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DETECTION OF FAR-INFRARED ^{13}CO LINE EMISSION

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ABSTRACT

We have detected far-infrared ^{13}CO line emission toward the core of Orion-KL. About 10–30 $M_\odot$ of dense and warm ($T \geq 200$ K) gas are required to account for the 151 μm $J = 18 \rightarrow 17$ ^{13}CO line flux. At line center the $J = 18 \rightarrow 17$ ^{13}CO line is about 25 times weaker than the $17 \rightarrow 16$ ^{12}CO line. The ^{13}CO line has an intrinsic width of $\leq$17 km s^{-1} (FWHM), as compared to 27 km s^{-1} for the ^{12}CO line.

The ^{13}CO and ^{12}CO far-infrared lines cannot come from a single, optically thin component of gas. The emission could originate either from an optically thick source of temperature near 200 K or, more likely, from several components of gas. In the latter case, gas in two regions probably contribute about equally to the $18 \rightarrow 17$ ^{13}CO flux. First, there is optically thin emission over a broad velocity range from a high-temperature ($T \geq 700$ K) zone which probably represents shocked gas in the high-velocity outflow from the infrared cluster. The ^{12}CO/^{13}CO flux ratio in this component is 85 ± 20.

Second, there is an optically thick emission region of high column density ($N_{\rm CO} \sim 10^{20}$ cm^{-2}), but low-velocity dispersion ($\Delta v \sim 10$ km s^{-1}) which we identify with the "hot core." From comparison of the ^{13}CO $18 \rightarrow 17$ and $1 \rightarrow 0$ line fluxes we find that the molecular hydrogen volume density in the hot core exceeds 10^7 cm^{-3} and the gas temperature is at least 200 K.

Subject headings: interstellar: matter — interstellar: molecules — nebulae: Orion Nebula

I. OBSERVATIONS AND RESULTS

^{12}CO far-infrared line emission from excited rotational states was first discovered toward the center of the Orion-KL star-forming region by Watson *et al.* (1980). The far-infrared line emission comes from high-velocity gas, as the velocity width is about 30 km s^{-1} (Crawford *et al.* 1986; Watson *et al.* 1985). Draine and Roberge (1982), Chernoff, Hollenbach, and McKee (1982), and Watson *et al.* (1985) have interpreted the far-infrared CO emission to come from hot, optically thin gas excited by a C-type shock advancing into the quiescent molecular cloud. From near-infrared spectroscopy of the 4.6 μm CO rovibrational transitions toward BN, Scoville *et al.* (1982) find a ^{12}CO/^{13}CO fractional abundance ratio of 96 ± 5 for the high-velocity molecular gas in Orion-KL. In the following, we refer to this ratio as the "standard" value.

The data were taken on the NASA Kuiper Airborne Observatory in 1988 January with the MkII UCB cryogenic tandem Fabry-Perot spectrometer (Lugten 1987). For observation of the weak isotopic CO line, we chose the $J = 18 \rightarrow 17$ transition at 151.4315 μm which is in a wavelength region clear of telluric absorption features. For comparison, we also observed the nearby ^{12}CO $J = 17 \rightarrow 16$ line (153.2669 μm). We employed a three-element linear array of stressed Ge:Ga detectors with a spatial resolution of 55″ (cf. Stacey *et al.* 1988). Two data sets were taken at spectral resolutions of FWHM 42 and 32 km s^{-1} (Fig. 1) for the central detector. The telescope's secondary chopped at 33 Hz about 3.′7 in azimuth (approximately east-west). Absolute line fluxes at 150 μm were determined by observing Jupiter (3.1×10^5 Jy: Loewenstein *et al.* 1977) and the Orion-KL continuum (41,000 Jy: M. Werner, private communication). In addition, we also observed in 1987 January the 124 μm $J = 21 \rightarrow 20$ ^{12}CO and $J = 22 \rightarrow 21$ ^{13}CO transitions in a spectral scan covering both lines (resolution 50 km s^{-1}). A 3 σ upper limit to the $22 \rightarrow 21$ ^{13}CO flux was about 2×10^{-18} W cm^{-2}, or 3×10^{-2} of the $21 \rightarrow 20$ ^{12}CO line.

