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DETECTION OF ^{13}CO $J = 3 \to 2$ IN IC 342: WARM, CLUMPY MOLECULAR GAS

W. F. Wall and D. T. Jaffe
Department of Astronomy, University of Texas at Austin
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ABSTRACT

We report the first detection of the ^{13}CO $J = 3 \to 2$ line and present a 15″ resolution, seven-point map of the ^{12}CO $J = 3 \to 2$ line in IC 342. The ^{13}CO $J = 3 \to 2$ line strength, when compared to the lower J ^{13}CO line strengths at similar spatial resolution, suggests that the ^{13}CO lines are optically thick in the inner 200 pc of IC 342. Ratios of C^{18}O to ^{13}CO millimeter lines support this conclusion. The brightness temperatures of the ^{12}CO $J = 3 \to 2$, $J = 2 \to 1$, $J = 1 \to 0$ lines are 6–10 times stronger than the corresponding ^{13}CO lines suggesting that some of the ^{12}CO emission comes from a separate component and that the ^{13}CO-emitting gas has a small filling factor. The ^{13}CO filling factor is similar to that of the warm NH_3 and the CS $J = 2 \to 1$ emission in the nuclear region. The physical conditions in the molecular gas in the inner region of IC 342 are similar to the conditions in the inner 200 pc of our own Galaxy.

Subject headings: galaxies: individual (IC 342) — galaxies: interstellar matter — interstellar: molecules

I. INTRODUCTION

IC 342 is an almost face-on ($i = 25°$; Newton 1980) Scd galaxy. When examined with $<60''$ beam sizes, its central region is one of the strongest extragalactic sources in the millimeter lines of CO (Morris and Lo 1978; Knapp *et al.* 1980). At $\sim 10''$ resolution, a $\sim 30''$ north-south bar dominates the millimeter CO line emission (Lo *et al.* 1984; Hayashi *et al.* 1986). At 2″ resolution, the bar breaks up into two filaments extending $\sim 10''$ north and south from a 5″ diameter central ring. The peak CO $J = 1 \to 0$ brightness temperature in these filaments is ~ 20 K (Ishizuki *et al.* 1990). Non–LTE modeling of 14″–21″ resolution observations of ^{12}CO, ^{13}CO, and C^{18}O $J = 1 \to 0$ and $2 \to 1$ in the inner part of IC 342 yields temperatures of ≥ 20 K and densities of 10^3–10^4 cm^{-3} (Eckart *et al.* 1990). Earlier observations suggest that a fraction of the ^{12}CO $J = 3 \to 2$ line flux arises in ≥ 30 K optically thin gas (Ho, Turner, and Martin 1987). Observations of metastable NH_3 lines yield kinetic temperatures for some of the molecular material in IC 342 of up to 70 K (Martin and Ho 1986). Millimeter rotation line emission from more difficult to excite molecular transitions (e.g., CS $J = 2 \to 1$, $3 \to 2$, and possibly $5 \to 4$) also indicates substantial amounts of high-density [$n(H_2)$ up to 10^5 cm^{-3}] material in the central 60″ of IC 342 (Henkel, Mauersberger, and Schilke 1989; Mauersberger and Henkel 1989).

On a large scale, the molecular interstellar medium of a galaxy is heterogeneous—containing clouds with a range of sizes, densities, and temperatures. Carbon monoxide is the molecule of choice for studying the bulk of this material. Its abundance makes it readily detectable in many galaxies, it is present almost everywhere H_2 exists, it has isotopes with smaller abundances which allow one to examine regions of higher column density, and its small dipole moment makes the lowest J rotational lines easy to excite. By looking at higher J lines of CO, one is more sensitive to warmer, denser gas. The $J = 3$ state of ^{13}CO, for example, lies 32 K above ground versus 5.3 K for $J = 1$ and the $J = 3 \to 2$ transition has a critical density 20 times that of $J = 1 \to 0$ (i.e., 5×10^4 cm^{-3} vs. 2×10^3 cm^{-3}). Therefore, ^{13}CO $J = 3 \to 2$ observations add to studies of millimeter isotopic CO lines by providing a probe which is more sensitive to variations in the amount of warm dense molecular gas, with reduced saturation effects as compared to ^{12}CO $J = 3 \to 2$. We have made the first ^{13}CO $J = 3 \to 2$, detection and new ^{12}CO $J = 3 \to 2$ observations with beams comparable to the beams used in the $J = 2 \to 1$ and $J = 1 \to 0$ work of Eckart *et al.* (1990). We will use the millimeter and submillimeter CO lines to investigate the excitation in the central region of IC 342. We can then compare the overall state of the molecular material in the inner part of this galaxy to the inner region of the Milky Way.

