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WARM DENSE GAS IN LUMINOUS PROTOSTELLAR REGIONS: A SUBMILLIMETER AND FAR-INFRARED CO LINE STUDY

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ABSTRACT

We have observed the luminous star formation regions W51 IRS 2, W51 Main, G34.3+0.1, and W49 in the CO $J = 7 \rightarrow 6$ transition at 372 μm, and W51 IRS 2 and W51 Main in the CO 163 μm $J = 16 \rightarrow 15$ transition. All CO $7 \rightarrow 6$ spectra show emission from the warm quiescent molecular cloud core. A component of high-velocity emission is apparent in the spectra of W51 IRS 2, W51 Main, and possibly W49. The high-velocity emission from W51 IRS 2 comes from hot ($\sim 10^3$ K), dense (5×10^4 cm^{-3}) material with a total mass of $\sim 10^2$ $M_\odot$. The inferred mass-loss rates in the Galaxy's most luminous star formation regions are at least one order of magnitude larger than in Orion.

The $7 \rightarrow 6$ line profiles from the quiescent cloud cores differ strongly from profiles of lower J lines. The Planck brightness temperatures of the $7 \rightarrow 6$ lines are significantly higher than in the $1 \rightarrow 0$ and $2 \rightarrow 1$ lines. These differences indicate the presence of a warm (80–150 K) component of quiescent gas. The $J = 7 \rightarrow 6$ lines in W49 and G34.3+0.1 also do not have the sharp central reversal present in the millimeter profiles of ^{12}CO. This lack clearly indicates that the absorbing material must either be cool ($T_k < 25$ K at $n_{H_2} = 10^4$ cm^{-3}) or not very dense ($n_{H_2} < 2 \times 10^3$ cm^{-3} at $T_k = 35$ K) foreground gas or gas close to the source with a significantly lower pressure than the warm core. In addition, it demonstrates that self-absorption strongly affects the appearance of the $J = 1 \rightarrow 0$ and $2 \rightarrow 1$ transitions of ^{12}CO along many lines of sight in the galactic plane.

Subject headings: infrared: sources — interstellar: molecules — stars: formation

I. INTRODUCTION

Observations of short-submillimeter and far-IR rotational transitions of CO now permit a more precise determination of the physical characteristics of different gas components in molecular clouds. We have observed the 372 μm CO $J = 7 \rightarrow 6$ and 163 μm $J = 16 \rightarrow 15$ transitions in several luminous star formation regions. These lines lie beyond the peak of the excitation curve for the bulk of the material in these sources, so their excitation is strongly affected by small changes in physical conditions. They produce valuable information about material with a wide range of excitation. Molecular material at the low end of the CO excitation spectrum is in $n_{H_2} = 10^3$ cm^{-3}, $T = 20$ K quiescent regions throughout the galactic disk where the $J = 7$ level (155 K above ground state) is very subthermally populated. At the high end is $n_{H_2} = 10^4$ cm^{-3}, $T = 500$–1000 K gas in supersonic molecular flows where the CO levels are fully thermalized and the lines are often optically thin. The new observations characterize molecular gas in several of the most luminous galactic star formation regions.

II. OBSERVATIONS

We used the UC Berkeley submillimeter heterodyne spectrometer (Harris, Jaffe, and Genzel 1986) to observe the $J = 7 \rightarrow 6$ transition of CO (371.6505 μm, 806.6517 GHz) toward W51, W49, and G34.3+0.1 on 1984 June 12–14 from the NASA IRTF on Mauna Kea. The receiver consists of an open structure Schottky diode mixer (corner reflector with 4λ longwire antenna) quasi-optically coupled to the telescope and to an optically pumped far-IR laser local oscillator. The backend consisted of two filter spectrometers. The narrow-band spectrometer had 40 channels, each 5 MHz (1.9 km s^{-1}) wide. The broad-band spectrometer had 64×20 MHz (7.5 km s^{-1}) channels. The single sideband noise temperature measured at the telescope was 12,500 K. We calibrated the system gain by observations of ambient and solid CO_2 temperature blackbodies. We repeatedly measured the emission temperature of the atmosphere at different airmasses, then assumed a sec (z) law for the sky opacity and a sky temperature of 270 K to estimate the atmospheric transmission at the observing wavelength of 372 μm. The derived values for the zenith transmission were $\sim 15\%$ on June 12, 30% $\pm$ 1% on June 13, and 12.5% $\pm$ 1% on June 14. The CO $7 \rightarrow 6$ line lies near the long wavelength end of the 350 μm atmospheric window. The image sideband of receiver is 7.4 GHz below the signal sideband, at a frequency with lower atmospheric transmission than the signal sideband. The simultaneous detection of the signal and image sidebands for the calibration measurements results in an underestimate of the transmission and therefore, an overestimate of the line temperatures in the signal sideband. To obtain main beam brightness temperature, T_{MB}, we have multiplied the apparent submillimeter line temperatures by 0.85 to account for the different transmissions in the two sidebands. Based on measurements of Mars, Jupiter, and the Moon, the beam efficiency of our system on the 3 m IRTF was 0.4. The beam size, derived from mapping observations of Mars, was 32″ full width to half-maximum (FWHM). The aperture efficiency was ~ 0.35. The telescope secondary chopped at 17 Hz between the source and a reference position 185″ to the east or west.

Systematic errors in the temperature scale dominate the uncertainties in the measured line strengths for the profiles we discuss here. The errors most likely arise in the measurement of the forward coupling efficiency of the receiver and telescope (the main-beam efficiency) and in the determination of the atmospheric transmission. Our estimate for the maximum likely combined error in the temperature scale is $\pm 30\%$.

We observed the (162.8116 μm, 1843 GHz) CO $J = 16 \rightarrow 15$ line toward W51 IRS 2 and W51 Main on 1985 July 1 with the UC Berkeley Mark II tandem Fabry-Perot spectrometer (Lugten, Crawford, and Genzel 1986) on the 0.9 m NASA Kuiper Airborne Observatory. We observed W51 IRS 2 with FWHM resolution of 85 km s^{-1} and 45 km s^{-1} and W51 Main with 85 km s^{-1} resolution. The beam size on the sky was 55" full width to half-maximum (solid angle 9×10^{-8} sr). The telescope secondary chopped between the source and a position 3'.5 away in azimuth (approximately NE-SW for these observations). We corrected for variations in the instrumental response with wavelength by dividing the astronomical spectra by the spectrum of a reference blackbody. After correction for interorder leakage, we scaled the observed continuum to