a) ^{12}CO *and* ^{13}CO *Line Fluxes and Mass of Warm Molecular Gas*

The $18 \rightarrow 17$ ^{13}CO line flux is $2.3 \pm 0.7 \times 10^{-18}$ W cm^{-2} (2.6×10^{-4} ergs s^{-1} cm^{-2} sr^{-1}). The ratio of $17 \rightarrow 16$ ^{12}CO (8.2×10^{-17} W cm^{-2}) to $18 \rightarrow 17$ ^{13}CO line fluxes is 37 ± 8. Taking into account the different line widths (see § I*b*, below), the ratio of ^{12}CO to ^{13}CO intensities at line center is $\leq$25. Note that the $J = 17 \rightarrow 16$ ^{12}CO flux is the same as the $18 \rightarrow 17$ ^{12}CO flux to within a few percent (Stacey *et al.* 1982; Watson *et al.* 1985).

The ^{13}CO $18 \rightarrow 17$ flux can be used directly for a first estimate of the mass of warm molecular gas at the core of Orion-KL. With the optically thin CO emissivities given by McKee *et al.* (1982) and a ^{13}CO/H_2 fractional abundance of 10^{-6}, total gas masses of 5 $M_\odot$ at a gas temperature of 500 K and 50 $M_\odot$ at 200 K are required to account for the ^{13}CO flux in local thermodynamical equilibrium (LTE). For H_2 densities less than 10^8 cm^{-3} an even larger amount of warm gas is implied. For comparison, the total mass of interstellar matter within 20″ of Orion-IRc2, as estimated from millimeter and submillimeter continuum measurements of dust emission, is between 20 and 100 $M_\odot$ (see § II*c*). Hence, warm, very dense gas makes up a significant fraction of interstellar matter at the core of Orion-KL.

b) ^{13}CO *and* ^{12}CO *Line Profiles and Spatial Distribution*

The ^{13}CO profile is narrower than the ^{12}CO profile (Fig. 1). The ^{13}CO line is barely resolved at a velocity resolution of 32

