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HOT GAS IN THE NUCLEUS OF M82: ^{12}CO AND ^{13}CO $J = 3$–2 OBSERVATIONS

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ABSTRACT

We report observations of the $J = 3$–2 transitions of ^{12}CO and ^{13}CO in the starburst galaxy M82. We have detected and mapped the ^{12}CO $J = 3$–2 transition in the nuclear region at 22″ resolution. The high main beam brightness temperature of the line, 6.4 K, when compared to the $J = 1$–0 and $J = 2$–1 intensities, requires a hot ($T_k \gtrsim 40$ K), moderately optically thin gas. We place a lower limit of ~ 15 on the $I_{\rm CO}/I_{^{13}\rm CO}$, implying that $\tau_{32} \lesssim 6$ and $\tau_{10} < 1$ for this warm component. There are $\sim 10^8\ M_\odot$ of warm molecular gas within a radius of 360 pc of M82. The low optical depths and high densities required to excite the $J = 3$–2 transition may imply sheetlike or filamentary clumping. The pressure in the molecular gas is high, $nT \sim 10^6$–10^7 cm^{-3} K. The unusually high pressure and filamentary nature of the interstellar medium in M82 are probably related to winds and shocks originating in the starburst.

Subject headings: galaxies: individual (M82) — galaxies: interstellar matter — galaxies: nuclei

I. INTRODUCTION

To study the properties of star formation in starburst galaxies, it is instructive to examine the dense and warm molecular matter closely associated with young stars. Two useful tools for tracing high-temperature gas have been the ammonia lines (Martin and Ho 1986) and the higher rotational transitions of CO (Knapp *et al.* 1980). The CO $J = 1$–0 transition usually samples lower temperature optically thick regions, even at interferometric resolutions of $\sim 5''$ (Lo *et al.* 1987). Higher rotational transitions of CO are more sensitive to warm gas. Intense $J = 3$–2 emission has been detected in the nearby spiral galaxy IC 342, indicating that gas temperatures are greater than ~ 40 K over the inner 200 pc (Ho, Turner, and Martin 1987).

The starburst galaxy M82 is an excellent candidate for detection of the hot molecular component. M82 has a large nuclear starburst, as indicated by strong Brackett lines (Simon, Simon, and Joyce 1979), radio continuum (Kronberg, Biermann, and Schwab 1985), mid- and far-infrared emission (Rieke *et al.* 1980; Telesco and Harper 1980), and CO (1–0) emission (Rickard *et al.* 1977). CO (1–0) maps have been made by Nakai *et al.* (1987), Olofsson and Rydbeck (1984), and Young and Scoville (1984; ^{13}CO) and CO (2–1) maps by Sutton, Masson, and Phillips (1983) and Loiseau *et al.* (1988*a*, *b*; CO, ^{13}CO). Bright CO (1–0) emission has been mapped on small scales (~ 100 pc) in the core of M82 by Lo *et al.* (1987). Knapp *et al.* (1980) and Loiseau *et al.* (1988*a*) found that the CO $J = 2$–1 line intensity is ~ 3 times the $J = 1$–0 intensity, indicating optically thin gas; Stark and Carlson (1984) found ^{13}CO and C^{18}O ratios consistent with this result. We report here the detection and mapping of ^{12}CO $J = 3$–2 emission, and an upper limit to the ^{13}CO line, which require optically thin gas with excitation temperatures of greater than 50 K.

II. OBSERVATIONS

The ^{12}CO observations were made during 1987 and 1988 February and the ^{13}CO observations during 1989 February and March with the 12 m telescope of the National Radio Astronomy Observatory[1] at Kitt Peak, Arizona. The 1989 observations of ^{12}CO and ^{13}CO employed a new subreflector figured to compensate for defects in the primary, thereby improving the high-frequency beam pattern. The beam size at 870 μm, measured with continuum drift scans of Saturn, was 22″ in 1987 and 1988 and 20″ for the 1989 data. The aperture efficiency for all observations was 14% (P. Jewell, private communication).

Observations of ^{12}CO $J = 3$–2 at 345.79598 GHz and ^{13}CO at 330.58797 GHz were made using a filterbank of 256 contiguous channels of separation and resolution 2 MHz, or 1.73 km s^{-1} for ^{12}CO and 1.81 km s^{-1} for ^{13}CO. Data were taken in double-sideband mode, since image sideband rejection was not available at 330–345 GHz. The assumption that the gains in the two sidebands were equal seems to be good since the measured ^{12}CO $J = 3$–2 intensity in Orion was at the expected value of $T_R^* \sim 75$ K. Calibration was by the standard chopper-wheel method (Ulich and Haas 1976).