IC 342 lies close to the Galactic plane and is therefore heavily extincted by Galactic dust making distance determinations difficult without a careful consideration of reddening and extinction effects. Distances cited in the literature range from 1.5 to 8 Mpc (Ables 1971; Sandage and Tammann 1974). Recent efforts by McCall (1989) and G. de Vaucouleurs (1989, personal communication) place IC 342 at a distance of 1.6–2.0 Mpc. We will adopt here a distance of 1.8 Mpc, significantly less than the 4.5 Mpc usually used by millimeter line and radio continuum observers (Rogstad, Shostak, and Rots 1973). At the adopted distance, 24″ is equal to 210 pc.

II. OBSERVATIONS

We detected the ^{13}CO $J = 3 \to 2$ line ($\nu = 330.588$ GHz) toward the 2 μm nucleus (see Table 1) of IC 342 and made a seven-point map in the ^{12}CO $J = 3 \to 2$ line ($\nu = 345.796$ GHz). We observed the ^{13}CO $J = 3 \to 2$ line on 1989 November 7 with the Caltech Submillimeter Observatory telescope on Mauna Kea, where the beam size was 24″ FWHM. Periodic pointing checks on Jupiter showed that the pointing was repeatable to better than 3″–5″. We calibrated the data in terms of main beam radiation temperature, T_{MB}, the radiation temperature (Rayleigh-Jeans brightness temperature) of a uniform source filling the beam to the first null. The main beam efficiency, $\eta_{MB} = 0.5$ (defined by T_A^*/T_{MB}), was measured on Mars and Jupiter on previous observing runs and the zenith opacity was ~ 0.25. The peak T_{MB} toward Orion/IRc2 is 87 K (but note that Orion is very extended). The chopper wheel calibration used to account for the atmospheric opacity (Davis and Vanden Bout 1973) assumes that the opacity in the signal and image sidebands is the same. It therefore does not correct for the higher opacity at the ^{13}CO $J = 3 \rightarrow 2$ line frequency (if this line is observed in the lower sideband with a 1.4 GHz IF) resulting from the wings of a nearby atmospheric water vapor absorption line. Atmospheric modeling shows that this correction is $\sim 10\%$ for our IC 342 observations (E. N. Grossman 1989, private communication).

We also observed the ^{12}CO $J = 3 \rightarrow 2$ line on 1988 August 10 with the 15 m James Clerk Maxwell Telescope on Mauna Kea. On this exceptionally dry night, the zenith opacity was ~ 0.05. The pointing was checked on Mars and Jupiter and varied by less than 5″ throughout the night. The main beam efficiency was measured on Mars (assuming $T_{\rm disk} = 210$ K). The double-sideband T_A^* of Mars was 84 K. Correcting for the beam size (15″ FWHM) and the size of Mars (18.7″), this T_A^* yields $\eta_{\rm MB} = 0.6$. The peak $T_{\rm MB}$ toward Orion/IRc2 is 150 K.

III. RESULTS

Figure 1 shows the ^{13}CO $J = 3 \rightarrow 2$ spectrum, Figure 2 shows the seven ^{12}CO $J = 3 \rightarrow 2$ spectra toward IC 342, and Table 1 lists the observed line parameters. There are two principal results:

1. The ^{13}CO $J = 3 \rightarrow 2$ line strength is about equal to those of the ^{13}CO $J = 2 \rightarrow 1$ and ^{13}CO $J = 1 \rightarrow 0$ lines, implying that all three lines are optically thick.
2. The ^{12}CO $J = 3 \rightarrow 2$ lines have significantly higher $T_{\rm MB}$ and $\int T_{\rm MB}\, dV$ values than the ^{13}CO lines. This implies that at least some of the ^{12}CO emission comes from a more extended component in the ISM of IC 342 which is optically thin in the $J = 1 \rightarrow 0$, $J = 2 \rightarrow 1$, $J = 3 \rightarrow 2$ lines of ^{13}CO. In addition, there is no evidence in the ^{12}CO data for a hot, optically thin emission component.

a) ^{13}CO *Emission from Dense Cloud Cores*

The observed line strengths of the three lowest rotational transitions of ^{13}CO imply that all three have $\tau \geq 1$. The ^{13}CO $J = 3 \rightarrow 2$ integrated line strength is 18 K km s^{-1} in a 24″ beam. The ^{13}CO $J = 1 \rightarrow 0$ integrated line strength in a 21″ beam is 19 K km s^{-1} (Eckart *et al.* 1990). Smoothing Eckart *et al.*'s 14″ resolution ^{13}CO $J = 2 \rightarrow 1$ data to 21″, we derive an integrated line strength of 21 K km s^{-1}. If the three lowest levels of ^{13}CO are thermally populated, we would expect the observed $\sim 1{:}1{:}1$ integrated line strength ratio for emission from warm optically thick gas.