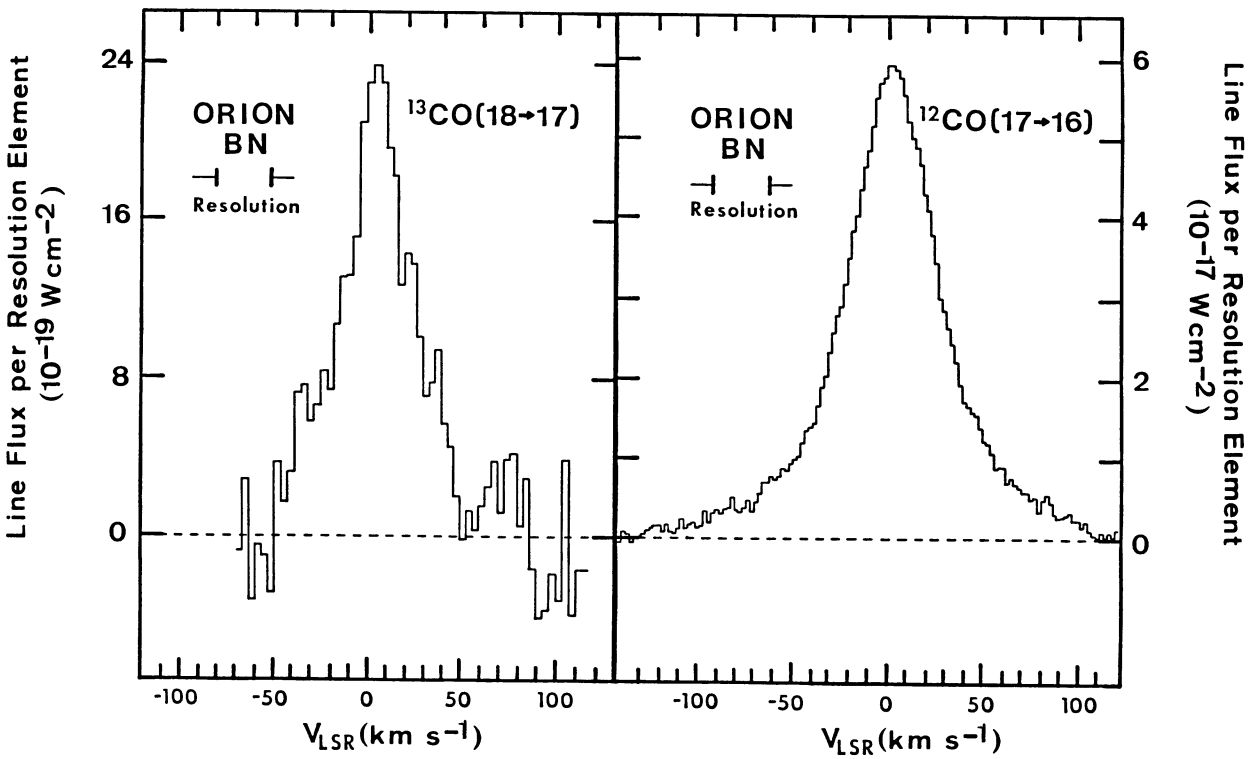

FIG. 1.—Spectra of the 151.4315 μm $J = 18 \rightarrow 17$ transition of ^{13}CO (*left*) and of the 153.2669 μm $J = 17 \rightarrow 16$ transition of ^{12}CO (*right*) toward the position of the BN object (R.A. = 05^{h}32^{m}46^s.7, decl. = −05°24′17″ [1950]). Both observations employed about the same spatial (55″ FWHM) and spectral (32 km s^{-1} FWHM) resolutions. The instrumental profile is a modified Lorentzian (see Lugten 1987).

km s^{-1}, but the ^{12}CO line is about 35% wider than our spectral resolution. A maximum entropy (MEM) deconvolution of both line profiles indicates that the intrinsic width of the ^{13}CO line is ≤17 km s^{-1} (FWHM). The ^{12}CO 17 → 16 line has an intrinsic width near 27 km s^{-1}, consistent with the results for other high-J ^{12}CO transitions (Crawford *et al.* 1986; Poglitsch *et al.* 1988). In addition to strong emission of relatively narrow velocity spread, there is weaker, high-velocity ^{13}CO 18 → 17 emission ranging from −40 to +30 km s^{-1} LSR. High-velocity ^{12}CO 17 → 16 emission is detected between −60 and +50 km s^{-1} LSR. Significant ^{13}CO emission was also detected in one of the off-center detectors (55″ northwest from center). The line flux at position 55″ NW is about 0.3 times the central value, and at position 55″ SE it is ≤0.15 times the central value. The ^{13}CO source may have an intrinsic size of about 40″ (FWHM), similar to the diameters of the 150 μm continuum and of the ^{12}CO emission (Watson *et al.* 1985; Poglitsch *et al.* 1988).

II. DISCUSSION

Our measurements show that ^{13}CO and ^{12}CO far-infrared lines have different line profiles and that the ^{13}CO 18 → 17 line flux is significantly larger than expected for a single, optically thin ^{12}CO far-infrared emission component. There are two likely interpretations which we will discuss in the following. First, the far-infrared ^{12}CO emission may be optically thick. Second, there may be two or more emission components which have different physical parameters and which contribute differently to the ^{12}CO and ^{13}CO lines. Another explanation for the relatively low ^{12}CO/^{13}CO flux ratio, of course, is a low ^{12}CO/^{13}CO abundance ratio (∼25–40; cf. Blake *et al.* 1986).

a) Optically Thick ^{12}CO Emission

The optical depth of the ^{12}CO high-J emission, as derived from comparison of observed Rayleigh-Jeans brightness temperature (∼40 K) and kinetic temperature (∼700 K), is about 0.1. However, the low brightness of the ^{12}CO lines is also consistent with optically thick emission if the area filling factor of the emitting gas is small. The ratio of ^{12}CO and ^{13}CO intensities then indicates that the ^{12}CO 17 → 16 optical depth has to be about 2 or greater for a standard fractional abundance ratio. That optical depth is also consistent with the wider ^{12}CO far-infrared profile.

