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AST/RO OBSERVATIONS OF ATOMIC CARBON NEAR THE GALACTIC CENTER

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ABSTRACT

We present a coarsely sampled map of the region $|l| \leq 2^\circ$, $|b| \leq 0.1^\circ$ in the 492 GHz ($^3P_1 \rightarrow ^3P_0$) fine-structure transition of neutral carbon, observed with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). The distribution of [C I] emission is similar on the large scale to that of CO $J = 1 \rightarrow 0$. On average, the ratio of the integrated intensities, $I_{[\text{C I}]} / I_{12\text{CO}}$, is higher in the Galactic disk than in the Galactic center region. This result is accounted for by the absorption of ^{12}CO within the clouds located in the outer Galactic disk. The ratio $I_{[\text{C I}]} / I_{12\text{CO}}$ is surprisingly uniform over the variety of environments near the Galactic center. On average, [C I] is optically thin [or as optically thin as ^{13}CO ($J = 1 \rightarrow 0$)], even in the dense molecular clouds of the Galactic center region.

Subject headings: Galaxy: abundances — Galaxy: center — ISM: atoms — ISM: general — ISM: molecules

1. INTRODUCTION

The Galactic center is a complex region displaying an array of interesting astrophysical phenomena, many of which indicate an environment very different from the Galactic disk (see Morris & Serabyn 1996 for a recent review). One striking feature is that the average density of molecular material is much higher in the Galactic center than anywhere else in the Galaxy, with the Galactic center interstellar medium (ISM) dominated by molecular cloud complexes. Though the inner 500 pc of the Galaxy is less than 0.2% by volume of the Galactic disk, it contains nearly 10% of the Galaxy's molecular mass. Galactic center molecular clouds are distinctly different from molecular clouds in the disk. They have large internal velocity dispersions with line widths 4–5 times wider than is typical of the Galactic disk. They are warm and have a high density, which lets them survive the tidal disruptions of the central mass concentration (Stark et al. 1991).

The fine-structure lines of neutral atomic carbon C^0 are an important source of information about the physics and chemistry of molecular clouds and play an important role in their energy balance. These lines are predicted to be the primary coolants throughout the partially opaque ($A_v \sim 1\text{--}3$) regions of molecular clouds (Wolfire et al. 1995). The fine-structure [C I] ($^3P_1 \rightarrow ^3P_0$) transition of neutral carbon is excited at densities $n \gtrsim 500 \text{ cm}^{-3}$ and temperatures $T \gtrsim 24 \text{ K}$. It traces phases of the molecular ISM where CO either will not be excited (the critical density for the CO $J = 1 \rightarrow 0$ transition is $n_{\text{cr}} \sim 1500 \text{ cm}^{-3}$) or will have been dissociated (Keene et al. 1996). It has been argued (Stark et al. 1997a) that such “photon-dominated regions” or “photodissociation regions” (PDRs) are more extensive in metal-poor environments (as the shortage of dust exposes more CO molecules to the dissociating UV radiation), resulting in a higher C/CO ratio. Because the Galactic

center has higher metallicity than the Galactic disk (e.g., Afflerbach, Churchwell, & Werner 1997), studying the C/CO ratio there helps in deriving a possible relationship between metallicity and $I_{[\text{C I}]} / I_{12\text{CO}}$ (Bolatto et al. 2000). Such a relationship may be a valuable tool for estimating the metallicity of distant galaxies.

Past observations of the Galactic center in [C I] include those of White & Padman (1991), Serabyn et al. (1994), and Jaffe, Plume, & Evans (1996). Serabyn et al. present high-resolution observations of a part of the Galactic center region. Jaffe et al. (1996) find that [C I] has very similar distribution (in longitude and velocity) to emission in CS and ^{13}CO . They report that the mean [C I] properties of the Galactic center gas show little change with position.

2. OBSERVATIONS

The low humidity, high atmospheric stability, and thin troposphere at the South Pole make it an excellent site for submillimeter astronomy (Chamberlin, Lane, & Stark 1997; Lane 1998). AST/RO is a general-purpose telescope built to take advantage of this site. It is a 1.7 m diameter, offset Gregorian telescope currently capable of observing at wavelengths between 350 μm and 1.3 mm (Stark et al. 1997b; Stark et al. 2000).