Optically thin gas cannot easily produce the observed line ratios. Optically thin ^{13}CO emission can, in principle, produce

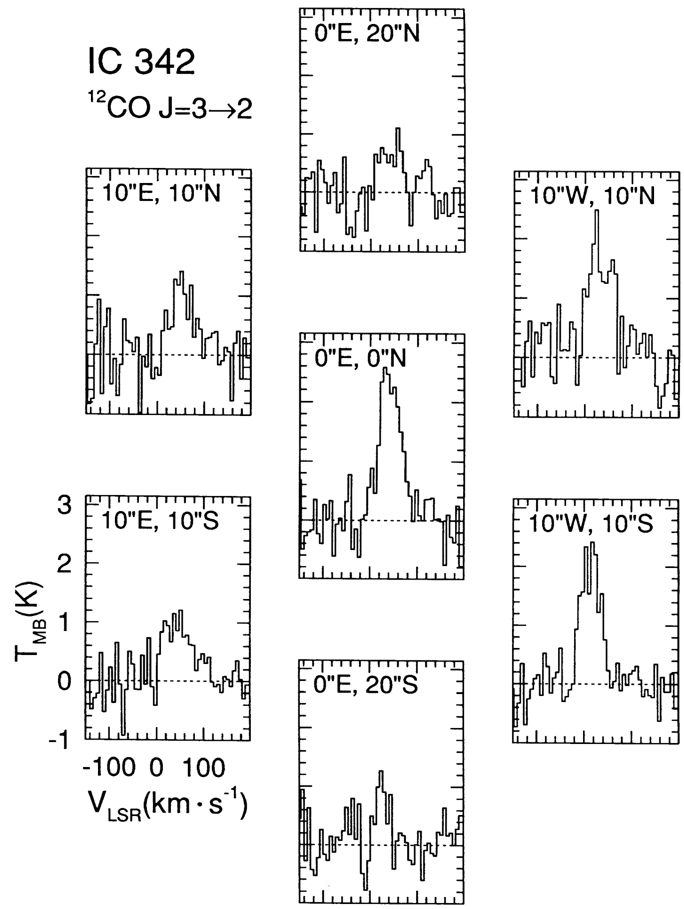

FIG. 2.—^{12}CO $J = 3 \rightarrow 2$ spectra of IC 342. The vertical scale is $T_{\rm MB}$.

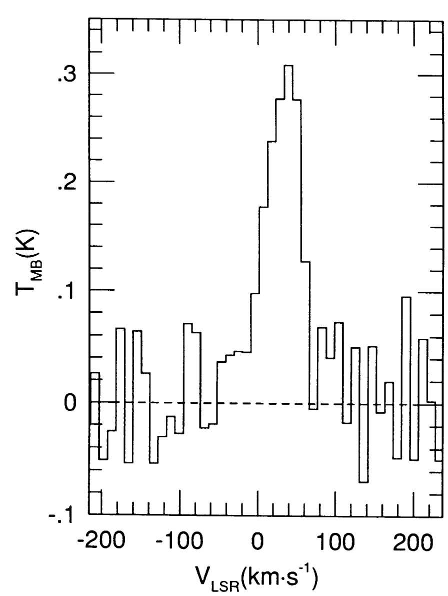

FIG. 1.—^{13}CO $J = 3 \rightarrow 2$ spectrum toward the (0, 0) position in IC 342. Position offsets are relative to $\alpha(1950) = 3^h41^m57\overset{s}{.}0$, $\delta(1950) = 67°56'29''$. The vertical scale is main beam radiation temperature $T_{\rm MB}$.