In order to check the validity and consequences of this and alternative interpretations more quantitatively, we computed level populations of the lowest 35 rotational levels of ^{12}CO and ^{13}CO and the corresponding emergent line intensities as a function of molecular hydrogen density, temperature, and column density in an escape probability, radiative transfer formalism. We assumed statistical equilibrium, a CO/H_2 abundance ratio of 10^{-4} (Watson *et al.* 1985) and a ^{12}CO/^{13}CO fractional abundance ratio of 90. Collisional cross sections of CO with H_2 were taken from McKee *et al.* (1982) and Schinke *et al.* (1985) (see also Viscuso and Chernoff 1988). The parameters of representative, best-fitting models are listed in Table 1. The "optically thick" model is plotted in Figure 2 as model I, together with the CO data points. The millimeter and submillimeter CO emission component of the dynamically active gas is referred to as the "plateau." The high-velocity far-infrared emission is referred to as the "shocked gas." The data can be fitted by a range of parameters. Temperatures between 200 and 240 K and hydrogen densities between 5×10^6 and 3×10^7 cm^{-3} describe the far-infrared measurements ade-

TABLE 1

BEST-FIT MODELS OF CO EMISSION IN ORION-KL

Model[a]	T (K)	$n(H_2)$ (cm^{-3})	N_{CO} (cm^{-2})	θ_{source} (FWHM)	$M(H_2)$ ($M_\odot$)
I—Single-component model:					
"Optically thick"[b], $\Delta v = 20$ km s^{-1} (FWHM)	200	10^7	5×10^{19}	35″ × 55″ $\Phi = 0.28$[c]	30
II—Three-component model:					
IIa—Warm plateau[b] ($\Delta v = 30$ km s^{-1})	200 → 400	3×10^5	5×10^{18}	25″ $\Phi \sim 1$	3
IIb—Shock[b] ($\Delta v = 30$ km s^{-1})	700	10^6	2.7×10^{17}	35″ × 55″ $\Phi = 1$	0.5
IIc—Hot core ($\Delta v = 10$ km s^{-1})	230	3×10^7	10^{20}	10″ $\Phi \sim 1$	10

[a] Assumed relative abundances: $^{12}CO/H_2 = 10^{-4}$, $^{12}CO/^{13}CO = 90$.

[b] Representative single temperature model only; a more realistic model will include a range of temperatures (and densities). In particular, the ^{12}CO transitions for $J > 26$ require gas of temperature significantly higher than 1000 K (Watson *et al.* 1985).

[c] Area filling factor of emission within θ_{source}.

quately. For physical parameters in this range and a total CO column density near 5×10^{19} cm^{-2}, the far-infrared ^{12}CO lines also have the necessary optical depth (e.g., $\tau[18 \to 17] \approx 7$) to account for the difference in ^{12}CO and ^{13}CO 18 → 17 line width. Figure 2 indicates that the model also accounts for a major fraction of the ^{12}CO 1 → 0, 2 → 1, and 3 → 2 plateau flux.

While the optically thick model can explain some features of the CO rotational emission, there are, however, three main problems. The first and least serious is its failure to explain the intensities of ^{12}CO lines with $J \geq 26$. Additional gas at higher temperture may account for this emission. A more serious problem of the optically thick model is its prediction that millimeter and far-infrared CO source sizes should be about the same. The observations indicate that the far-infrared CO source is almost twice as large as the source of millimeter CO emission (Poglitsch *et al.* 1988). The most serious problem is the discrepancy between observed and predicted submillimeter