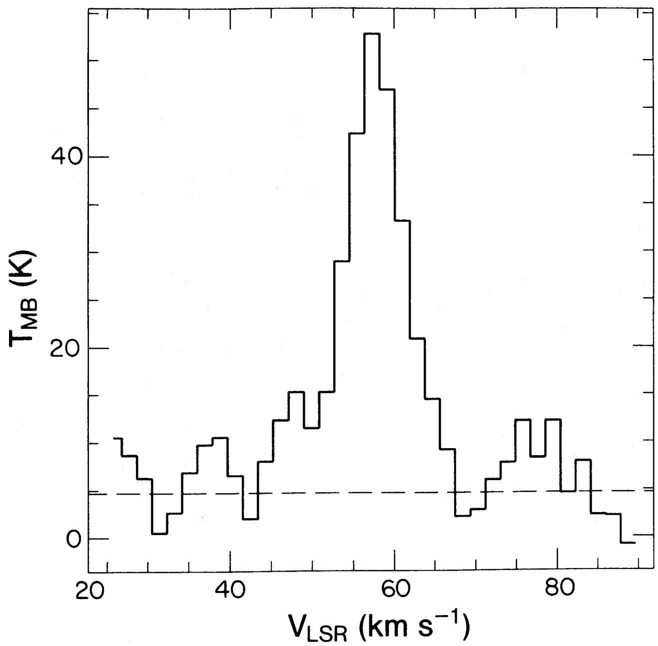

FIG. 1*a*

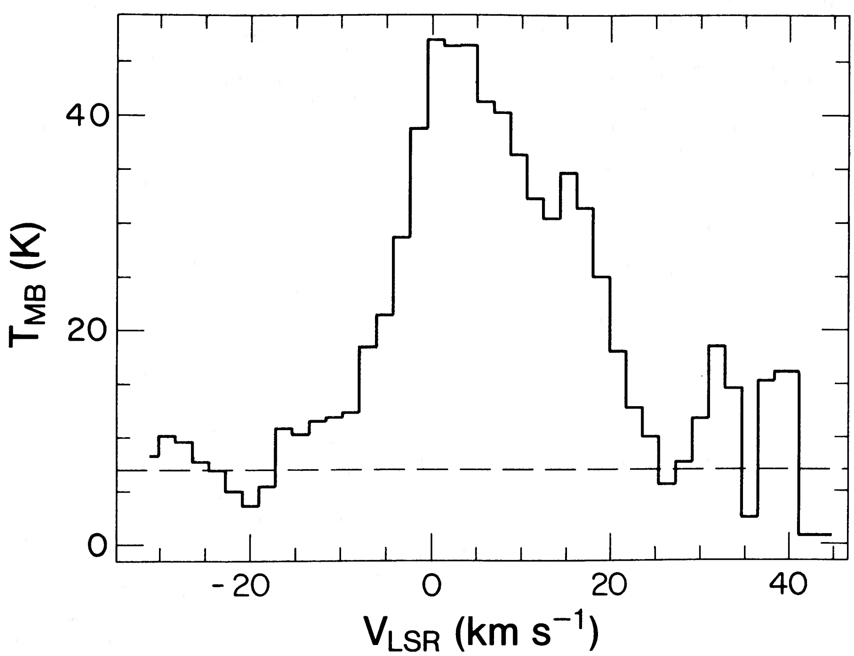

FIG. 1*b*

FIG. 1.—CO $7 \rightarrow 6$ spectra. The temperature scale is CO $7 \rightarrow 6$ main-beam brightness temperature. All spectra except (*f*) have 1.9 km s^{-1} resolution. (*a*) G34.3+0.1. (*b*) The central position in W49. (*c*) W51 IRS 2. (*d*) 15" South of W51 IRS 2. (*e*) W51 Main. (*f*) The central position in W49 with the low-resolution spectrometer (7.5 km s^{-1} resolution).

match the 163 μm continuum fluxes derived for W51 IRS 2 (13,000 Jy) and W51 Main (16,000 Jy) by Jaffe *et al.* (1986). The line-to-continuum ratio then gives the line fluxes directly.

III. RESULTS

a) The Spectra

Figure 1 shows the CO $J = 7 \rightarrow 6$ profiles observed toward G34.3+0.1, W49, W51 IRS 2, a position 15″ south of W51 IRS 2, and W51 Main. Figure 2 is a comparison of the $7 \rightarrow 6$ profiles with lower J transitions of $^{12}C\,^{16}O$ and $^{12}C\,^{18}O$ toward the same sources (White *et al.* 1985). Figure 3 gives CO $7 \rightarrow 6$ mapping results toward the core of W49. For a number of the observations, local radio frequency interference contaminated several channels at the extreme right in the spectra in Figures 1–3. We have not displayed these channels in the affected profiles. Table 1 lists the positions for the single point observations and the center position of the W49 map. Table 2 contains the line parameters derived from all of the $J = 7 \rightarrow 6$ profiles. The baselines for the CO $7 \rightarrow 6$ spectra lie 4–8 K above zero in all of the sources (Fig. 1). The absolute value of this offset and the relative value from source to source are consistent with the

TABLE 1

SOURCE CENTER POSITIONS

Source	Right Ascension	Declination (1950)
G34.3+0.1	$18^h50^m46^s.1$	+01°11′11″
W49....................	19 07 49.9	09 01 17
W51 IRS 2	19 21 22.5	14 25 13
W51 Main	19 21 26.2	14 24 38

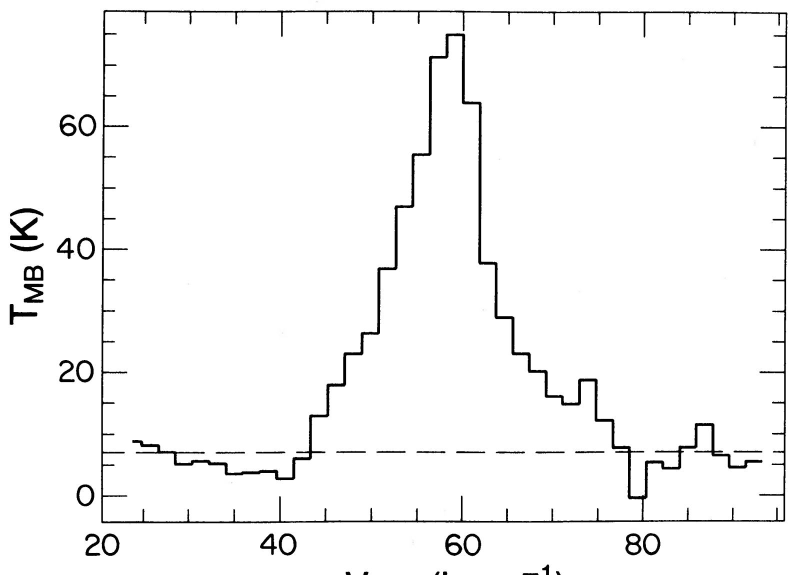

FIG. 1*c*

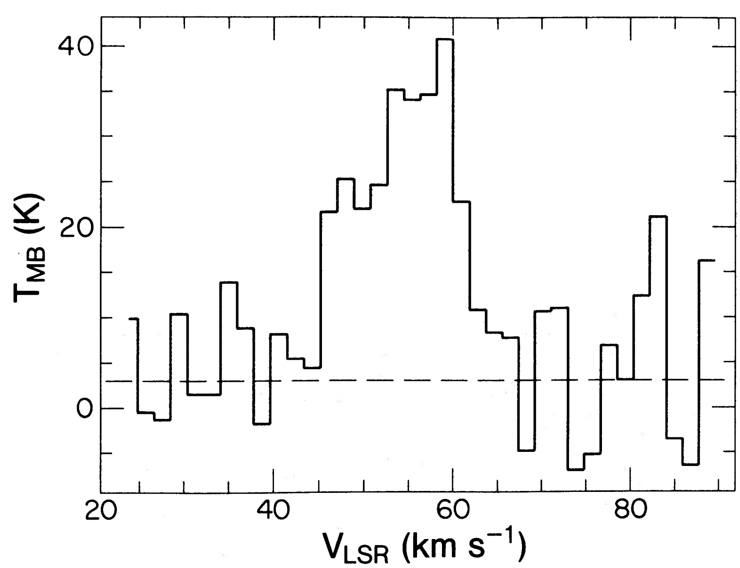

FIG. 1*d*

observed 400 μm continuum flux from warm dust (Jaffe, Becklin, and Hildebrand 1984, and unpublished observations).

Figure 4 shows the CO $J = 16 \rightarrow 15$ profile toward W51 IRS 2. Based on both the 85 km s^{-1} and 45 km s^{-1} resolution observations, the best value for the deconvolved width of the $16 \rightarrow 15$ line toward IRS 2 is 70 km s^{-1}. The $J = 16 \rightarrow 15$ line flux is $5.0 \pm 1.5 \times 10^{-18}$ W cm^{-2} toward IRS 2 and $3.8 \pm 1.5 \times 10^{-18}$ W cm^{-2} toward W51 Main. The corresponding velocity integrated line intensities are 5.5×10^{-4} and 4.2×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}.

b) *Basic Results*

We summarize the basic observational results from the observations presented in Figures 1–3 and Tables 1 and 2.