TABLE 1

IC 342 CO $J = 3 \rightarrow 2$ LINE PARAMETERS

Position[a] ($\Delta\alpha''$, $\Delta\delta''$)	$T_{\rm MB}$ (Peak) (K)	$\int T_{\rm MB}\, dV$ (K km s^{-1})	$V_{\rm peak}$ (km s^{-1})	$V_{\rm mean}$ (km s^{-1})	$\Delta V_{\rm (FWHM)}$ (km s^{-1})
^{13}CO $J = 3 \rightarrow 2$ in 24″ Beam					
0, 0......	0.3	18	39	30	55
^{12}CO $J = 3 \rightarrow 2$ in 15″ Beam					
−10, −10......	2.4	109	18	15	50
−10, 10......	2.0	113	25	30	70
0, −20......	1.3	36	25	26	27
0, 0......	2.6	139	31	40	46
0, 20......	0.8	42	35	43	60
10, −10......	1.2	68	51	42	73
10, 10......	1.4	65	51	50	40

[a] (0, 0) is the 2 μm nucleus position (Becklin *et al.* 1980): α(1950 = $3^h41^m57\overset{s}{.}0$, $\delta(1950) = 67°56'29''$.

$2 \rightarrow 1/1 \rightarrow 0$ integrated line strength ratios with any value ≤ 4 and $3 \rightarrow 2/1 \rightarrow 0$ ratios with any value ≤ 9. The maximum 1:4:9 ratio occurs for high-temperature, high-density gas. In optically thin, high-density gas cold enough to explain the $2 \rightarrow 1/1 \rightarrow 0$ integrated line strength ratio of 1 ($T_K = 7$ K), the $3 \rightarrow 2/1 \rightarrow 0$ line ratio would be only about one-third of the observed value. For lower density, subthermally excited gas, there is only a narrow range in parameter space where optically thin gas can produce the observed line ratios. Based on large velocity gradient models (see de Jong, Chu, and Dalgarno 1975), we find that for gas with $T_K < 200$ K only pressures, $n(H_2)T_K$, within a factor of ~ 2 of 4×10^4 cm^{-3} K can reproduce the observed line ratios. There is no corroborating evidence for such material from observations of other molecular lines.

A comparison of the ^{13}CO and $C^{18}O$ line strengths in the millimeter transitions (Eckart *et al.* 1990) confirms the conclusion that the ^{13}CO lines are optically thick. The $^{13}CO/C^{18}O$ line ratios for the $J = 2 \rightarrow 1$ and $1 \rightarrow 0$ transitions are 3.8 and 3.6, respectively. These values imply ^{13}CO opacities of 1–3 if the $^{13}CO/C^{18}O$ abundance ratio = 5.5–9.0.

Based on the peak T_{MB} of the ^{13}CO $J = 3 \rightarrow 2$ line, the area filling factor per velocity interval, η_{ff}, is ~ 0.15 of the filling factor for ^{12}CO toward the center of IC 342, if both lines are optically thick and both transitions have the same excitation temperature. For ^{13}CO $J = 3 \rightarrow 2$, η_{ff} is $\sim 6 \times 10^{-3}$ for 50 K gas in our 24″ beam. The ^{13}CO $J = 3 \rightarrow 2$ brightness temperature is about 3 times larger than the CS $J = 2 \rightarrow 1$ brightness temperature in the same beam (Mauersberger and Henkel 1989), implying roughly comparable filling factors for the two transitions and that the lines arise primarily in the same regions. Since the CS emission must come from relatively warm, dense gas (Mauersberger and Henkel, 1989), the ^{13}CO $J = 3 \rightarrow 2$ emission then arises in regions where the level populations as high as $J = 3$ are close to LTE, consistent with our conclusion that the ^{13}CO lines are optically thick. The area filling factor of the NH_3 (1,1) emission for our beam is ~ 5 times smaller than the ^{13}CO η_{ff} (Martin and Ho 1986; Ho, Martin, and Turner 1990). The ratio of ^{13}CO to NH_3 filling factors is roughly comparable to that in Galactic clouds such as M17SW (Thronson and Lada 1983; Guesten and Fiebig 1988), Sgr B2 (Lis and Goldsmith 1989; Morris *et al.* 1973), and the "50 km s^{-1}" Cloud in the Galactic center (Armstrong and Barrett 1985; Guesten, Walmsley, and Pauls 1981).