Weather during the observations was good: the atmospheric water vapor content ranged from 1 to 4 mm, as determined by an infrared absorption meter measurement against the Sun. The corresponding zenith optical depths were 0.4–0.6. The effective system temperature of the telescope, referred to above the atmosphere, ranged from 600 to 12,000 K for ^{12}CO and 20,000–26,000 K for ^{13}CO. Pointing was checked every few

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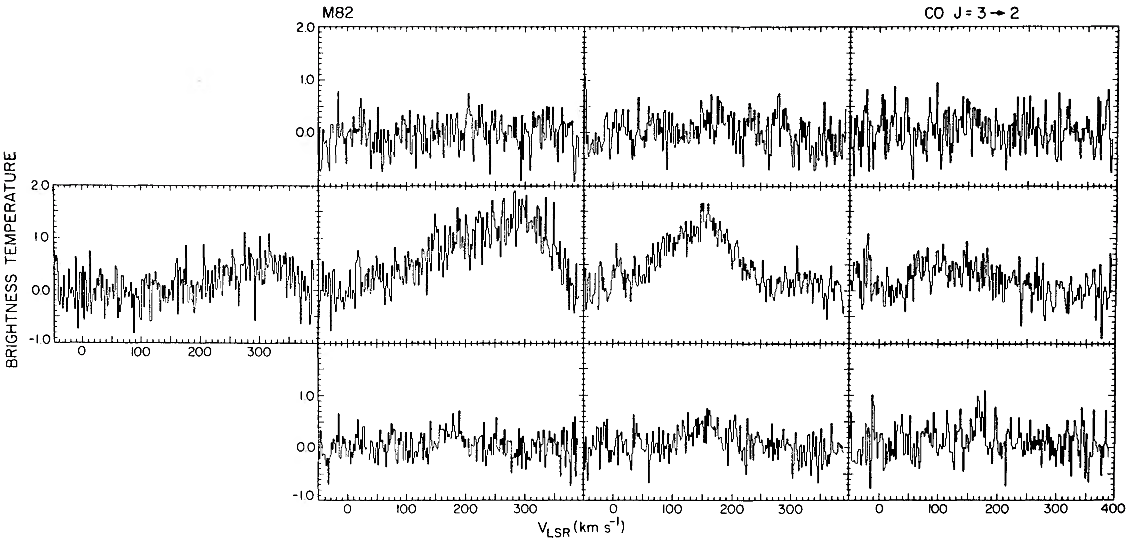

FIG. 1.—^{12}CO $J = 3$–2 spectra. The map is centered at $\alpha = 9^h51^m42^s$, $\delta = 59°54'57''$. The spectra are spaced at 14″ intervals in α and δ, corresponding to a 20″ grid oriented at p.a. 45°. The beam size is 22″, FWHM; spectral resolution is 1.81 km s^{-1}.

hours on planets and strong line sources, and was repeatable to $\sim$10″ day-to-day. The ^{12}CO map and ^{13}CO/^{12}CO comparison spectra were made on single evening sessions; pointing runs within a spread of several hours on a single object showed considerably less scatter than day-to-day pointing. We estimate that the relative pointing accuracy is $\sim$3″–4″. Finally, we make a significant correction for the error beam, since the fraction of power in the main beam compared to total forward power in the main beam plus error beam is 22% at 870 μm (P. Jewell, private communication). This corrected beam efficiency improved to 25%–30% in 1989. The main beam correction is described in the next section.

III. RESULTS

a) Detection of Warm Optically Thin CO $J = 3$–2 *Emitting Gas;* ^{13}CO *Upper Limit*

We detected ^{12}CO $J = 3$–2 emission in several positions in M82 (Fig. 1). The central position is $\alpha = 9^h51^m42^s$, $\delta = 69°54'57''$ and the other spectra are spaced at $\Delta\alpha = \Delta\delta = 14''$ intervals, corresponding to a 20″ grid rotated to a p.a. of 45°. The $J = 3$–2 emission is present over the velocity range $\sim$50–350 km s^{-1}, similar to that measured for the ^{12}CO (Rickard *et al.* 1977; Olofsson and Rydbeck 1984; Nakai *et al.* 1987). The two positions with the most intense emission have peak antenna temperatures at $V_{LSR} = 150$ and 285 km s^{-1}. Comparison with the $J = 1$–0 aperture synthesis maps of Lo *et al.* (1987) suggests that these spectra are situated on the two strong $J = 1$–0 components at $\sim$10″ to the northeast and $\sim$10″ to the southwest of center.