1. *High-velocity gas.*—The submillimeter/far-IR CO data show high-velocity ($\Delta v \geq 25$ km s^{-1}) components in a sample

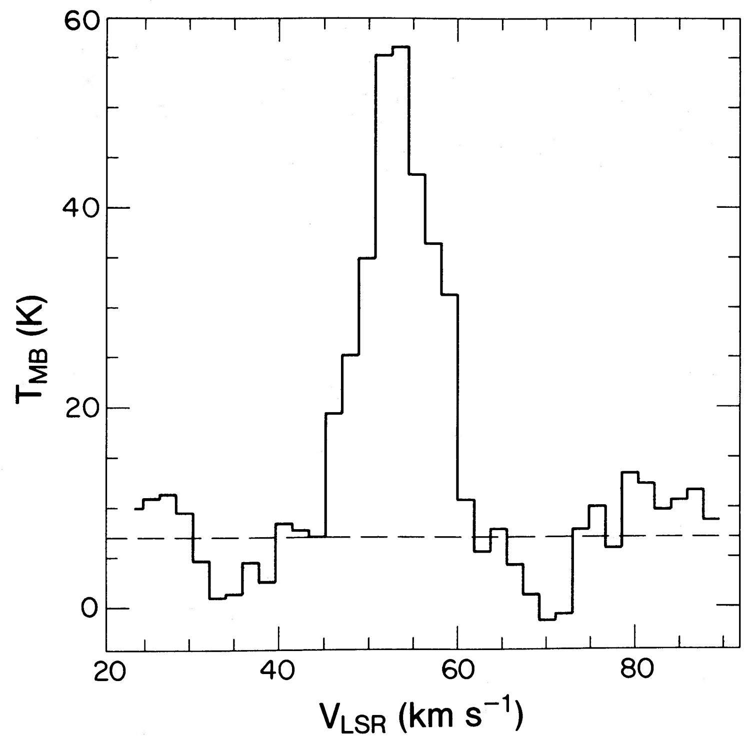

FIG. 1*e*

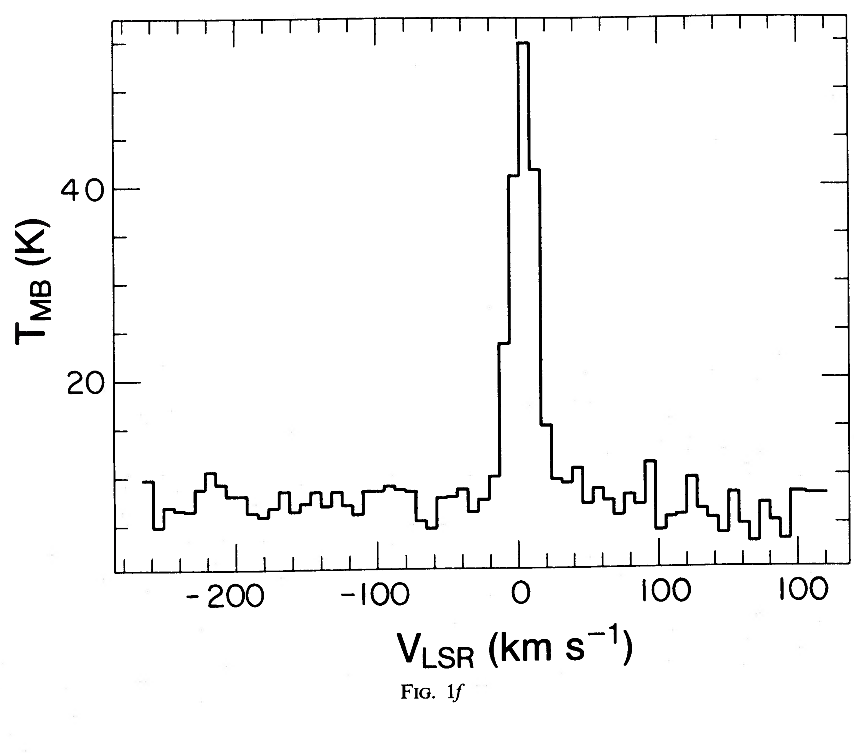

FIG. 1*f*

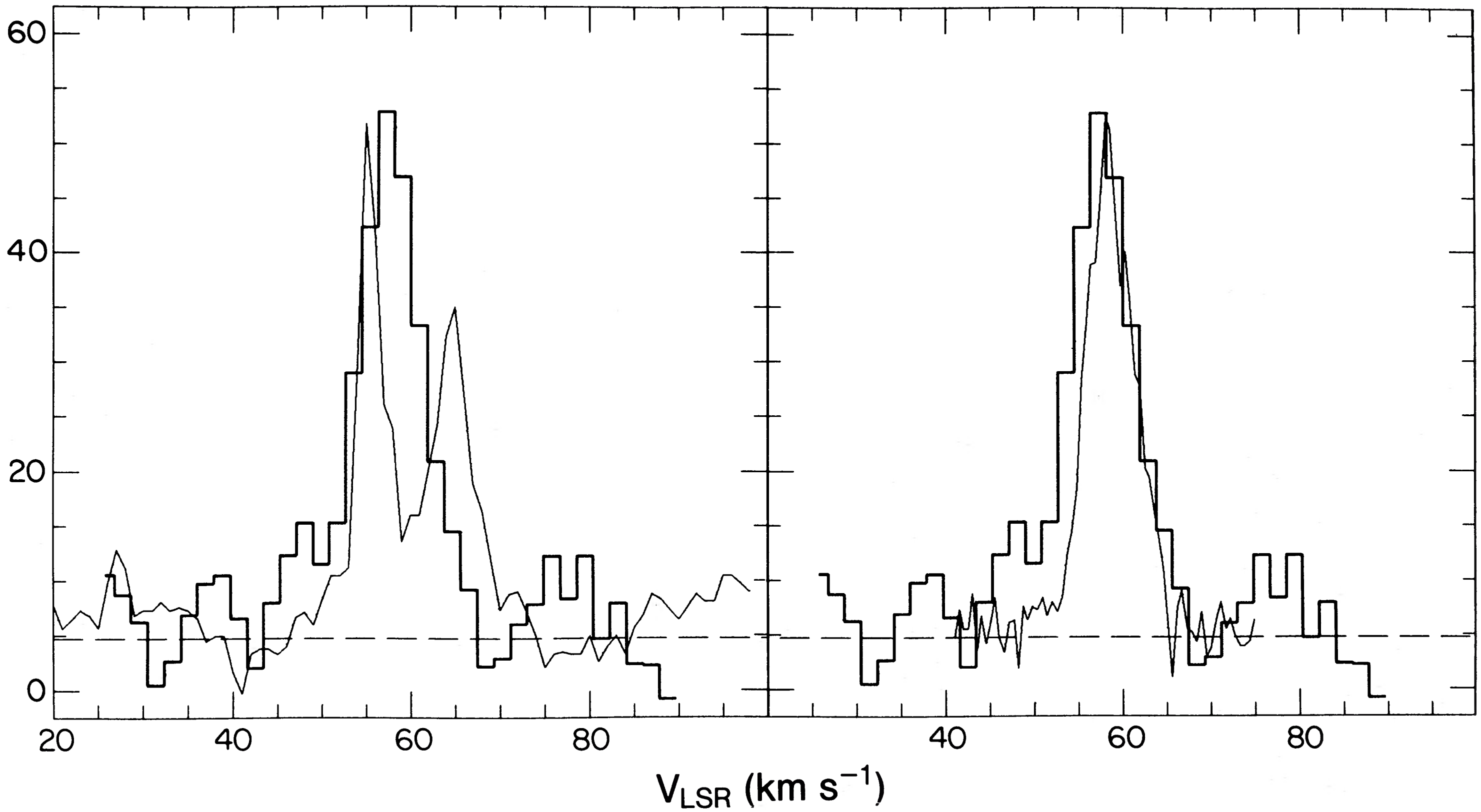

FIG. 2*a*

FIG. 2.—Comparison of the CO 7 → 6 spectra with millimeter CO lines. The heavy line is CO 7 → 6. The thin line is the millimeter CO spectrum scaled to aid comparison of line shapes. The vertical axis is CO 7 → 6 main-beam brightness temperature. (*a*) G34.3+0.1. *Left*: ^{12}CO 2 → 1 multiplied by 2.5 (Evans 1986, personal communication). *Right*: C^{18}O 1 → 0 multiplied by 10 (Jaffe, Keene, and Hildebrand 1985, hereafter JKH). (*b*) W49. *Left*: ^{12}CO 1 → 0 multiplied by 2 (JKH). *Right*: C^{18}O 1 → 0 multiplied by 40 (JKH). (*c*) W51 IRS 2 ^{12}CO 2 → 1 multiplied by 1.3 (Downes 1985, personal communication). (*d*) W51 Main. *Left*: ^{12}CO 3 → 2 multiplied by 2.2 (White *et al.* 1985). *Right*: C^{18}O 1 → 0 multiplied by 20 (JHK).