Using AST/RO's quasi-optical SIS receiver (Engargiola, Zmuidzinas, & Lo 1994) with a receiver noise temperature of 180 K, we observed the fine-structure [C I] ($^3P_1 \rightarrow ^3P_0$) neutral carbon transition at 492.1607 GHz during the austral winter of 1995. The telescope beam has half-power beamwidth (HPBW) $\sim 2'$ at this frequency. The absolute pointing error was less than half a beamwidth. The backend was a 1.1 GHz wide acousto-optical spectrometer (Schieder, Tolls, & Winnewisser 1989), with 1.07 MHz wide (0.65 km s^{-1}) channels and a channel spacing of 674 kHz. The observations were made using position switching $90'$ away in

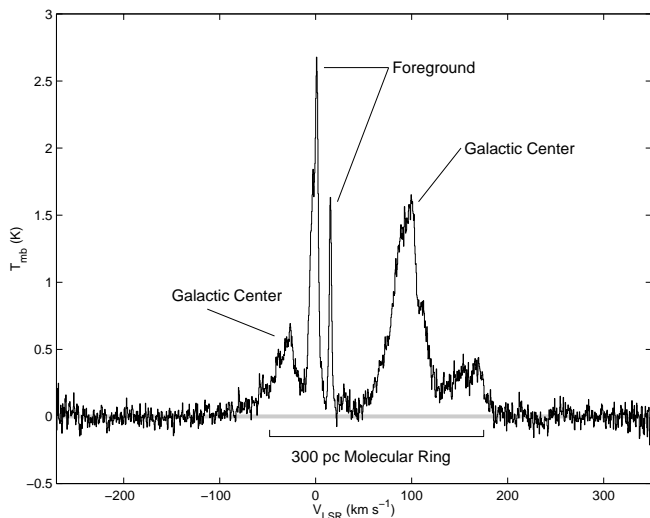


FIG. 1.—Typical [C I] spectrum in the Galactic center region at $l = 0^\circ$, $b = +0^\circ.1$. The narrow features are Galactic center and foreground clouds. The 300 pc nuclear disk emits weakly between -110 and 200 km s $^{-1}$.

azimuth (or right ascension, since they are identical at the South Pole). The data were calibrated using the procedure described by Stark et al. (2000). The typical calibration uncertainty in 492 GHz data obtained by AST/RO is $\lesssim 10\%$.

A total of 74 sparsely sampled spectra were obtained toward the Galactic center region $|l| \leq 2^\circ$, $|b| \leq 0^\circ.1$. The

spacing between observed spectra was $\Delta l = 0^\circ.1$ for $|l| \leq 1^\circ$, and $\Delta l = 0^\circ.2$ for $1^\circ \leq |l| \leq 2^\circ$ at three latitudes: $b = 0^\circ$ and $b = \pm 0^\circ.1$. A typical spectrum is shown in Figure 1, and the l - v diagram of the data set is shown in Figure 2. Typical rms noise was 0.1 K in 1.07 MHz wide channels.

Neutral carbon emission is detected at all positions in all the molecular features of the inner Galaxy, including the 300 pc nuclear disk.

3. RESULTS

To compare the molecular and atomic phases of the PDR, we have extracted ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$ spectra from the Bally et al. (1987) survey, which have the same positions and angular resolution as the [C I] data. These CO data are shown in Figures 3 and 4 (*contours*), together with the [C I] data (*color scale*).

The rectangular regions shown in Figure 2 were chosen to be unconfused samples of emission either from Galactic center molecular material or from foreground clouds. The $I_{[\text{C I}]} / I_{^{12}\text{CO}}$ ratio is shown next to each region, with the corresponding $I_{[\text{C I}]} / I_{^{13}\text{CO}}$ ratio in parentheses. These ratios are summarized in Table 1.