We can estimate the column density of the ^{13}CO–emitting gas using the optically thin millimeter lines of $C^{18}O$. For $T_K =$ 50 K (from the NH_3 observations of Martin and Ho 1986), the $C^{18}O$ $J = 1 \rightarrow 0$ line strength (Eckart *et al.* 1990) requires a beam-averaged column density, $\langle N(C^{18}O) \rangle$, of 1.4×10^{16} cm^{-2}. Assuming Galactic abundances, this corresponds to $\langle N(H_2) \rangle \approx 7 \times 10^{22}$ cm^{-2} (Frerking, Langer, and Wilson 1982). The mass of the $^{13}CO(C^{18}O)$–emitting component in the central 200 pc diameter is then 4×10^7 $M_\odot$. If the emitting clouds have velocity widths of 10 km s^{-1}, then the emitting gas at all velocities in the line profile covers roughly (50/10) $\times 6 \times 10^{-3}$ or $\sim 3 \times 10^{-2}$ of the beam area. The column density along an emitting-gas line of sight is then $N(H_2) \approx 7 \times 10^{22}$ cm$^{-2}/3 \times 10^{-2} \approx 2 \times 10^{24}$ cm^{-2}. This is comparable to the column density necessary for ^{13}CO $J = 1 \rightarrow 0$ to be optically thick in clouds with 10 km s^{-1} wide lines.

The ^{13}CO–emitting cores are comparable in size to the densest regions in Galactic giant molecular clouds (GMCs). The line-of-sight column density, $N(H_2) \approx 2 \times 10^{24}$ cm^{-2}, and the density derived from CS observations, $n(H_2) \leq 10^5$ cm^{-3} (Mauersberger and Henkel 1989), imply path lengths of $\geq 6(\Delta v/10$ km s$^{-1})$ pc through the high-density cores, where Δv is the line width of the individual cores. The area filling factor and path length together imply that ≤ 40 dense clouds of mass $\geq 10^6$ $M_\odot$ contribute to the observed $C^{18}O$ emission.

b) *Origin of the* ^{12}CO *Emission*

One-third or more of the ^{12}CO emission from the center of IC 342 can arise from the ^{13}CO–emitting clouds. Tauber and Goldsmith (1990) and Gierens (1990) have examined the coupled radiative transfer, excitation, and chemistry problem for CO emission from photodissociation regions (PDRs) on the surfaces of clumps in cloud cores illuminated by far-UV radiation. Their models can produce the $^{12}CO/^{13}CO$ $J = 3 \rightarrow 2$ line ratios of 3–5 observed in Galactic GMCs and the same brightness temperatures for lines originating in states from $J = 1$ to $J = 3$ at densities $\sim 10^5$ cm^{-3}. The high ratios arise despite the high opacity in both ^{13}CO and ^{12}CO lines. The higher opacity of the ^{12}CO lines means that they become opaque in the hotter parts of the PDRs and also leads to larger effective sizes for the ^{12}CO–emitting regions in the presence of density gradients. The clouds in the center of IC 342 are illuminated by a UV field $\sim 10^3$ times the Galactic interstellar radiation field (Wolfire, Hollenbach, and Tielens 1989). While a field of this magnitude is optimally effective at heating ^{12}CO in clumpy clouds (Tauber and Goldsmith 1990), it is not likely that PDRs in dense gas alone can explain the $^{12}CO/^{13}CO$ line strength ratio of 10 observed in IC 342 in the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ lines.

The balance of the ^{12}CO emission from IC 342 must come from a component which will not contribute much ^{13}CO emission in any transition. The most likely source of this emission is a population of small clouds. Observations of a sample of small clouds with low opacities in our Galaxy (Knapp and Bowers 1988) show that they typically have $^{12}CO/^{13}CO$ $J = 1 \rightarrow 0$ line ratios of ~ 20. The ^{12}CO $J = 2 \rightarrow 1/J = 1 \rightarrow 0$ line ratio is ~ 1 in these clouds. Physical conditions in the central part of IC 342 are different from those in the disk of our Galaxy—higher radiation fields and stronger tidal forces may result in a warmer, denser population of small clouds. The higher temperatures will increase the $^{12}CO/^{13}CO$ line ratios by making the optically thick ^{12}CO lines brighter and spreading the ^{13}CO population over a larger number of states. The higher density will allow the ^{12}CO $J = 3 \rightarrow 2$ line to be almost as bright as millimeter lines. Nonetheless, if the density is not much higher than the $n(H_2) < 100$ cm^{-3} observed for small clouds in our Galaxy (Knapp and Bowers 1988), the ^{13}CO $J = 3$ state will be subthermally populated while radiative trapping will populate the $J = 3$ state of ^{12}CO. The existence of such low-density gas within the central ~ 100 pc diameter of our own Galaxy has been inferred from the observations of Zylka, Mezger, and Wink (1990).