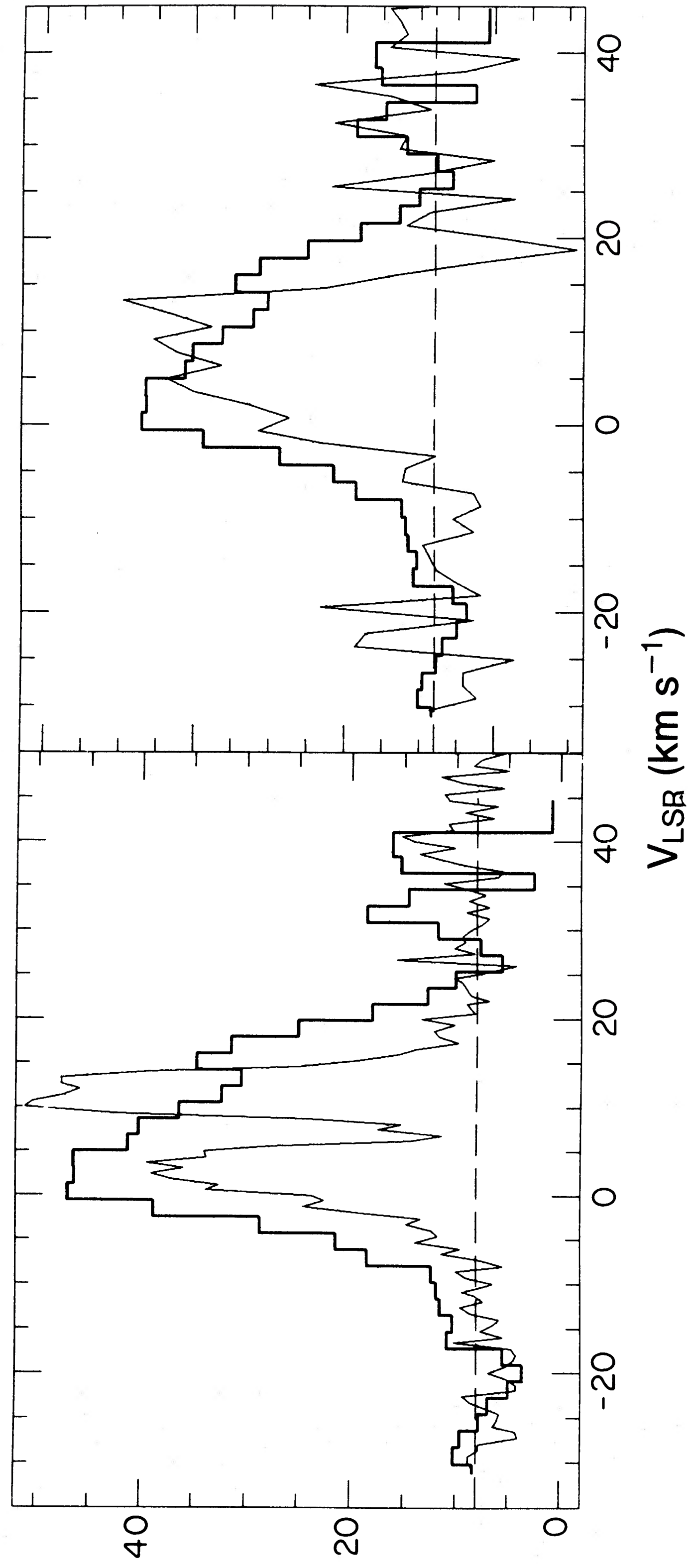

FIG. 2b

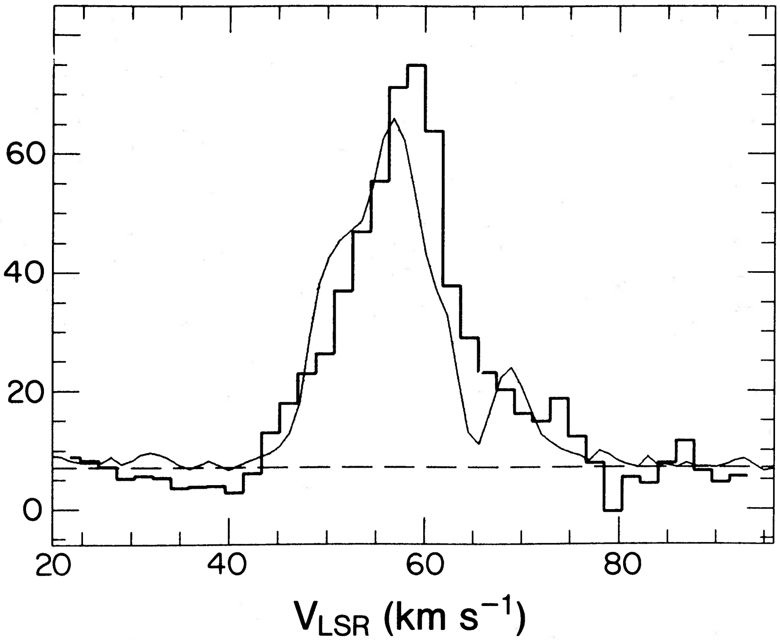

FIG. 2c

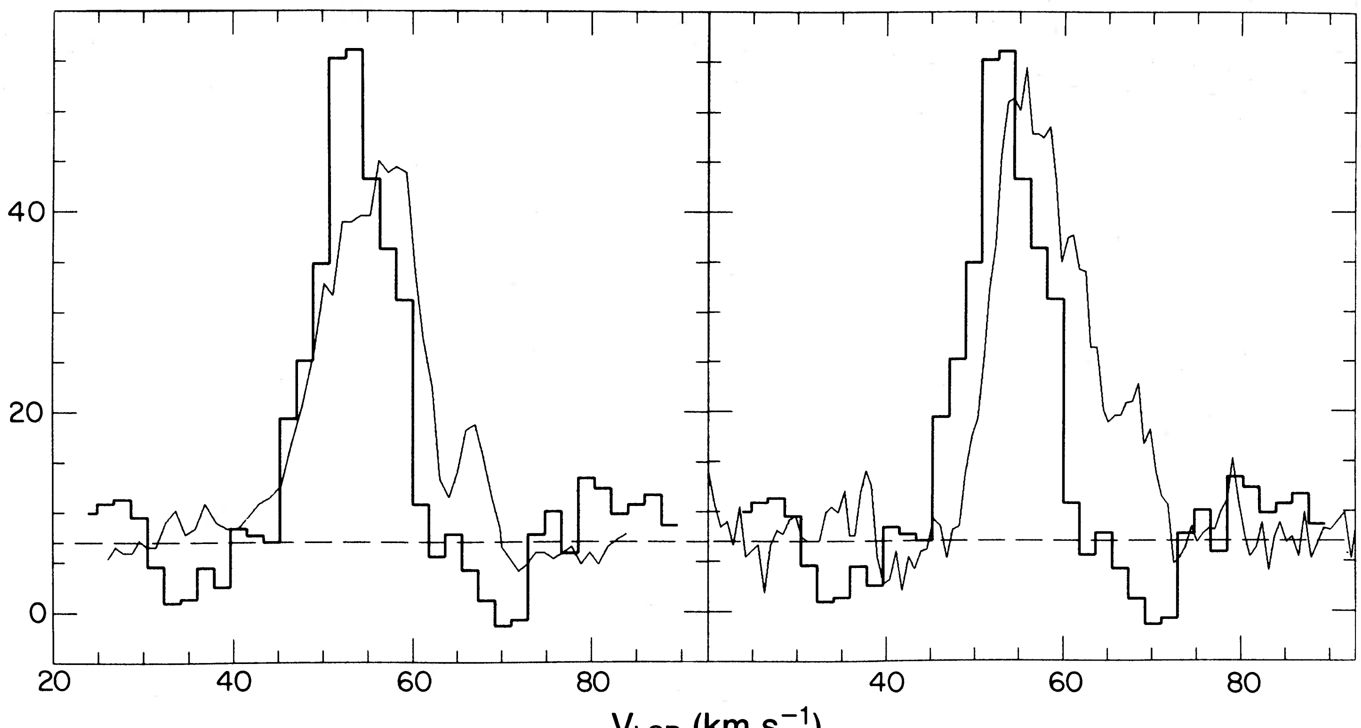

FIG. 2d

TABLE 2

CO $J = 7 \rightarrow 6$ LINE PARAMETERS

Source	T_{MB} (K)	T_{Planck} (K)	V_{LSR} (km s^{-1})	ΔV (km s^{-1})
G34.3+0.1	49	75	57	9
W49	41	68	8	24
W51 IRS 2	69	93	59	11
W51 Main	51	76	53	11

of the most luminous ($L \geq 10^6$ $L_\odot$) star formation regions in the galaxy. The $J = 7 \rightarrow 6$ profile toward W51 IRS 2 has two components. The high-velocity component has a full width to half-maximum (FWHM) of 27 km s^{-1} and a peak temperature of 15 K (Fig. 1*c*). This broad component is less obvious in the $J = 7 \rightarrow 6$ spectrum taken 15″ S of the IRS 