Although the Galactic center material has uniformly higher metallicity than the outer Galaxy, it varies widely in density, temperature, and optical depth. For example, the diffuse nuclear-disk material is a noncloudy (i.e., bound to the Galaxy as a whole and not to any small region), pervasive medium with moderate density ($n \sim 1000$ cm $^{-3}$) and temperature (Stark et al. 1989), whereas Sgr B2 is among the largest, hottest, and densest clouds in the Galaxy. Neverthe-

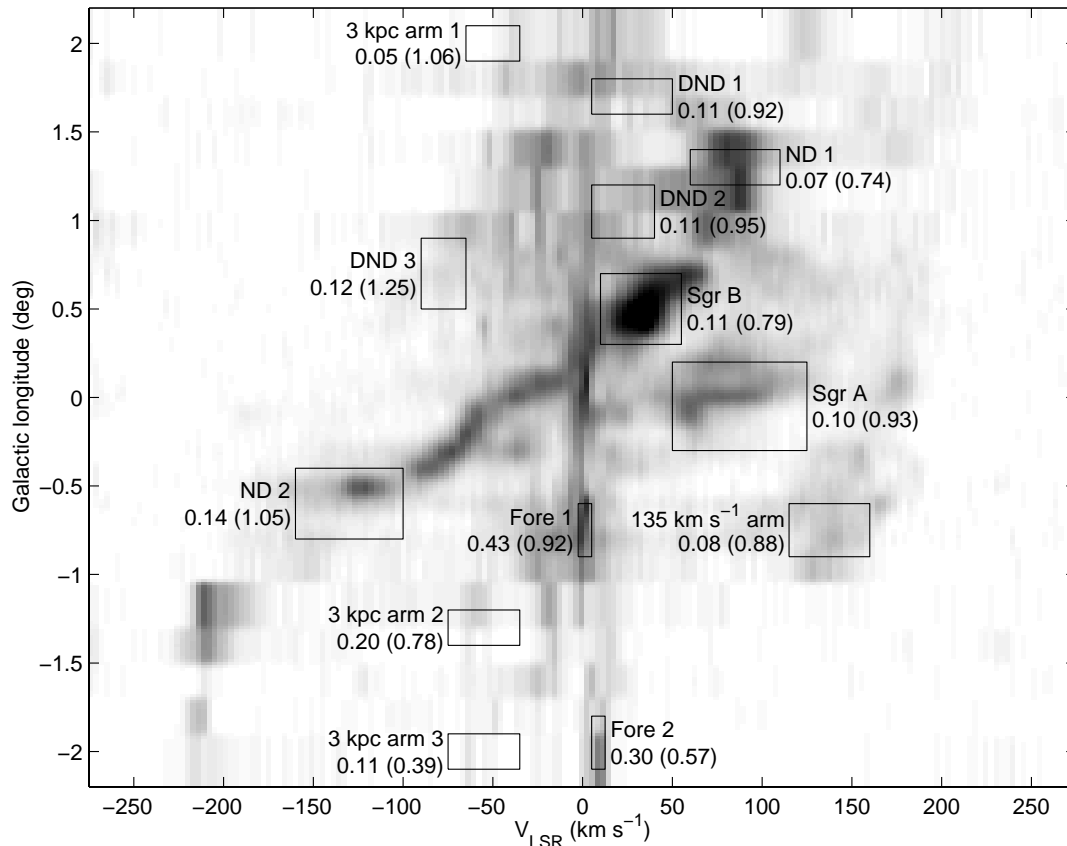


FIG. 2.—Position velocity diagram of [C I] emission. Unconfused regions defined in Table 1 are denoted by boxes. Adjacent to each box are the corresponding [C I]/ ^{12}CO intensity ratio with the [C I]/ ^{13}CO intensity ratio in parentheses (intensities in K km s $^{-1}$). Errors on these values are less than 10% in all cases. Note that $I_{[\text{C I}]} / I_{^{12}\text{CO}} \sim 0.1$ for all Galactic center region clouds, whereas $I_{[\text{C I}]} / I_{^{12}\text{CO}} \sim 0.35$ for foreground material.