We observed ^{13}CO at a central position corresponding to a point half-way between the two peak positions in the ^{12}CO map of Figure 1. During the 1989 session this ^{12}CO spectrum was taken immediately before and after the ^{13}CO spectrum to check for pointing drifts, and was repeatable. ^{12}CO at this position (Fig. 2) has a peak intensity of $T_R^* = 0.8$ K and integrated intensity of $I_{CO} = 200$ K km s^{-1}. ^{13}CO (Fig. 2) is undetected at an rms level of $\sim$0.15 *K*; $I_{^{13}CO} < 5$ K km s^{-1}. The ratio $I_{CO}/I_{^{13}CO} > 40$ would imply $\tau_{32} \lesssim 2$ for [^{12}CO]/[^{13}CO] = 90. However, there may be thick components corresponding to the NE and SW emission peaks that have narrower velocity widths; if the linewidths are $\sim$50–100 km s^{-1} as observed in CO(1–0) (e.g., Nakai *et al.* 1987), then for these components $I_{CO}/I_{^{13}CO}$ could be as low as 15–30, and consequently τ_{32} could be as high as 3–6. In fact the intensity ratios and the high $J_{21}(T_{ex})$ toward these peak positions discussed in the next section tend to favor $\tau_{32} > 2$, in order that τ_{21} be moderately thick. For the warm ($T_k > 40$ K, § III*b*) gas we are observing $\tau_{10} \sim 0.2\tau_{32}$, and we would predict $\tau_{10} \sim 0.5$

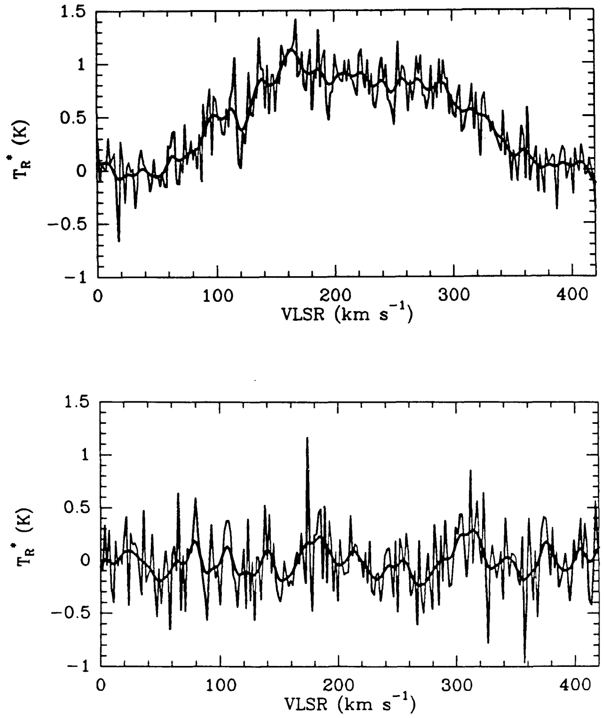

FIG. 2.—(*Top*) ^{12}CO spectrum; (*bottom*) ^{13}CO $J = 3$–2 spectrum. The ^{12}CO spectrum is an average of spectra taken immediately before and after the ^{13}CO measurement. The rms in the ^{13}CO spectrum is $T_R^* = 0.15$ K. The thick line underlying the spectrum corresponds to degrading the velocity resolution to 10 km s^{-1}.

– 1. However, Stark and Carlson (1984) and Young and Scoville (1984) find $T_R{}^*({}^{12}\mathrm{CO})/T_R{}^*({}^{13}\mathrm{CO}) \sim 20$–30 for the $J = 1$–0 transition, corresponding to $\tau_{10} \sim 4.5$, and Loiseau *et al.* find that $\tau_{21} \sim 2$–7. We conclude that there must be a cooler, optically thick (at $J = 3$–2 especially) component contributing to the $J = 1$–0 lines that does not contribute significantly to the $J = 3$–2 emission. This is similar to what was inferred from the $J = 3$–2 observations of IC 342 (Ho, Turner, and Martin 1987).

