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Multitransition Observations of Molecular Clouds in the Far Outer Galaxy

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Millimeter-wave observations of three molecular clouds in the far outer Galaxy, all with apparent Galactocentric distances $R \gtrsim 20$ kpc, are presented, along with a preliminary analysis of their properties. These clouds are among the farthest from the Galactic center of any known, and although they are near or beyond the edge of the star-forming disk, one has been found to contain an H II region. The observations of lines of CO, ^{13}CO, and CS presented here indicate that the dense clumps in this cloud are distinctly different from those in the others.

INTRODUCTION

In this poster we present observations of three molecular clouds that are near or possibly beyond the outermost extent of on-going star formation in the Milky Way. The clouds were discovered in a survey of CO emission toward peaks of N(H I) at large distances (Digel, de Geus, and Thaddeus 1994; DDT); all have kinematic Galactocentric distances $R \gtrsim 20$ kpc. Here we present the original CO observations of clouds 1, 2, and 4 of DDT with the CfA 1.2 m and follow-up observations in CO and other molecules with the NRAO 12 m and the IRAM 30 m telescopes.

Because the clouds have such great Galactocentric distances (Table 1) and were not selected for study because of possible associations with star-forming regions, they might not be expected to have any on-going star formation. The edge of the star-forming disk of the Milky Way is generally agreed to lie within the range R = 14–17 kpc (DDT, Brand & Wouterloot 1994; BW, and references therein). It is therefore noteworthy that an optical H II region, excited by an early B star, was found by de Geus et al. (1993) to be associated with cloud 2. We present here a preliminary investigation of the manifestations of this difference between cloud 2 and clouds 1 and 4 in the millimeter-wave observations.

Brand & Wouterloot (BW; Brand & Wouterloot 1995) recently published a study of several other molecular clouds in the far outer Galaxy. The primary distinction between the clouds under consideration here and those mapped by BW is that the latter all contain a luminous ($L > 2000\ L_{\odot}$) embedded star-forming region. The BW clouds were in fact discovered through CO observations toward selected bright IRAS point sources (Wouterloot & Brand 1989). Clouds like the two presented here without apparent massive star formation are absent from the BW sample, which is also necessarily limited to the region within the star-forming disk of the Milky Way.

OBSERVATIONS & ANALYSIS

CO maps of the three clouds from CfA, NRAO, and IRAM observations are presented in Figure 1. The figure also indicates any positionally-associated IRAS sources from the Point Source Catalog and the Faint Source Catalog (IRAS Explanatory Supplement 1988; IRAS FSS Explanatory Supplement 1992). Only cloud 2 has any associated sources. The optical H II region discovered by de Geus et al. (1993) is coincident with the IRAS point source near (+3', +2') in the map of cloud 2 (Fig. 1*b*).

All of the clouds are clumpy at the resolution of even the IRAM observations. Prominent clumps are indicated with letters in the NRAO and IRAM maps and Figure 2 shows spectra of these clumps obtained with the NRAO telescope in other transitions. The properties of the clumps. including the intensities of the lines, are presented in Tables 2 & 3. The brightest clumps have velocity widths of 2–3 km s^{-1} and sizes of several parsecs.

The clumps in cloud 2 are seen in the maps, figures, and tables to be qualitatively different from those of clouds 1 and 4. Cloud 2 is the only one detected in CS, which indicates the presence of dense, ~10^5 cm^{-3}, gas. The clumps in cloud 2 are warmer and more massive than those of the other clouds.

The relative magnitudes of the virial and CO masses of the clumps (Table 3) are consistent with cloud 2 being warmer than clouds 1 and 4, i.e., cloud 2 is brighter in CO per unit virial mass. Owing to the uncertainty of the $N(H_2)/W_{CO}$ ratio at such great Galactocentric distances, the absolute masses of the clumps can be determined only approximately.