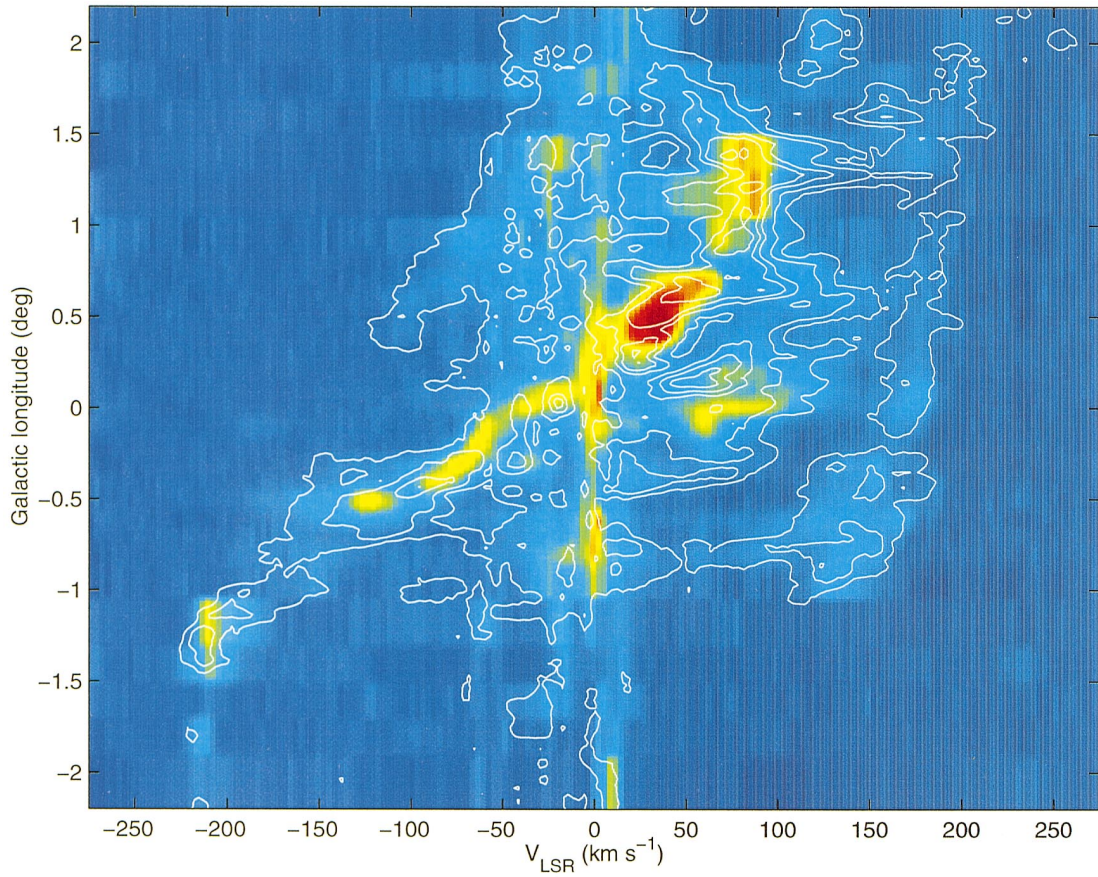


FIG. 3.—Position velocity diagram for [C I] emission (*color*) with $^{12}\text{CO } J=1 \rightarrow 0$ contours overlaid (contours are 2, 5, 11, 15, and 20 K km s^{-1})