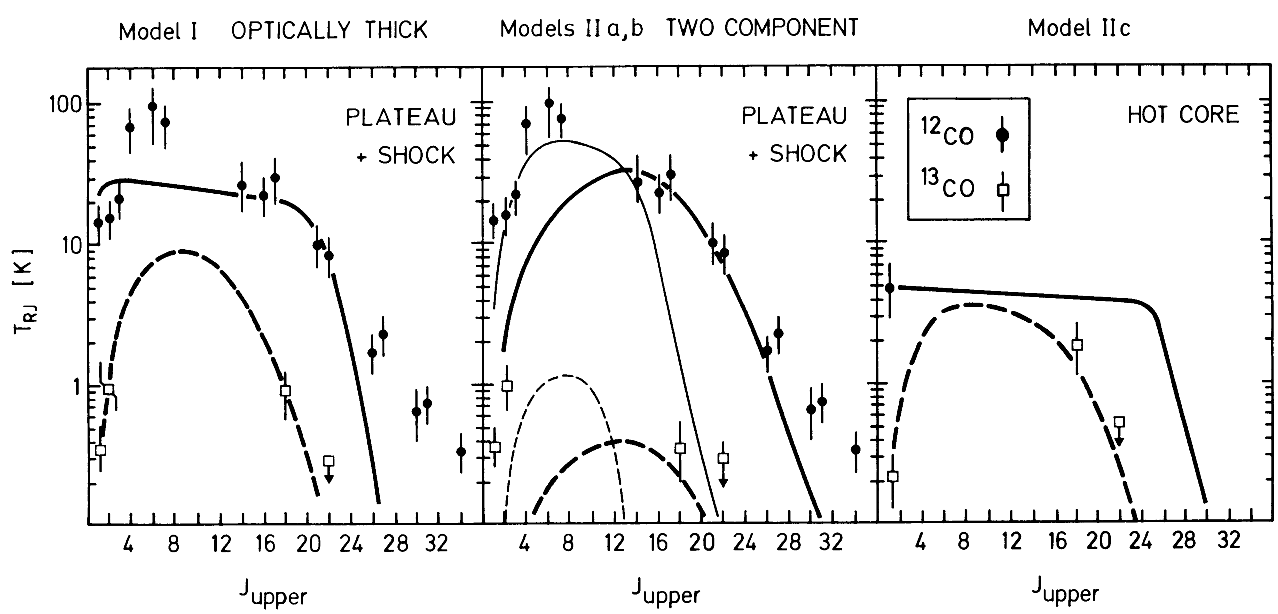

FIG. 2.—Representative models of the millimeter, submillimeter, and far-infrared, high-velocity CO emission in Orion-KL. All measurements are expressed in terms of Rayleigh-Jeans brightness temperatures at line center and are converted to a common beam size (1′ FWHM). We assumed a FWHM line width of 30 km s^{-1} for the "plateau" and "shocked gas" components, and 10 km s^{-1} for the hot core. In order to convert data measured with different beam sizes to a 1′ beam, we assumed source sizes of 25″ (FWHM) for the plateau, 35″ × 55″ for the shocked gas (Poglitsch *et al.* 1988) and 10″ for the hot core. ^{12}CO data are given as filled circles, ^{13}CO data as open quadrangles. The millimeter data are from Snell *et al.* (1984) and Masson *et al.* (1984, 1987); the submillimeter and FIR data are from Walker *et al.* 1988, Erickson *et al.* (1982), Koepf *et al.* (1982), Watson *et al.* (1985), and Poglitsch *et al.* (1988). The numbers of the models refer to Table 1, and the models are the continuous curves for ^{12}CO and dashed curves for ^{13}CO. For the "optically thick" model on the left (model IIa), we have used the total flux of the ^{13}CO 18 → 17 line and a 20 km s^{-1} line width. The middle panel shows the models for plateau (IIa: *thin*) and shock (IIb: *heavy*). The bright panel shows the model for the hot core (IIc).

brightness temperatures. The observed Rayleigh-Jeans brightness temperatures of the broad $6 \rightarrow 5$ and $7 \rightarrow 6$ lines are near 200 K for beam sizes of about 30″ to 40″ (Koepf *et al.* 1982; Poglitsch *et al.* 1988), corresponding to intrinsic temperatures of at least 300 K. In contrast, the optically thick model predicts a peak temperature of ~ 85 K, correcting the thermalized emission ($T_{RJ} \sim 200$ K) in the optically thick model for the beam dilution factor (0.4) necessary to fit the far-infrared data. Any additional component of emission which can account for the submillimeter CO data would also dominate the emission lines between $J = 14$ and 20 and would require optically thin, subthermally excited far-infrared emission, in contradiction to the basic assumption of the optically thick model. We conclude that the single-component, optically thick model is in agreement with some of the far-infrared CO measurements, but is inconsistent with the submillimeter CO plateau line emission.