2 position (Fig. 1*d*). The CO $16 \rightarrow 15$ profile toward W51 IRS 2 has a deconvolved FWHM of $\sim$70 km s^{-1}. The ratio of total line fluxes of the $16 \rightarrow 15$ to $7 \rightarrow 6$ lines in IRS 2 is 2.5 ± 1 and the ratio of the

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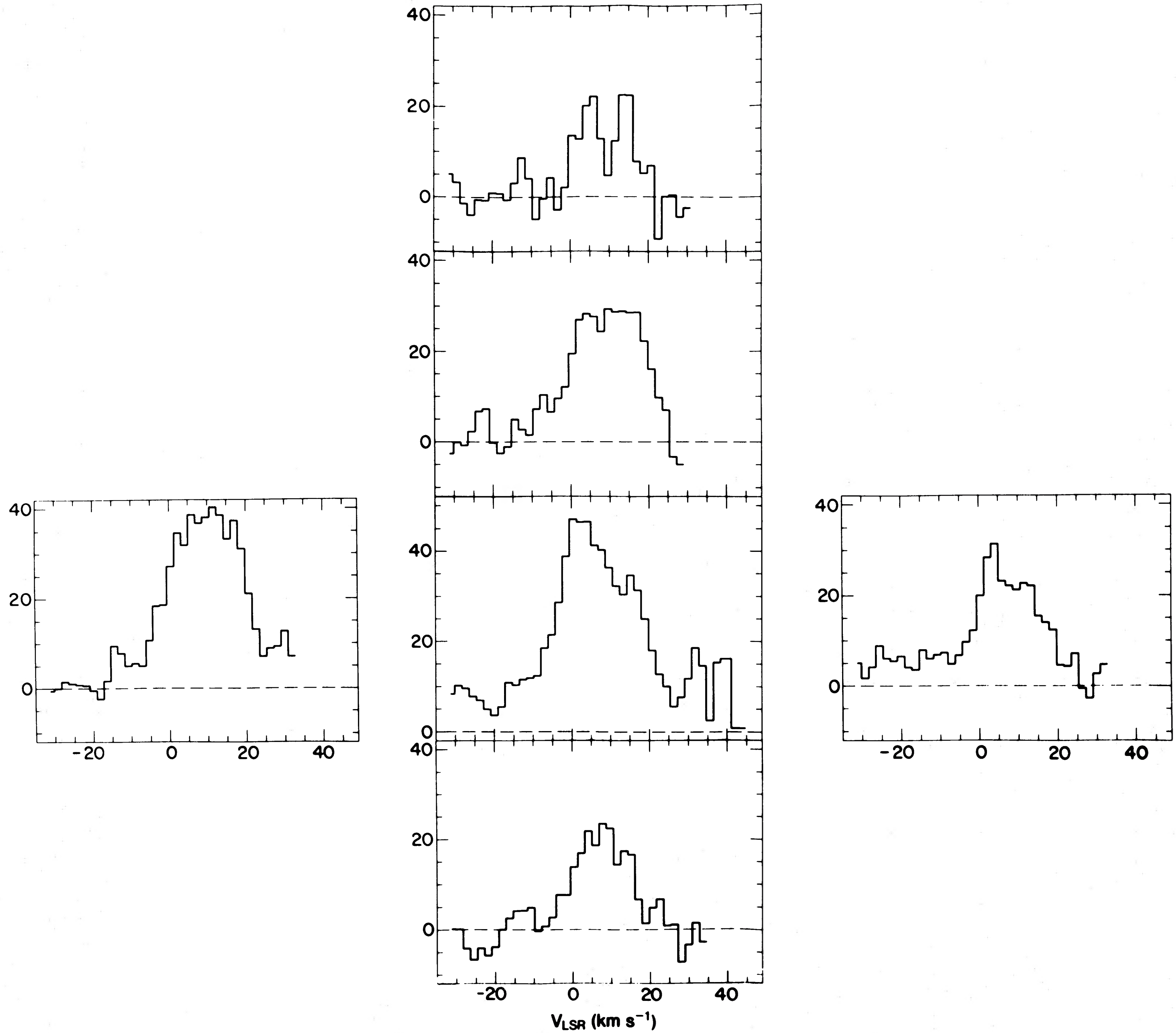

FIG. 3.—CO 7 → 6 map of the W49 core. The temperature scale is main-beam brightness temperature.

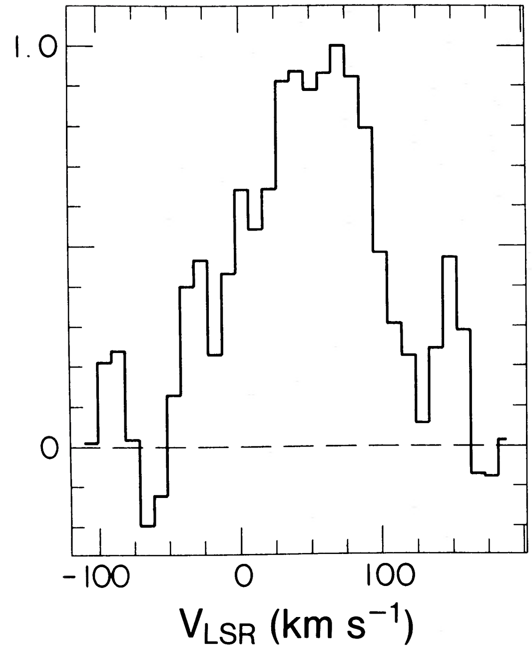

FIG. 4.—CO $16 \rightarrow 15$ profile toward W51 IRS 2. The peak Rayleigh-Jeans temperature of the line (1.0 units) is $\sim$1.5 K. The total flux in the line is 5×10^{-18} W cm^{-2} (5.5×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}).