b) High Temperatures and Pressures

Gas temperatures and optical depths can be derived by comparing the intensity of the ^{12}CO $J = 3$–2 emission with those of the 2–1 and 1–0 transitions. The peak beam-diluted antenna temperature for the $J = 3$–2 line is $T_R{}^* = 1.4$ K. To convert to brightness temperature, we apply the forward beam coupling factor, $\eta_f = T_R{}^*/J_\nu(T_{\mathrm{ex}})$ (Ulich and Haas 1976; Kutner and Ulich 1981). For the 12 m telescope prior to 1989, $\eta_f = 0.22\theta_S{}^2/(\theta_S{}^2 + \theta_B{}^2)$ at 330–345 GHz (Ho, Turner, and Martin 1987), where θ_S is the source size, and θ_B the beam size, FWHM; for the 1989 observations the fraction of total forward power in the main beam increased to 0.25–0.30 (P. Jewell, private communication). This expression for η_f is accurate for $\theta_S \ll$ the error beam ($\sim 5'$, FWHM), which holds for M82.

We can obtain a strict lower limit to the brightness temperature $J_\nu(T_{\mathrm{ex}}) = \lambda^2 I/2k$, by taking $\theta_S \gg \theta_B$ in the above expression for η_f. Doing so, we find that $T_R{}^* \sim 1.4$ K corresponds to a main beam brightness temperature of $J_{32}(T_{\mathrm{ex}}) = 6.4$ K, or, applying the Rayleigh-Jeans correction, a minimum excitation temperature of $T_{\mathrm{ex}} = 13$ K. This is already a high temperature considering it is an average over 22″, or 360 pc at the distance (3.4 Mpc assumed) of M82. The true value of $J_{32}(T_{\mathrm{ex}})$ is underestimated due to the unknown beam filling factor and optical depth. Moreover, to obtain the kinetic temperature of the gas, T_k, from T_{ex}, one must account for the degree of thermalization ($T_{\mathrm{ex}} \leqslant T_k$). Clearly $T_k = 13$ K is a conservative lower limit.

We can estimate the optical depth and a direct value for the excitation temperature by comparing the $J = 3$–2 peak intensity with those of the $J = 1$–0 and $J = 2$–1 lines. Unfortunately, these observations have different beam sizes, ranging from 16″ to 2′; comparison of the main beam intensities and mapping indicate both extended and unresolved structures. From the observed intensities, the $J = 2$–1 emission region (Sutton, Masson, and Phillips 1983; Stark and Carlson 1984; Loiseau *et al.* 1988*a*) appears to be pointlike [$J_\nu(T_{\mathrm{ex}}) \propto \theta_B = 16''$ to $50''$]. From these data, we estimate that $J_{21}(T_{\mathrm{ex}}) \sim 6.8$ K in a 22″ beam. Similarly, the $J = 1$–0 intensities increase as $J_{10}(T_{\mathrm{ex}}) \propto \theta_B{}^{-1}$ for $\theta_B = 16''$ to $50''$ (data from Nakai *et al.* 1987; Olofsson and Rydbeck 1984; Stark and Carlson 1984; Young and Scoville 1984), which yields $J_{10}(T_{\mathrm{ex}}) \sim 3.8$ K in a 22″ beam. [All $J_\nu(T_{\mathrm{ex}})$ have been corrected upward by the cosmic microwave background temperature, $J_\nu(2.7\ \mathrm{K})$, since $T_R{}^*$ or $T_A{}^*$ measure only temperatures in excess of $J_\nu(2.7\ \mathrm{K})$]. At the resolution of our $J = 3$–2 observations, the estimated intensity ratios are then $J_{32}(T_{\mathrm{ex}})/J_{10}(T_{\mathrm{ex}}) = 1.7$, $J_{32}(T_{\mathrm{ex}})/J_{21}(T_{\mathrm{ex}}) = 0.94$, and $J_{32}(T_{\mathrm{ex}})/J_{21}(T_{\mathrm{ex}}) = 1.8$. The ratio $J_{32}(T_{\mathrm{ex}})/J_{10}(T_{\mathrm{ex}}) = 1.7$ implies that $T_{\mathrm{ex}} > 25_{25}{}^{35}$ K at our lower bound of $\tau_{32} = 2$ (Ho, Turner, and Martin 1987), where the subscript and superscript indicate error bars of ±10% in the individual $J_\nu(T_{\mathrm{ex}})$. Our upper limit $\tau_{32} \lesssim 5$ constrains T_{ex} to be $\lesssim 70_{40}{}^{140}$ K. Similar constraints on T_{ex} are obtained from the other line ratios. The fact that $J_{32}(T_{\mathrm{ex}})/J_{21}(T_{\mathrm{ex}}) \sim 1$ indicates that the warm molecular component is becoming optically thick at $J = 2$–1. Since τ_{32} cannot be small, the higher limits on T_{ex} should be favored. In addition, if there is a cold CO component, these ratios will represent an average over the warm and cold components, and T_{ex} for the warm component will be underestimated. For these reasons, we estimate that for the warm, $J = 3$–2 emitting component, $T_k \gtrsim 40$–50 K. These T_{ex} are somewhat lower than $T_{\mathrm{ex}} \sim 100$ K observed in HCN and HCO$^+$ by Carlstrom (1988); the actual T_{ex} (3–2) may be close to this value. For the derivation of masses below, we adopt $T_{\mathrm{ex}} = T_k = 50$ K.