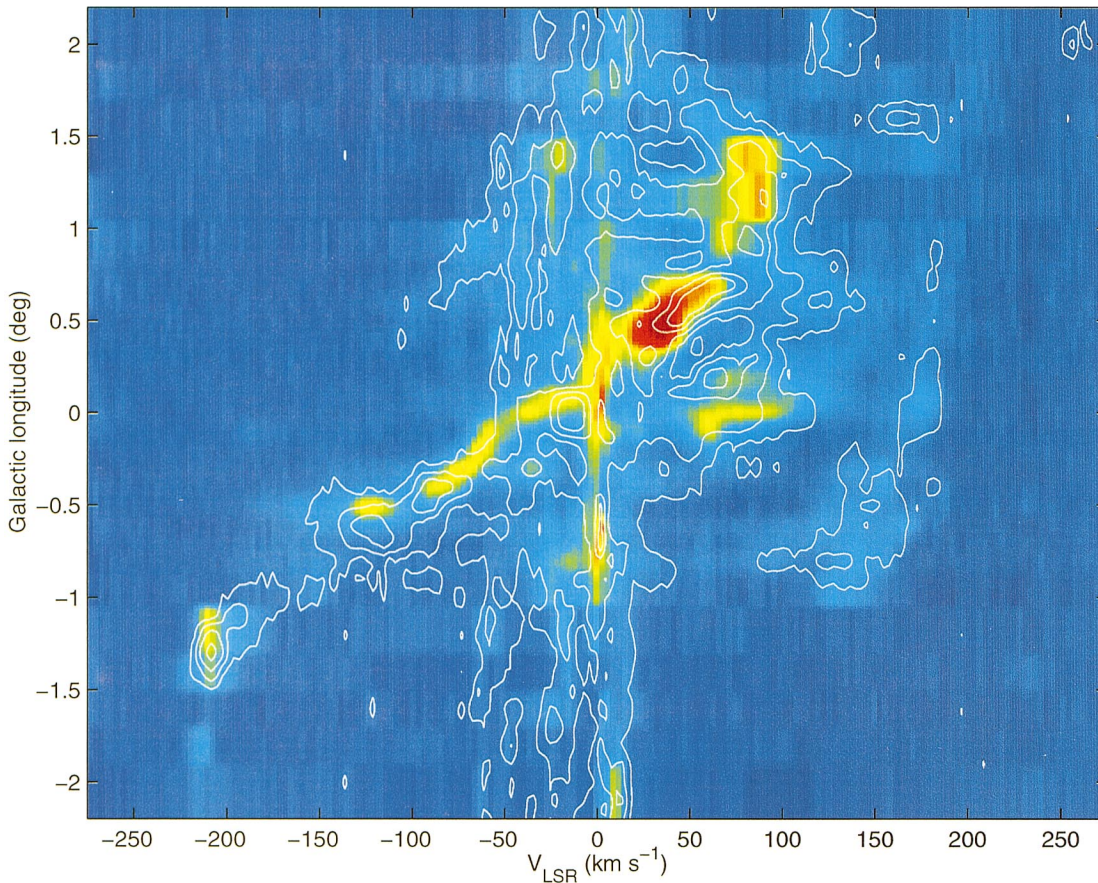


FIG. 4.—Position velocity diagram for [C I] emission (*color*) with $^{13}\text{CO } J=1 \rightarrow 0$ contours overlaid (contours are 0.3, 0.8, 1.5, 2.5, and 3.5 K km s^{-1})

TABLE 1
[C I]/CO RATIOS AT THE GALACTIC CENTER

Region	l^a (deg)	V_{LSR} (km s $^{-1}$)	$I_{[\text{C I}]} / I_{12\text{CO}}^b$	$I_{[\text{C I}]} / I_{13\text{CO}}^c$
135 km s $^{-1}$ arm.....	-0.6 to -0.9	115-160	0.08 ± 0.004	0.88 ± 0.08
Sgr A	0.1 to -0.3	50-125	0.10 ± 0.008	0.93 ± 0.02
Diffuse nuclear disk:				
Region 1.....	1.8-1.6	5-50	0.11 ± 0.012	0.92 ± 0.05
Region 2.....	1.2-0.9	5-40	0.11 ± 0.004	0.95 ± 0.07
Region 3.....	0.9-0.5	-90 to -65	0.12 ± 0.005	1.25 ± 0.15
3 kpc arm:				
Region 1.....	2.0	-65 to -35	0.05 ± 0.006	1.06 ± 0.54
Region 2.....	-1.2 to -1.4	-75 to -35	0.20 ± 0.034	0.78 ± 0.20
Region 3.....	-2.0	-75 to -35	0.11 ± 0.041	0.39 ± 0.06
Sgr B	0.7-0.3	10-55	0.11 ± 0.001	0.79 ± 0.01
300 pc nuclear disk:				
Region 1.....	1.4-1.2	60-110	0.07 ± 0.001	0.74 ± 0.01
Region 2.....	-0.4 to -0.8	-160 to -100	0.14 ± 0.007	1.05 ± 0.03
Foreground 1.....	-0.6 to -0.9	-2.5-5	0.43 ± 0.020	0.92 ± 0.02
Foreground 2.....	-2.0	5-12.5	0.30 ± 0.039	0.57 ± 0.02

^a The Galactic latitude range is $b = -0^\circ 1 - 0^\circ 1$ in all cases.