Smartt, Dufton, & Rolleston (1995) recently undertook a spectroscopic study of the star exciting the H II region in cloud 2 and found its velocity to be consistent with that of the cloud, but its distance much less than the kinematic distance, corresponding to R = 15–19 kpc. Even at the closer distance the clumps of cloud 2 would be more massive than the others, although on-going star formation would be less remarkable.

CONCLUSIONS

High resolution maps of the some of most distant molecular clouds known in the outer Galaxy indicate qualitative differences between the star-forming and non-star-forming clouds there. Only cloud 2 apparently contains embedded IRAS sources and is supporting on-going massive star formation. Although not likely to be as remote as its kinematic distance indicates, the clumps in this cloud are certainly warmer and more massive than their counterparts in the other clouds.

References

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TABLE 1 - LOCATIONS AND DISTANCES OF CLOUDS

Name	Map Reference Position (l, b)	(1950 α, δ)	V_{LSR} (km s^{-1})	R[1] (kpc)	D (kpc)
Cloud 1	131°.12, 1°.43	2:01:11.1, 62:53:20	-102	22	16
Cloud 2	137.75, -1.00	2:44:44.8, 58:15:00	-102	28	21
Cloud 4	145.38, -0.09	3:35:55.4, 55:06:40	-70	19	11

[1]Kinematic, derived on the assumption of a flat rotation curve with $R_{\odot}$ = 8.5 kpc and $V_{\odot}$ = 220 km s^{-1}.

TABLE 2 - OBSERVED PROPERTIES OF CLUMPS

Clump Name	Offset ($\Delta\alpha$, $\Delta\delta$)	ΔV (FWHM) (km s^{-1})	T_R[1](K) CO(1–0)	T_R[1](K) CO(2–1)	T_R[1](K) ^{13}CO(1–0)	T_R[1](K) CS(2–1)
1a	+2′.5, -2′.5	2.2	4.5	3.0	1.2	< 0.03
1b	-4.0, +7.0	2.7	4.7	3.4	0.9	< 0.03
2a	+1.5, +2.0	1.9	10	6.3	2.3	0.17
2b	+1.0, +1.0	2.6	8.4	5.4	1.0	0.14
2c	-0.5, -4.0	2.1	8.0	—	—	0.27
4a	+1.5, +3.0	1.0	4.6	2.9	1.0	< 0.03

[1]Radiation temperatures are T_R^* corrected for source coupling efficiency (J. Howe, private communication).

TABLE 3 - DERIVED PROPERTIES OF CLUMPS

Clump Name	r[1] (pc)	M_{CO}[2] (10^3 $M_{\odot}$)	M_{vir}[3] (10^3 $M_{\odot}$)
1a	4.3	1.5	4.8
1b	3.4	1.5	6.0
2a	4.3	5.1	3.6
2b	6.1	7.1	10
2c	4.3	5.9	4.8
4a	3.5	1.0	0.8

[1]Radius of half-peak intensity contour in NRAO or IRAM CO map, corrected for beam size.
[2]CO luminosity-inferred mass, on the assumption that $N(H_2)/W_{CO} = 2 \times 10^{20}$ cm^{-2} (K km $s^{-1})^{-1}$.
[3]Mass of a uniform, spherical cloud in virial equilibrium.