Kinetic temperatures of greater than ~40 K are unusually high for regions of ~200 pc extent. Molecular clouds in the Galaxy have $T_k \sim 10$–20 K for sizes of 30–100 pc (Scoville and Good 1989). Gas temperatures of ~40–100 K occur in molecular cores, within ~0.1 pc of H II regions. However, in M82, high temperatures appear to prevail for molecular clouds within the central half kpc. The only other places where high temperatures have been observed over hundred-parsec size scales are the nucleus of the star-forming galaxy IC 342 (Ho, Turner, and Martin 1987) and our own Galactic center (Morris *et al.* 1983).

The high temperatures and high critical densities (5×10^4 cm^{-3} for $T_k = 50$ K, $\tau \sim 1$) of the $J = 3$–2 emitting gas imply that the pressure in the molecular gas is unusually high for these size scales. The pressure implied is $nT \gtrsim 3 \times 10^6$ cm^{-2} K. This is not an unusually high pressure for molecular cloud cores, which are dynamic regions of collapse or turbulent support; but it is a thousand times higher than pressures observed over large size scales in the Galaxy, $nT \sim 3000$ cm^{-2} K. It is suggestive that the value we obtain is similar to that inferred for the tenuous X-ray–emitting gas in M82, $nT \sim 10^7$ cm^{-2} K (Schaaf *et al.* 1989).

c) Mass and Distribution of the Warm Molecular Gas

The fact that the ^{12}CO $J = 3$–2 emission is relatively optically thin enables us to derive relatively accurate masses for this component if we assume that the chemistry (i.e., [CO]/H$_2$]) is not significantly different than Galactic. Assuming $T_k = 50$ K, we obtain $N_{\mathrm{CO}} = 9.0 \times 10^{15} \int T_R{}^*\,dv/(\mathrm{K\ km\ s^{-1}})$, where N_{CO} is the total column density of CO summed over all rotational levels, assuming thermalization. For the southwest region, where $\int T_R{}^*\,dv = 140$ K km s^{-1}, $N_{\mathrm{CO}} = 1.3 \times 10^{18}$ cm^{-2}, and $N_{\mathrm{H_2}} = 1.5 \times 10^{22}$ cm^{-2} for [CO]/[H$_2$] = 8.5×10^{-5} (Frerking, Langer, and Wilson 1982; Black and Willner 1984). For the northeast region, $\int T_R{}^*\,dv = 300$ K km s^{-1}, and $N_{\mathrm{H_2}} = 3.2 \times 10^{22}$ cm^{-2}. The total H$_2$ mass in the inner 44″ diameter, or 720 pc, is therefore $\sim 8 \times 10^7\ M_\odot$, or a total mass of gas including He, of $M_{\mathrm{gas}} = 10^8\ M_\odot$. This represents an H$_2$ surface density of $\sim 500\ M_\odot$ pc^{-2}, a factor of 50 higher than in the Galactic molecular ring (Sanders, Solomon, and Scoville 1984) but similar to what is inferred for our own and other galactic centers (Young 1986).