There is no evidence for a hot component of molecular gas which is optically thin in the ^{12}CO $J = 3 \rightarrow 2$ line as suggested by Ho, Turner, and Martin (1987). Both the ^{12}CO $J = 3 \rightarrow 2$ results we present and those of Steppe *et al.* (1990) are consistent with emission from optically thick ^{12}CO $J = 3 \rightarrow 2$. Steppe *et al.* (1990) find T_{MB} (^{12}CO $J = 3 \rightarrow 2)/T_{MB}(^{12}CO$ $J = 2 \rightarrow 1) \approx 0.8$, whereas our observations suggest $T_{MB}(^{12}CO$ $J = 3 \rightarrow 2)/T_{MB}(^{12}CO$ $J = 2 \rightarrow 1) \approx 0.5$. The ^{12}CO $J = 3 \rightarrow 2$ inconsistencies show clearly why ^{13}CO $J = 3 \rightarrow 2$, whose intensity varies more rapidly with excitation, is a better probe of the large-scale properties of molecular gas in galaxies.

IV. DISCUSSION

A picture in which the molecular cloud ensemble in the center of IC 342 consists of dense compact cloud cores (producing most of the ^{13}CO line emission) plus a number of small molecular clouds (producing additional ^{12}CO line emission) can explain our observations of the center of IC 342.

The physical properties of the ISM in the center IC 342 are similar to those in our Galaxy. The far-infrared luminosity of the central 500 pc diameter region of IC 342 (6.4×10^8 $L_\odot$, scaled to $D = 1.8$ Mpc; Becklin *et al.* 1980) is comparable to that of the Galaxy (4.4×10^8 $L_\odot$; Stier *et al.* 1982). The central $\sim 13'' \times 30''$ bar in IC 342 has a linear size of 110 by 260 pc. Broad-band far-IR measurements of the Milky Way's Galactic center region show a $\sim 2°$ (300 pc at 8.5 kpc) long structure extending along the plane from Sgr A (Odenwald and Fazio 1984), and submillimeter dust temperatures are $\gtrsim 30$ K over the entire region (Stier *et al.* 1982). The dust temperature in the central region of IC 342 is ~ 42 K (Becklin *et al.* 1980). The gas temperatures over 300 pc of the inner Galaxy derived from NH_3 observations are ≥ 50 K (Guesten *et al.* 1985), comparable to the temperatures derived from NH_3 in IC 342 (Morris *et al.* 1983; Martin and Ho 1986).

We can model the molecular gas in the central region of IC 342 as a composite of the molecular clouds observed in our Galaxy. In IC 342, for the ^{13}CO–emitting gas, we have $N(H_2) \approx 2 \times 10^{24} \Delta V_{10}$ cm^{-2}, where ΔV_{10} is the line width (of the individual clouds) in units of 10 km s^{-1}, $M \approx 4 \times 10^7$ $M_\odot$, and the luminosity in the ^{13}CO $J = 1 \rightarrow 0$ line, L^{13}, is ~ 20 $L_\odot$. The ^{13}CO column densities in the cores of Galactic molecular clouds and the mass-to-L^{13} ratios are comparable to those in the center of IC 342. Sgr B2 has $N(H_2) \approx 5 \times 10^{23} \Delta V_{10}$ cm^{-2}, $M \approx 10^7$ $M_\odot$, and $L^{13} \approx 3$ $L_\odot$ (Lis and Goldsmith 1989). In M17SW, for the ^{13}CO–emitting gas, we have $N(H_2) \approx 10^{23}$–$10^{24} \Delta V_{10}$ cm^{-2}, $M \approx 10^4$ $M_\odot$, $L^{13} \approx 0.01$ $L_\odot$ (Stutzki and Guesten 1990; Thronson and Lada 1983). In addition, both Sgr B2 and M17SW have optically thick ^{13}CO lines at some positions (Lis and Goldsmith 1989; Stutzki *et al.* 1988). An ensemble of clouds ranging from the size of M17SW up to something approaching Sgr B2 could explain the IC 342 CO emission. The central 200 pc diameter of IC 342 would require ~ 1000 GMCs like M17SW by ^{13}CO luminosity or by mass to comprise its ^{13}CO–emitting gas, or significantly fewer if the clouds more closely resemble Sgr B2.

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D. T. Jaffe and W. F. Wall: Department of Astronomy, RLM 15·308, University of Texas at Austin, Austin, TX 78712