$16 \rightarrow 15$ flux to the flux in the broad $7 \rightarrow 6$ component is 7 ± 3. In W51 Main, the CO $16 \rightarrow 15$ line is $\sim$90 km s^{-1} wide. We did not detect a high-velocity component toward the source in the $7 \rightarrow 6$ transition. If the $7 \rightarrow 6$ emission spreads over 90 km s^{-1} the $(16 \rightarrow 15)/(7 \rightarrow 6)$ ratio is 5 or greater. If, as in W51 IRS 2, the $7 < 6$ line is only 27 km s^{-1} wide the $(16 \rightarrow 15)/(7 \rightarrow 6)$ flux ratio must be 13 or greater.

Toward W49, the $7 \rightarrow 6$ data in the high- and low-resolution spectrometers (Figs. 1*b* and 1*f*) show a broad line of FWHM $\sim$ 26 km s^{-1} and total velocity range (FWZP) of 50 km s^{-1} or greater. This component has a similar width to the $1 \rightarrow 0$ CO "bipolar" emission from interferometric measurements by Scoville *et al.* (1986).

2. *Line Temperatures.*—The line temperatures of the $7 \rightarrow 6$ line from the low velocity, quiescent gas toward the luminous protostellar regions are remarkably high (T_{MB} = 40-70 K, Table 2). The Planck brightness temperatures of the $7 \rightarrow 6$ lines T_P range between 70 and 90 K, where

$$T_P = \left(\frac{h\nu}{k}\right)\left\{\ln\left[\left(\frac{h\nu}{kT_{MB}}\right) + 1\right]\right\}^{-1} \tag{1}$$

and are up to a factor of 3 higher than the CO $2 \rightarrow 1$ and $1 \rightarrow 0$ brightness temperatures toward the same regions. This factor is larger than the likely combined calibration errors for the millimeter and submillimeter lines ($\sim$50%). All of the observed sources are extended with respect to the beam sizes in the millimeter ^{12}CO lines. Strictly speaking, therefore, we observe the high $7 \rightarrow 6/1 \rightarrow 0$ or $2 \rightarrow 1$ ratio for 370 μm beam sizes of 32″ or smaller in all sources. In some sources, the high ratio may also exist on larger scale sizes.

There are strong point-to-point peak CO $7 \rightarrow 6$ line temperature variations in the individual sources. The peak line temperature drops by $\sim$50% between W51 IRS 2 and the position 15″ south of IRS 2. Toward W51 Main, 70″ to the southeast of IRS 2, the peak temperature is 50 K, compared to 70 K at IRS 2. The peak line brightness temperatures in W49 drop from 40 K toward the center position to an average of 28 K 30″ from this peak (Fig. 3). The high Planck brightness temperature of the $7 \rightarrow 6$ line alone argues for warm (> 70–90 K) emission regions in the cores of giant molecular clouds. If the regions are optically thin in the $7 \rightarrow 6$ line, have low density ($n_{H2} \ll 10^6$ cm^{-3}), have sizes comparable to or smaller than our 32″ beam, or have a clumpy distribution, then the actual kinetic temperature could be considerably higher.

3. *Line Shapes.*—The overall widths and detailed lineshapes of the $7 \rightarrow 6$ lines differ significantly from the corresponding $1 \rightarrow 0$ and $2 \rightarrow 1$ line parameters. In W49 and G34.3+0.1 (Fig. 2), the $1 \rightarrow 0$ and $2 \rightarrow 1$ ^{12}CO lines show a strong central reversal which is absent in the $7 \rightarrow 6$ spectra. The reversal in the millimeter lines extends over the entire area mapped in the $7 \rightarrow 6$ line in W49. The $7 \rightarrow 6$ line in W49 is wider than the $1 \rightarrow 0$ or $2 \rightarrow 1$ lines in that source ($\Delta v \approx 16$ km s^{-1}) or than any millimeter/submillimeter CO lines in other giant molecular cloud cores (see Table 2). The $J = 7 \rightarrow 6$ map of W49 shows that the broad line emission extends over $\sim$60″ (4 pc). There are no systematic changes in center velocity or line shape over the map. The large line width may be caused by random motions (local turbulence) or by systematic motions on a scale smaller than a few pc (see the data by Dreher *et al.* 1986 and Scoville *et al.* 1986).

We do not believe that spectral contamination from CO $7 \rightarrow 6$ emission at the off-source reference positions is significant for the line profiles in Figures 1 and 2. The warm cloud cores in W51 and W49 lie near the centers of cooler clouds which extend over 10–20 arcminutes in the $J = 1 \rightarrow 0$ transition (Mufson and Liszt 1977, 1979). If there is any significant excitation of the $J = 7$ level in the two clouds over these size scales, emission in the reference beams would contaminate the observed profiles. However, CO $7 \rightarrow 6$ mapping results in W49 show that, unlike the $1 \rightarrow 0$ emission, the higher J emission drops significantly within 30″–60″ of the source center. The line profiles toward W49 show no indication for a dip at the center, except at the position 60″ N (Fig. 3). One would expect such a dip based on the $1 \rightarrow 0$ map if there were a significant amount of cooler gas emitting in the CO $7 \rightarrow 6$ line in the reference beams, since the $1 < 0$ profiles are considerably narrower and weaker at these positions than at the source center (Mufson and Liszt 1979). By a similar argument, the symmetry and regularity of the W51 IRS 2 profile also support the thesis that reference beam contamination is unimportant. In W51 Main, the center velocity of the line (54 km s^{-1}) is quite different from the center velocity in the lower J transitions (57 km s^{-1}). Comparison with the $J = 2 \rightarrow 1$ east-west cut of Phillips *et al.* (1981) indicates that this difference in velocity and in line shape could be due either to emission in the reference beam or to self-absorption in the $2 \rightarrow 1$ line at the velocity of the $7 \rightarrow 6$ peak. The clear examples of self-absorption in the millimeter lines toward W49 and G34.3+0.1 lend credence to this latter possibility. Alternatively, the $7 \rightarrow 6$ peak could be at an intrinsically different velocity since much of the narrow component emission from quiescent gas could come from different gas than that responsible for the $2 \rightarrow 1$ emission. The ^{12}CO $3 \rightarrow 2$ and C^{18}O $1 \rightarrow 0$ profiles overlayed on the W51 Main profile in Figure 2 show that the line shape and center velocity clearly vary as a function of both excitation and opacity.

IV. DISCUSSION

In the following, we derive and discuss the physical parameters of the far-IR/submillimeter CO emission in luminous star formation regions. To obtain these parameters, we compare the measurements to model calculations of the line excitation and profiles. The non–LTE models employ an escape probability radiative transfer formalism. The models assume a plane-parallel geometry and CO/H_2 abundance ratio of 8×10^{-5} (Dickman 1978; Frerking, Langer, and Wilson 1982). We use the $CO\text{-}H_2$ collision rates of Flower and Launay (1985) for temperatures 100 K or less and CO-He collision rates from McKee *et al.* (1982) for higher temperatures.

a) High-Velocity Gas

i) *Physical Parameters*

The high-velocity gas in W51 IRS 2 is hot ($T_{kin} > 500$ K) and dense ($n_{H_2} \geq 2 \times 10^4$ cm^{-3}). The observed $(16 \rightarrow 15)/(7 \rightarrow 6)$ line flux ratio for the high-velocity gas is 7 ± 3. The observed $(7 \rightarrow 6)/(2 \rightarrow 1)$ ratio in this gas is 250 or greater (assuming conservatively that the source is larger than the 10″ $2 \rightarrow 1$ beam). We first compare these measured values to the infinite temperature LTE limits. The $(16 \rightarrow 15)/(7 \rightarrow 6)$ ratio, $R_{16/7}$, is lower than the limit value for both the optically thick ($R_{16/7} = 12$) and thin cases ($R_{16/7} = 63$). The $(7 \rightarrow 6)/(2 \rightarrow 1)$ ratio, $R_{7/2}$, is higher than the optically thick limit for this pair ($R_{7/2} = 43$) and only somewhat below the optically thin value ($R_{7/2} = 525$). The $(7 \rightarrow 6)/(2 \rightarrow 1)$ limit implies a $7 \rightarrow 6$ opacity of 1 or less.