Our estimate for $M_{\mathrm{H_2}}$ is consistent with those derived from optically thin dust emission by Jaffe, Becklin, and Hildebrand (1984; $8 \times 10^7\ M_\odot$, inner 45″), and Thronson, Walker, and Maloney (1989; $1.5 \times 10^8\ M_\odot$, inner 60″), which is somewhat surprising since we clearly do not detect all of the CO. This may indicate that the dust emissivity is slightly steeper than the ν^1 law assumed by these authors or that the [CO]/[H$_2$] ratio is higher than assumed here. Our mass is in good agreement with the mass of $M_{\mathrm{H_2}} = 7.7 \times 10^7\ M_\odot$ derived by Lo *et al.* (1987) from their ^{12}CO $J = 1$–0 aperture synthesis observations (corrected to $[CO]/[H_2] = 8.5 \times 10^{-5}$). Apparently most of the compact $J = 1$–0 emission appears in the $J = 3$–2 line and it must be warm, as inferred by Lo *et al.* We estimate that the warm molecular gas represents at least $\sim 10\%$ of the total mass in the inner 40″ diameter of M82, where the total mass of $1.2 \times 10^9\ M_\odot$ was derived using the Burbidge, Burbidge, and Rubin (1964) and O'Connell and Mangano (1978) rotation curves, assuming a spherical mass distribution. If the mass distribution deviates from spherical, or if a substantial cold molecular component is present, the percentage of molecular gas could rise to 20%–30%.

From the observed molecular column densities we can constrain the spatial distribution (" clumping ") of the warm molecular gas. For $N_{H_2} = 1$–3×10^{22} cm^{-2}, the mean molecular density is $\langle n_{H_2} \rangle \sim 10$–$30$ cm^{-3}. This is far lower than the critical density required for thermalization of the $J = 3$ level, which is $\sim 5 \times 10^4$ cm^{-3}. Thus, we infer a low volume filling factor of $f_{vol} \sim 2$–6×10^{-4}, in agreement with Knapp *et al.* (1980) for $J = 2$–1, and similar to that observed for C^+ by Lugten *et al.* (1986). The areal filling factor cannot be so low: based on our high observed intensities and by comparison with the $J = 1$–0 interferometer maps of Lo *et al.* (1987), we estimate that $f_{areal} \sim 0.1$–0.2. This yields $f_{vol}/f_{areal} \sim 1$–6×10^{-3}. The ratio f_{vol}/f_{areal} = [the line of sight dimension/the beam size], and so we infer that the typical linear size scale of the molecular clouds is ~ 0.3–2 pc along the line of sight. The relatively high f_{areal} would require $\sim 10^4$–10^6 spherical clumps of diameter ~ 1 pc. An interpretation in this case is that the hot gas represents hot cores surrounding a very large number of distributed exciting sources. A lesser number of clumps would be possible if the line-of-sight dimension were significantly smaller than the transverse dimensions as in the case of sheets or filaments. There is evidence for sheetlike structures in the maps of Lo *et al.* (1987); the optical appearance of M82 is filamentary. The physical interpretation of these structures in terms of molecular gas is less clear. Spherical structures would be expected in the context of gravitational collapse. Sheetlike or filamentary structures might be believable in the dynamic environment of M82, where the observed high temperatures and pressures are probably due to shocks and winds within the starburst.

IV. CONCLUSIONS

We have detected and mapped ^{12}CO $J = 3$–2 emission in the nucleus of M82. We report an upper limit $I_{CO}/I_{^{13}CO} \lesssim 15$ from our nondetection of ^{13}CO, which indicates that the optical depth of the $J = 3$–2 transition is relatively low, $\tau_{32} \lesssim 6$, and that $\tau_{10} \lesssim 1$ for this warm component. The ^{12}CO $J = 3$–2 line is very intense, with a main beam brightness temperature of $J_{32}(T_{ex}) = 6.4$ K, corresponding to an excitation temperature $T_{ex} = 13$ K. By comparing the intensity of the $J = 3$–2 transition with those of the $J = 1$–0 and $J = 2$–1 transitions, we infer that $T_k \gtrsim 40$ K, and possibly as high as 100 K in the nuclear region of M82. We estimate a molecular mass $M_{gas} \sim 1 \times 10^8\ M_\odot$ within a galactocentric radius of 360 pc, and that the percentage of total mass in molecular gas is $>10\%$. We infer a low volume filling factor and a typical line-of-sight dimension of 0.5 pc for the clouds. The gas must either consist of $\sim 10^4$–10^6 clumps or must depart significantly from spherical structures. The large-scale pressure in the molecular gas is quite high, $nT = \sim 3 \times 10^6$ K cm^{-3}, comparable to that of the X-ray–emitting gas. The unusually high temperatures and pressures and the filamentary nature of the molecular gas may be a result of the turbulent nature of intense, confined star formation in the nucleus.

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