b) *Several Emission Components*

We now consider the alternate possibility that several emission components are necessary for describing the millimeter, submillimeter, and far-infrared CO data. The first is an optically thin, hot region (the shocked gas) which accounts for the far-infrared ^{12}CO data as proposed by Storey *et al.* (1981). The best-fitting parameters of the lines between $J = 14$ and $J = 26$ (for a FWHM line width of 30 km s^{-1}) are again listed in Table 1 and plotted in Figure 2 as model IIa. The parameters are essentially identical to those given by Watson *et al.* (1985). In order to account for the ^{12}CO emission at $J \geq 30$, an additional component of significantly higher temperature ($T > 1500$ K), but much smaller column density ($N_{CO} \sim 3 \times 10^{19}$ cm^{-2}) is required (Watson *et al.* 1985). More realistic descriptions of the ^{12}CO emission, as the C-type shock models, include a range of temperatures.

The second component is the spatially more compact, high-velocity plateau emission which accounts for the millimeter and submillimeter ^{12}CO lines. This component probably represents warm ($T \sim 100$–400 K) gas in the outflow from the infrared cluster. A representative model of 300 K kinetic temperature (IIb) can approximately describe the millimeter and submillimeter ^{12}CO line intensities, but fails to explain the ^{13}CO $1 \rightarrow 0$ and $2 \rightarrow 1$ emission. It is fairly obvious that gas of even lower temperature (~ 100 K), but higher column density, must be present in the outflow. In order to estimate the probable contribution of broad line emission to the ^{13}CO $18 \rightarrow 17$ line, we have used MEM deconvolution of the $18 \rightarrow 17$ data as well as direct comparison of the ^{12}CO and ^{13}CO profiles. Either method indicates that about 30%–50% of the ^{13}CO $18 \rightarrow 17$ flux comes from high-velocity gas. With a correction for ^{12}CO emission in the hot core (see below), we infer a ^{12}CO/^{13}CO relative abundance ratio of 85 ± 20. This is consistent with the assumption of optically thin emission and a near solar neighborhood fractional abundance ratio. The lower intensities in both ^{12}CO and ^{13}CO at the 55″ NW position do not allow an analysis of the line profiles in the same way as for the center position. If we assume optically thin emission, we obtain an abundance ratio of 50^{+50}_{-20}.

Explanation of $\sim 60\%$ of the ^{13}CO $18 \rightarrow 17$ flux and of an even higher fraction of the peak ^{13}CO brightness requires an additional component of high volume and high column density (to account for the ^{13}CO intensity), but small filling factor (to be consistent with a small contribution to the ^{12}CO emission) and relatively small line width ($\Delta v \leq 17$ km s^{-1}). This description is qualitatively matched by the "hot core," a warm, clumpy region of about 10″ (FWHM) diameter and FWHM velocity width near 10 km s^{-1}. In fact, a model of the submillimeter and far-infrared CO emission based on the standard parameters of the hot core region [$T_{kin} \sim 150$ K, $n(H_2) \sim 10^7$ cm^{-3}, $N_{CO} \sim 7 \times 10^{19}$ cm^{-2}: Masson *et al.* 1984] *predicts* a $18 \rightarrow 17$ ^{13}CO Rayleigh-Jeans line brightness of 0.6 K for a beam size of 55″. This is a significant fraction of the observed brightness temperature for line center (1–2 K). The best-fit parameters for the CO emission from the hot core, constrained by the ^{13}CO $18 \rightarrow 17$ line and the interferometer measurements of the ^{12}CO and ^{13}CO $1 \rightarrow 0$ transitions (Masson *et al.* 1984, 1987), are listed in Table 1 as model IIc. This model is plotted in the right panel of Figure 2.

The model with three or more emission components explains the overall CO rotational line emission from dynamically active gas better than the optically thick model. It also naturally fits in a physical picture where the less dense and cooler outflowing material is inside the more compressed, hotter shocked gas. Model II still does not account for the entire intensity of the submillimeter ^{12}CO lines and it predicts too much $14 \rightarrow 13$ flux. A lower hydrogen density than given in Table 1 would remedy the latter discrepancy, but would lead to an average H_2 density higher than the intrinsic H_2 density; this is not physical. Finally, the ^{13}CO flux in the off-center position taken at face value is not consistent with the small size of the hot core, or requires a higher ^{13}CO/^{12}CO ratio.

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