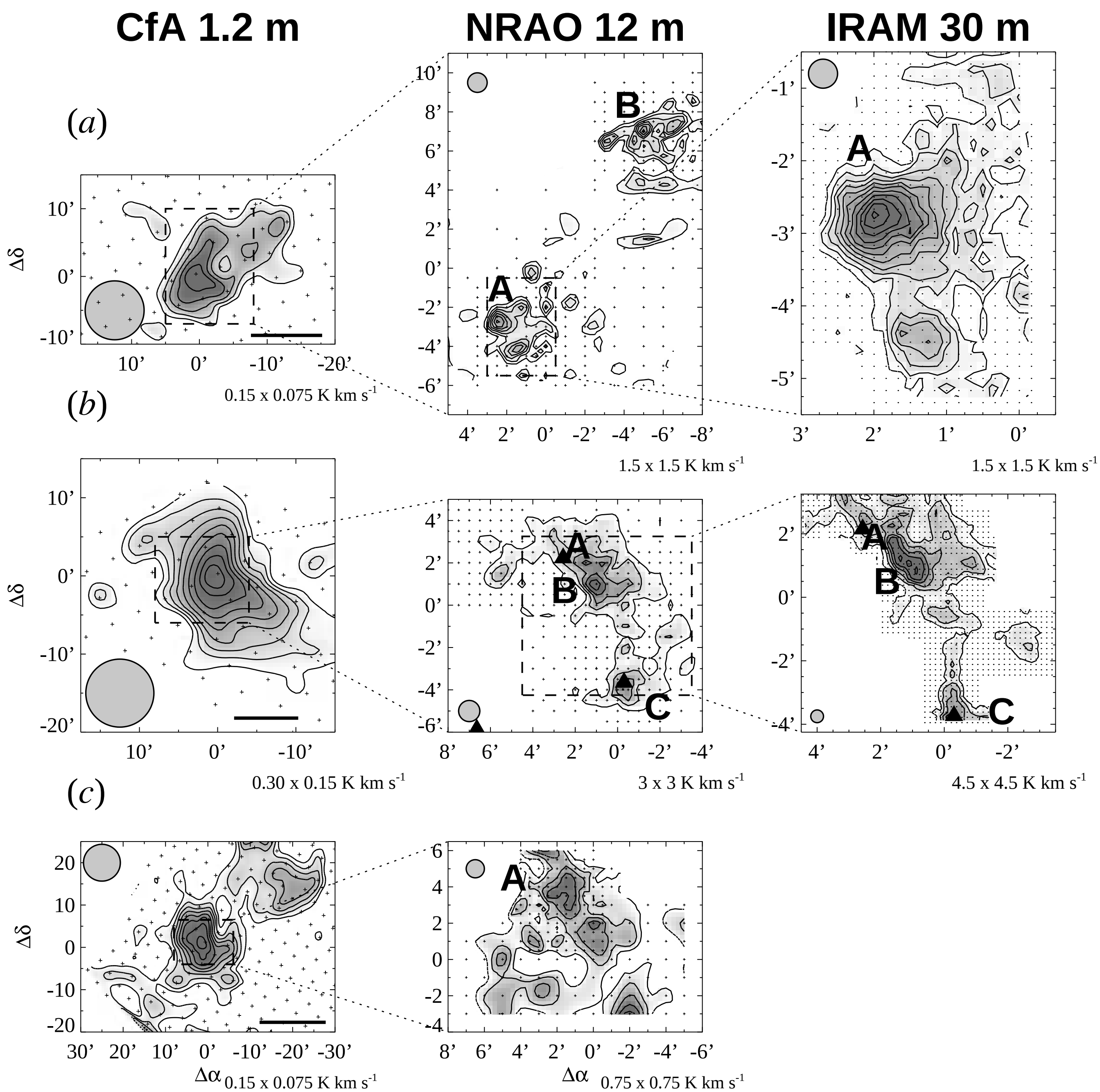

Figure 1

Figure 1. CO maps derived from the CfA, NRAO, and IRAM observations of the three clouds. The velocity ranges of integration include all emission. The resolution and sampling of the observations, as well as the contour intervals, are indicated. The bars correspond to 50 pc at the kinematic distances of the clouds (Table 1). The clumps in Table 2 are labeled. IRAS sources in the Point Source Catalog and the Faint Source Catalog positionally associated with any of the clouds are indicated by filled triangles in the NRAO and IRAM maps. (*a*) Cloud 1; (*b*) Cloud 2; (*c*) Cloud 4.