^b Ratio of integrated intensities (intensities in K km s $^{-1}$, to convert to a cooling ratio multiply by 78).

^c Ratio of integrated intensities (intensities in K km s $^{-1}$, to convert to a cooling ratio multiply by 89).

less, the $I_{[\text{C I}]} / I_{12\text{CO}}$ ratio is uniformly ~ 0.1 in our sample of Galactic center regions (Fig. 5).

Kaufman et al. (1999) compute this $I_{[\text{C I}]} / I_{12\text{CO}}$ ratio for PDR models using a wide range of density and incident far-ultraviolet (FUV) radiation field. Using Kaufman's results, our observed ratio (a conversion factor of 78 is needed to convert from our integrated intensity units of K km s $^{-1}$ to ergs s $^{-1}$ cm $^{-2}$ sr $^{-1}$) corresponds to a density of $\sim 3 \times 10^4 - 2 \times 10^5$ cm $^{-3}$ and does not constrain the FUV radiation field. This is unsurprising since the column density of [C I] is expected to be relatively independent of cloud density and the strength of FUV radiation; the radiation field simply determines the depth at which the C $^+$ /C I/CO transition occurs (Hollenbach, Takahashi, & Tielens 1991).

In contrast to the Galactic center material, the foreground regions have an $I_{[\text{C I}]} / I_{12\text{CO}}$ ratio ~ 0.35 . Unlike $I_{[\text{C I}]} / I_{12\text{CO}}$, the $I_{[\text{C I}]} / I_{13\text{CO}}$ ratio is essentially constant over all features of both the inner and outer Galaxy. This is in agreement with the results of Keene et al. (1996). Comparison between the ^{12}CO and ^{13}CO spectra (Fig. 6) shows that the ^{12}CO ($J = 1 \rightarrow 0$) emission is likely absorbed within the foreground clouds, thus explaining their anomalously high $I_{[\text{C I}]} / I_{12\text{CO}}$ ratios. This can also be appreciated in Figure 5. The spectra corresponding to foreground regions (*red symbols*) show anomalously high $I_{[\text{C I}]} / I_{12\text{CO}}$ and $I_{13\text{CO}} / I_{12\text{CO}}$ ratios but standard $I_{[\text{C I}]} / I_{13\text{CO}}$ ratios. Consequently, [C I] appears to be at least as optically thin as ^{13}CO in all Galactic center and foreground features. The values for the different ratios, averaged only over our sample of unconfused Galactic center clouds, are $I_{[\text{C I}]} / I_{12\text{CO}} \approx 0.08 \pm 0.01$, $I_{[\text{C I}]} / I_{13\text{CO}} \approx 0.75 \pm 0.20$, and $I_{13\text{CO}} / I_{12\text{CO}} \approx 0.11 \pm 0.01$. These ratios are broadly in agreement with the ratios reported by Jaffe et al. (1996).

How constant are these ratios throughout the Galactic center region? We have performed the following analysis on the entire ^{12}CO , ^{13}CO , and [C I] data sets: each position observed has been decomposed into 4 km s $^{-1}$ wide channels between -200 and 200 km s $^{-1}$ LSR velocity, and the

integrated intensity has been calculated for each bin. We have then examined the $I_{[\text{C I}]} / I_{12\text{CO}}$, $I_{[\text{C I}]} / I_{13\text{CO}}$, and $I_{13\text{CO}} / I_{12\text{CO}}$ intensity ratios as a function of the corresponding $I_{12\text{CO}}$, $I_{13\text{CO}}$, and $I_{12\text{CO}}$ intensities. These ratios are essentially flat across more than an order of magnitude in integrated intensity. The average ratios for the complete data set are $I_{[\text{C I}]} / I_{12\text{CO}} \approx 0.08 \pm 0.01$, $I_{[\text{C I}]} / I_{13\text{CO}} \approx 0.59 \pm 0.02$, and $I_{13\text{CO}} / I_{12\text{CO}} \approx 0.10 \pm 0.01$, basically indistinguishable from the average ratios obtained for our sample of unconfused Galactic center regions (Fig. 5). While the plot for $I_{[\text{C I}]} / I_{13\text{CO}}$ has some outlying points, this may not be significant as we have a small sample.