The observed line ratios fit excitation models with a range of temperatures and densities above 500 K and 2×10^4 cm^{-3}. A typical combination in this range is $T_k \approx 1200$ K and $n_{H_2} \approx 5 \times 10^4$ cm^{-3}. The area filling factor per velocity interval of the $7 \rightarrow 6$ emission region is ~ 0.05. The emission region is either small ($< 7''$) or highly clumped. The inferred mass of high-velocity gas derived from the calculations is $\sim 60\ M_\odot$ assuming a distance of 7 kpc (Genzel *et al.* 1982). This mass represents the actual mass in high-velocity material as long as no significant amount of the material in the flow is very optically thick in the $7 \rightarrow 6$ transition and as long as there is no comparable amount of cool (< 30 K) material.

Excitation by magnetohydrodynamic (MHD) shocks (Draine and Roberge 1982; Chernoff, Hollenbach, and McKee 1982) is a plausible mechanism for producing the intensities observed in the CO $J = 16 \rightarrow 15$ and $7 \rightarrow 6$ lines from the high-velocity gas in W51 IRS 2 and W51 Main. The MHD shock excitation models of Draine and Roberge (1984) can explain the emergent intensities observed toward W51 IRS 2 with shock speeds of 10–30 km s^{-1} and magnetic fields of 0.1–1 mG. The detection of 2 μm H_2 S(1) emission from W51 IRS 2 (Beckwith and Zuckerman 1982) lends further observational support to the shock interpretation.

Emission from hot shocked gas—dominating the submillimeter broad component CO lines—may also make up a significant fraction of the $1 \rightarrow 0$ and $2 \rightarrow 1$ line emission in luminous protostellar flows. Studies of the ^{12}CO and ^{13}CO $2 \rightarrow 1$ and $1 \rightarrow 0$ lines which are mostly sensitive to gas temperatures of 30 K or less are consistent with the high temperatures derived for the Orion outflow (Snell *et al.* 1984). In W51 IRS 2, a significant fraction of the $2 \rightarrow 1$ CO emission can be accounted for by the same hot component responsible for the $7 \rightarrow 6$ and $16 \rightarrow 15$ emission.

Observations of other luminous flows (Margulis and Lada 1985) imply much lower temperatures (7–15 K) for the gas emitting in the millimeter CO lines in these regions. However, radiative transfer effects can cause large errors in temperatures derived from the millimeter isotopic CO lines. It is possible, for example, for optically thin gas at temperatures greater than 100 K to have low apparent temperatures. Emission from 200–1000 K optically thin clumps and cooler (~ 100 K) clumps with of order unity optical depth in ^{12}CO in the same beam will result in line ratios which mimic those of optically thick 10–30 K gas. A more complete examination of high-J CO lines from a larger sample of luminous outflows would show whether or not the suggested low gas temperatures are correct.

ii) *Comparison with Other Observations*

The 27 km s^{-1} wide feature in the W51 IRS 2 CO $J = 7 \rightarrow 6$ profile (Fig. 1) is similar to, but slightly wider than, the broad feature in the $v = 0$, $J = 2 \rightarrow 1$ SiO line profile toward IRS 2 (Downes *et al.* 1982). The much larger (~ 70 km s^{-1}) width of the $J = 16 \rightarrow 15$ profile (Fig. 4) implies the presence of significant excitation gradients in the emitting region, in the sense that there is proportionally more high excitation gas at higher velocities. The smaller *total* velocity extent of the CO $7 \rightarrow 6$ line compared to the $16 \rightarrow 15$ line is probably due to the dynamic range of the spectrum.

There are presently three sources where enough CO transitions have been measured to permit one to derive the physical conditions in the hot molecular gas. These are Orion/KL (Storey *et al.* 1981; Watson *et al.* 1985; Phillips *et al.* 1977; Schultz *et al.* 1985; Koepf *et al.* 1982), the Galactic center molecular ring (Harris *et al.* 1985; Liszt *et al.* 1983), and W51 IRS 2 (this work; Downes 1985, personal communication). Watson *et al.* (1985) fitted the intensities of a large number of CO lines originating in states with $J > 15$ from the Orion/KL region with an optically thin non–LTE model. Most of the emission in their model arises from a component with a temperature of 750 K and a density of 3×10^6 cm^{-3}. Harris *et al.* (1985) used $J = 16 \rightarrow 15$, $7 \rightarrow 6$, $2 \rightarrow 1$, and $1 \rightarrow 0$ line fluxes and a non–LTE escape probability model to derive values for the temperature and density of 300 K and 3×10^4 cm^{-3} in the Galactic center molecular ring.

A simple comparison of the line ratios in the W51 IRS 2 emission region to those in Orion and the Galactic center reveals strong source to source variations in excitation. In all three sources, the $J = 7 \rightarrow 6$ to $J = 2 \rightarrow 1$ intensity ratio is greater than 120. This ratio is higher than the ratio of 43 for optically thick gas in LTE at infinite temperature, implying that at least some of the emission comes from optically thin gas. In the optically thin limit, the $7 \rightarrow 6/2 \rightarrow 1$ ratio implies kinetic temperatures of greater than 200 K for the emission regions if they are in LTE and even higher temperatures if they are subthermally excited. The $16 \rightarrow 15/7 \rightarrow 6$ intensity ratio ranges from 7 in W51 IRS 2, to 3 in Orion/KL, to 0.14 in the Galactic center. Non–LTE effects at any given density have a much stronger effect on the $16 \rightarrow 15/7 \rightarrow 6$ ratio than on the $7 \rightarrow 6/2 \rightarrow 1$ ratio. If the gas were in LTE, the range in values would imply a temperature variation from ~ 100 K in the Galactic center to ~ 250 K in W51 IRS 2. In strongly subthermally populated gas, the line intensity ratio implies a higher kinetic temperature and varies approximately as the gas pressure, $n_{H_2} T$. The pressure then must change by a factor of ~ 50 going from the Galactic center to W51 IRS 2.

The mass of hot, shock-excited CO in W51 IRS 2 and W51 Main is about one order of magnitude larger than in Orion/KL, as are the far–IR luminosities of these sources. The velocity range of the high-velocity gas is comparable, however. Hence, the mass and momentum of the outflows presumably driving the shocks probably scale with bolometric luminosity up to the most massive galactic star formation regions.

b) Quiescent Gas

In luminous star formation regions, the CO $7 \to 6$ results show that short wavelength submillimeter ^{12}CO transitions arise in warm ($T \geq 80$ K), dense ($n_{H_2} > 10^4$ cm^{-3}) gas at the cores of the clouds. The strength of the $7 \to 6$ line together with the significant differences between the $7 \to 6$ profiles and the millimeter CO profiles in some sources demonstrates first, that the submillimeter line arises closer to the heating sources than the millimeter lines, and second, that absorption in cooler overlying layers dominates the appearance of the millimeter lines. The mapping results in W49 indicate that "turbulence" or systematic motions on subparsec scales dominate the width of the extremely broad line in that region. Radiative transfer molecular excitation models of the regions show that the pressure ($n_{H_2}T$) must drop sharply away from the CO $7 \to 6$ emission region in order to produce the self-absorption in the millimeter CO transitions without significantly affecting the $7 \to 6$ line.

i) *Cores: Evidence for a Warm Component*

Taken at face value, the high intensity ratios of the $7 \to 6$ line to the millimeter CO lines from the quiescent cloud cores suggest a hot optically thin component that dominates the $7 \to 6$ emission, but is not a significant contributor to the lower J line strengths. The obvious influence of self-absorption on the millimeter lines (Fig. 2), however, makes this type of simple analysis incorrect.

