) to be injected into gas bulk motions by supernovae and stellar winds.

Finally, it should be noted that a few molecular clouds lying outside the dense central layer are already known. Nyman et al. (1987) studied a large ($\sim 10^5$ $M_\odot$) molecular cloud in Lupus whose kinematic distance of 2.4 kpc places it ~ 200 pc above the plane. Using indirect distance indicators, Mebold et al. (1985) have argued that a high-latitude cloud in Draco with an unusually large radial velocity (-22 km s^{-1}) lies more than 500 pc from the plane. There are also a few other examples of high-latitude clouds with large negative radial velocities (e.g., G211+63 at -39 km s^{-1}, Désert, Bazell, & Blitz 1990; G135+55 at -45 km s^{-1}, Heiles, Reach, & Koo 1988), suggestive of a cloud population with a large scale height. Studies of the *z* distribution of gas are difficult in external galaxies unless they are observed edge-on, like NGC 891, a fairly close spiral similar in many respects to the Milky Way. In NGC 891, Garcia-Burillo et al. (1992) have claimed a thick molecular disk much thicker than that here, with molecular gas more than 1 kpc from the plane.

We are grateful to T. Stark for very helpful discussions on sidelobe contamination and for obtaining confirming spectra with the AST/RO telescope, and to M. Namazi for help with the data taking.

REFERENCES

Abbott, D. C. 1982, ApJ, 263, 723
Bania, T. M., & Lockman, F. J. 1984, ApJS, 54, 513
Bronfman, L., Cohen, R. S., Alvarez, H., May, J., & Thaddeus, P. 1988, ApJ, 324, 248
Cohen, R. S., Dame, T. M., & Thaddeus, P. 1986, ApJS, 60, 695
Dame, T. M., et al. 1987, ApJ, 322, 706
Désert, F. X., Bazell, D., & Blitz, L. 1990, ApJ, 355, L51
de Vries, H. W., Heithausen, A., & Thaddeus, P. 1987, ApJ, 319, 723
Garcia-Burillo, S., Guélin, M., Cernicharo, J., & Dahlem, M. 1992, A&A, 266, 21
Heiles, C. 1984, ApJS, 55, 585
Heiles, C., Reach, W. T., & Koo, B.-C. 1988, ApJ, 332, 313
Koo, B.-C., Heiles, C., & Reach, W. T. 1992, ApJ, 390, 108
Lockman, F. J. 1984, ApJ, 283, 90
Lockman, F. J., & Gehman, C. S. 1991, ApJ, 382, 182
Mebold, U., Cernicharo, J., Velden, L., Reif, K., Crezelius, C., & Goerigk, W. 1985, A&A, 151, 427
Nyman, L.-Å., Thaddeus, P., Bronfman, L., & Cohen, R. S. 1987, ApJ, 314, 374
Polk, K. S., Knapp, G. R., Stark, A. A., & Wilson, R. W. 1988, ApJ, 332, 432
Sanders, D. B., Clemens, D. P., Scoville, N. Z., & Solomon, P. M. 1986, ApJS, 60, 1
Strong, A. W., et al. 1988, A&A, 207, 1
Weaver, H., & Williams, R. D. W. 1973, A&AS, 8, 1