4. SUMMARY AND CONCLUSIONS

We have presented a sparsely sampled [C I] map of the Galactic center region. The corresponding l - v diagram shows that neutral carbon emission is detected in all the molecular features of the inner Galaxy. Despite large variations in the environments and physical conditions throughout this region, the integrated intensity ratios $I_{[\text{C I}]} / I_{12\text{CO}}$ and $I_{[\text{C I}]} / I_{13\text{CO}}$ remain remarkably constant. For the material identified as foreground, we find that the $I_{[\text{C I}]} / I_{12\text{CO}}$ ratio is clearly higher than in the material unambiguously identified with the Galactic center. This effect we attribute to the absorption of ^{12}CO emission within the colder foreground material because (1) the $I_{[\text{C I}]} / I_{13\text{CO}}$ ratio is identical for Galactic center and foreground clouds and (2) the individual ^{12}CO spectra show depressions at the relevant velocities.

It is remarkable that the $I_{[\text{C I}]} / I_{13\text{CO}}$ ratio is uniform in clouds with such a wide variety of physical conditions and metallicity. This observational fact has as yet no satisfactory theoretical explanation.

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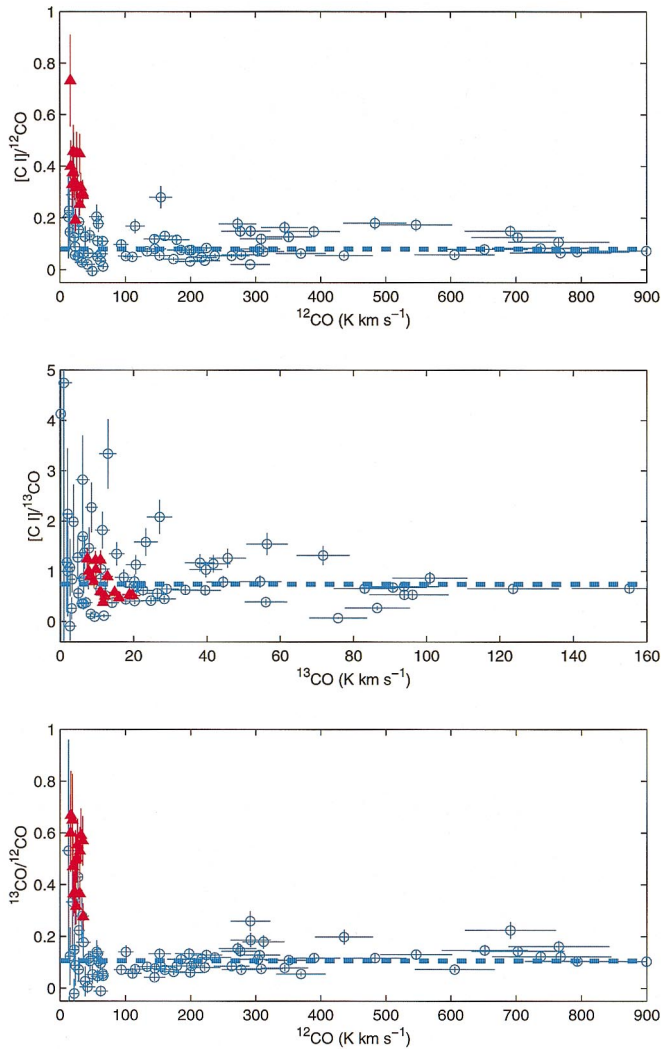


FIG. 5.—Plots of integrated intensity ratios for spectra associated with the features identified in Table 1 (one point per spectrum). Points for the foreground material are shown in red, while blue signifies Galactic center clouds. The error bars are 1σ and include 10% calibration uncertainty added in quadrature to statistical errors. The anomalous ratios evident in the foreground material are likely due to absorption of ^{12}CO by cooler foreground material. The median value for each ratio, computed using only the Galactic center emission, is indicated by the dashed line.