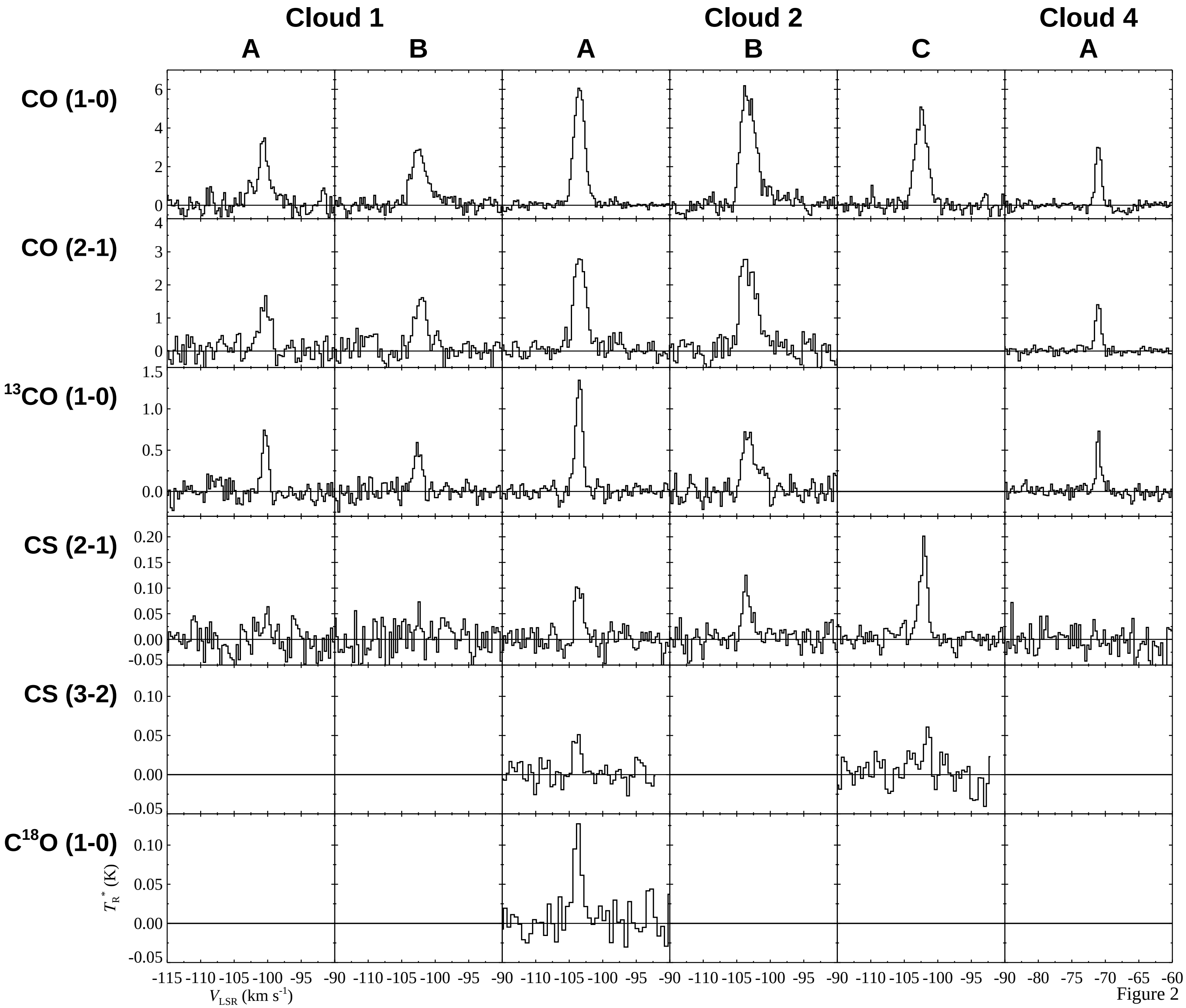

Figure 2. Spectra from NRAO observations of the clumps indicated in Fig. 1 and Table 2. CO (1–0), CO (2–1), ^{13}CO (1–0), CS (2–1), CS (3–2), and C^{18}O (1–0) spectra, where available, are shown on the same intensity scales. (*a*) Cloud 1; (*b*) Cloud 2; (*c*) Cloud 4.