In W51 IRS 2 and W51 Main, an upper limit on the excitation in the quiescent region comes from the $16 \to 15/7 \to 6$ ratio. A conservative upper limit to the CO $16 \to 15$ emission from this component is a strength equal in intensity to the detected broad line, but only one resolution element wide ($\leq 2.3 \times 10^{-18}$ W cm^{-2} for W51 IRS 2, $\leq 1.3 \times 10^{-18}$ W cm^{-2} for W51 Main). We assume a moderate source size, so the $16 \to 15/7 \to 6$ ratio will be some average of the line brightness and line flux ratios. The derived $16 \to 15/7 \to 6$ ratios are 1.3 or less for W51 IRS 2 and 1 or less for W51 Main. These upper limits are appropriate for model clouds with $T \leq 80$ K at $n_{H_2} = 10^6$ cm^{-3}, $T \leq 160$ K at $n_{H_2} = 10^5$, and $T \leq 750$ K at $n_{H_2} = 10^4$ cm^{-3}.

The $16 \to 15$ results provide good limits on the temperature of the "spike" emission region if it has high density. Observations of the 400 μm continuum radiation show that the bulk of the gas within 20″ IRS 2 or Main has a density of $n_{H_2} > 10^5$ cm^{-3} (Jaffe, Becklin, and Hildebrand 1984; Cunningham *et al.* 1984). If the CO $7 \to 6$ line comes from gas with a density of 10^5 cm^{-3} or greater, its temperature is 160 K or less. The Planck brightness temperature of the $7 \to 6$ line provides a lower limit to the gas kinetic temperature, $T_k \geq 70$ K for W51 Main and $T_k \geq 90$ K for W51 IRS 2. The temperature of a high-density emission region must then be between 70 K and 160 K. The $16 \to 15/7 \to 6$ results also indicate that if the $7 \to 6$ emission arises in a region with a low filling factor and a high temperature, its density must be less than 10^5 cm^{-3}. We have therefore constrained either the temperature of a single-component CO emission region or the density of the hot medium in a two-component emission model.

A macroturbulent core model (Martin, Sanders, and Hills 1984) offers a natural explanation of the run of line brightness and width with transition and with isotopic abundance. In such a model, a moderate number of clumps emit the observed line flux. Each of these clumps may be optically thick and have an internal velocity dispersion lower than the clump-clump velocity dispersion. If the clumps are in LTE and have optical depths of ~ 5 in the $1 \to 0$ line, they will have an optical depth ~ 100 in the $7 \to 6$ line for $T = 100$ K. The increased optical depth results in an increased area filling factor per velocity interval. For clumps with a Gaussian density profile and these optical depths, this increase is about a factor of 3; i.e., enough to match the observed increase in brightness temperature (Martin, Sanders, and Hills 1984). This type of model works fairly well on the central region of W49 but fails in the other sources where the millimeter and submillimeter line shapes differ more drastically.

ii) *Line Profiles and Core Structure*

The ^{12}CO $1 \to 0$ and $2 \to 1$ (Mufson and Liszt 1977; Phillips *et al.* 1981) and HCO$^+$ (Nyman 1983) profiles toward the central 2′–3′ of W49 peak at two velocities (+4 and +12 km s^{-1}). Several authors propose a model of the source as two separate molecular clouds with velocities ~ 4 km s^{-1} above and below the H II region velocity (Mufson and Liszt 1977; Miyawaki, Hayashi, and Hasegawa 1986). Observations of the less abundant molecular species like ^{13}CO, C^{18}O, and H^{13}CO$^+$ contradict this model since these lines have a single broad (14–16 km s^{-1}) emission profile which peaks at ~ 7 km s^{-1} (Mufson and Liszt 1977; Jaffe, Keene, and Hildebrand 1985; Nyman 1984). Comparison of these profiles with the ^{12}CO and HCO$^+$ profiles shows that the source emits a single broad line centered at 7 km s^{-1} and that this line is absorbed by a cool foreground cloud which is optically thin in the less abundant species. If this foreground cloud is highly clumped and has less than unity filling factor per velocity interval, it could also cause the slight dip seen in the CS $J = 1 \to 0$ and $2 \to 1$ lines (Nyman 1984; Miyawaki, Hayashi, and Hasegewa 1986).

The absence of self-absorption in the $7 \to 6$ line along lines of sight showing strong absorption in the millimeter CO lines is an important clue to the structure of the clouds and the physical conditions in the gas absorbing the millimeter lines. Gas with temperatures of 50–100 K and densities of $10^{3.5}$–10^5 cm^{-3} cannot be present along the line of sight to the warm CO seen in the hot cores. Either the cloud radiating in the $7 \to 6$ line must have little cooler gas associated with it and the absorption occurs in the 5–10 K, 10^2–10^{-3} interstellar clouds along the line of sight (Scoville and Solomon 1975; Gordon and Burton 1976), or the hot core must consist of well-defined clumps embedded in a medium with a much lower temperature and density.

Observations of the CO $J = 2 \to 1$ transition toward a sample of warm cores with CO $1 \to 0$ reversal source shows that they frequently have deeper absorption in the $2 \to 1$ line (Phillips *et al.* 1981). Phillips *et al.* modeled the reversals and showed that for absorbing CO clouds at 20–30 K, their depths increase as one goes from the $1 \to 0$ to the $3 \to 2$ transition of CO at molecular hydrogen densities higher than $10^{2.5}$ cm^{-3}. At lower densities, the $J = 3 \to 2$ reversal is less marked than the reversals in the lower lying transitions.

We have constructed additional models in order to understand the presence of deep central reversals in the $J = 1 \to 0$ and $2 \to 1$ profiles toward W49 and $2 \to 1$ profile toward G34.3+0.1 and their absence in the $J = 7 \to 6$ profiles. We searched the temperature and density plane for the region where the opacity in the $7 \to 6$ line is low ($\ll 1$) while the opacity in the $1 \to 0$, $2 \to 1$, and $3 \to 2$ lines is still high (> 1). The models met these conditions at $n_{H_2} = 10^3$ cm^{-3} for $T_k <$

150 K, at 3×10^3 cm^{-3} for $T_k < 50$ K and at 10^4 cm^{-3} for $T_k \leq 25$ K. These modeling results severely constrain the structure of the cloud cores. Gas at temperatures and densities between the 100 K and 10^5–10^6 cm^{-3} typical of the hot cores and the T_k and n_{H_2} values at which the $7 \rightarrow 6$ line in the envelope becomes optically thin will absorb strongly in this line.

V. CONCLUSIONS

We have combined spectroscopic measurements of two CO submillimeter/far-IR rotational lines for a study of molecular gas in four massive star formation regions.

In three of the four regions we find CO emission over a wide velocity range ($\Delta v = 20$–70 km s^{-1}). The data in W51 IRS 2 and W51 Main show that the high-velocity gas is hot ($T > 500$ K), presumably as a result of excitation in shocks. Mass outflows from newly formed stars in the two W51 sources carry an order of magnitude more momentum and mass than in the Orion/KL flow. We conclude that mass outflow rates scale with source luminosity up to the most luminous galactic star formation regions ($L \geq 10^6\ L_\odot$).

The $7 \rightarrow 6$ CO emission lines from the "quiescent" cloud cores have high brightness temperature ($T_p \approx 70$–90 K) and show no significant central self-reversal. The $7 \rightarrow 6$ profiles differ strongly from those of the low J millimeter CO lines, suggesting that the 372 μm CO $7 \rightarrow 6$ lines originate in warm dense gas near the exciting sources. CO gas in the more extended cloud envelopes must have low density (≤ 2–3×10^3 cm^{-3}) and low temperature (≤ 50 K).

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