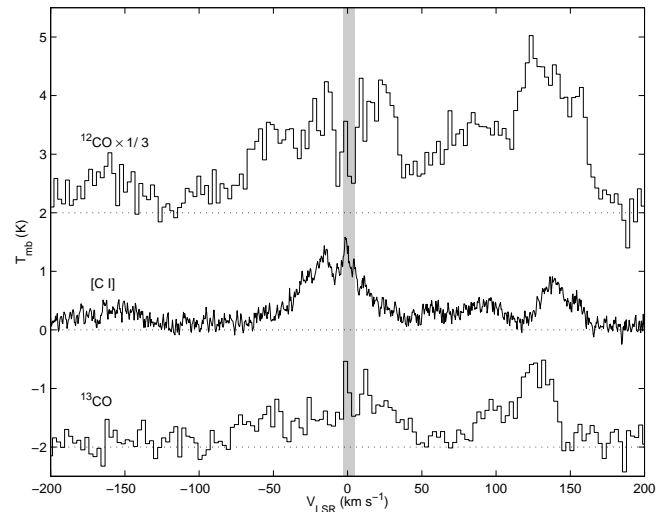


FIG. 6.—Comparison of ^{12}CO , ^{13}CO , and $[\text{C I}]$ spectra at a typical position with foreground emission ($l = -0^\circ 8$, $b = 0^\circ$). The ^{12}CO shows indications of absorption at the foreground velocities (-2.5 – 5 km s^{-1}).

REFERENCES

- Afflerbach, A., Churchwell, E., & Werner, M. W. 1997, *ApJ*, 478, 190
 Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, *ApJS*, 65, 13
 Bolatto, A. D., Jackson, J. M., Kraemer, K. E., & Zhang, X. 2000, *ApJ*, 541, L17
 Chamberlin, R. A., Lane, A. P., & Stark, A. A. 1997, *ApJ*, 476, 428
 Engargiola, G., Zmuidzinas, J., & Lo, K.-Y. 1994, *Radio Sci.*, 65, 1833
 Hollenbach, D. J., Takahashi, T., & Tielens, A. G. G. M. 1991, *ApJ*, 377, 192
 Jaffe, D. T., Plume, R., & Evans, N. J. 1996, in *ASP Conf. Ser. 102, The Galactic Center*, ed. R. Gredel (San Francisco: ASP), 16
 Kaufman, M. J., Wolfire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, *ApJ*, 527, 795
 Keene, J., Lis, D. C., Phillips, T. G., & Schilke, P. 1996, in *IAU Symp. 178, Molecules in Astrophysics: Probes & Processes*, ed. E. F. van Dishoeck (Cambridge: Cambridge Univ. Press), 129
 Lane, A. P. 1998, in *ASP Conf. Ser. 141, Astrophysics from Antarctica*, ed. G. Novak & R. H. Landsberg (San Francisco: ASP), 289
 Morris, M., & Serabyn, E. 1996, *ARA&A*, 34, 645
 Schieder, R., Tolls, V., & Winnewisser, G. 1989, *Exp. Astron.*, 1, 101
 Serabyn, E., Keene, J., Lis, D. C., & Phillips, T. G. 1994, *ApJ*, 424, L95
 Stark, A. A., Bally, J., Gerhard, O. E., & Binney, J. 1991, *MNRAS*, 248, 14
 Stark, A. A., Bally, J., Wilson, R. W., & Pound, M. W. 1989, in *IAU Symp. 136, The Center of the Galaxy*, ed. M. Morris (Cambridge: Cambridge Univ. Press), 129
 Stark, A. A., Bolatto, A. D., Chamberlin, R. A., Lane, A. P., Bania, T. M., Jackson, J. M., & Lo, K.-Y. 1997a, *ApJ*, 480, L59
 Stark, A. A., Chamberlin, R. A., Cheng, J., Ingalls, J. G., & Wright, G. A. 1997b, *Rev. Sci. Instrum.*, 68, 2200
 Stark, A. A., et al. 2000, *ApJ*, in press
 White, G. J., & Padman, R. 1991, *Nature*, 354, 511
 Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, *ApJ*, 443, 152