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2 CENTIMETER H_2CO EMISSION IN THE ρ OPHIUCHI CLOUD

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ABSTRACT

Strong emission in the 2 cm $J_{K_{-1}K_1} = 2_{12}$–2_{11} line of H_2CO has been found in the ρ Oph dark cloud (ρ Oph B). Previously this 2 cm H_2CO line has been detected in emission only in the warm ($T_K >$ 50 K) clouds OMC-1 and OMC-2. Densities in excess of 10^6 cm^{-3} are required to drive this 2 cm line into emission. The 2 mm $J_{K_{-1}K_1} = 2_{12}$–1_{11} ortho-H_2CO emission line at ρ Oph B appears to be self-reversed when compared to optically thin lines (e.g., $H_2{}^{13}CO$). The dense ρ Oph B core has a mass of $\sim$100 $M_{\odot}$ and an extinction of $A_v > 200$ mag similar to OMC-1 or OMC-2, but differs from them in temperature, being a cold region emitting strong lines of DCO^+. While near- and far-infrared and radio continuum searches cover the ρ Oph B region, no known sources are coincident with the region of 2 cm H_2CO emission. More sensitive searches are needed. The lack of observed signposts of star formation in an unusually dense cold region indicates ρ Oph B may represent an earlier stage of cloud evolution than either the OMC-1 or OMC-2 regions.

Subject headings: interstellar: molecules — stars: formation

I. INTRODUCTION

The ρ Oph cloud contains two separate dense cores, seen in the distribution of SO (Gottlieb *et al.* 1978). The first dense region (hereafter ρ Oph A) lies at $\alpha(1950) = 16^h23^m25^s$ and $\delta(1950) = -24°15'49''$. Carbon recombination line emission (Brown *et al.* 1974) and far-infrared emission (Fazio *et al.* 1976; Harvey, Campbell, and Hoffman 1979) have been detected toward ρ Oph A; and Loren, Evans, and Knapp (1979) find a core density of at least 3×10^5 cm^{-3} from observations of 2 cm and 2 mm H_2CO. The second SO emission peak (hereafter ρ Oph B) lies roughly 6′ S–10′ E of ρ Oph A. We have extended the H_2CO maps to include the ρ Oph B region.

The $J_{K_{-1}K_1} = 2_{12}$–2_{11} H_2CO transition (hereafter referred to as the 2 cm transition) is usually seen in absorption against galactic continuum sources or the 3 K background. This 2 cm line has been previously reported in emission only toward OMC-1 (Evans *et al.* 1975) and OMC-2 (Kutner, Evans, and Tucker 1976). Comparison of the 2 cm and the $J_{K_{-1}K_1} = 2_{12}$–1_{11} (hereafter 2 mm) H_2CO line intensities can be used to determine cloud densities and $X(H_2CO)$, the fractional abundance of H_2CO. The method was first used by Evans and Kutner (1976) and later by Wootten *et al.* (1978); Loren, Evans, and Knapp (1979); and Sandqvist and Bernes (1980). At the position of strongest 2 mm H_2CO emission in the dense cores of the R CrA and ρ Oph A clouds Loren, Evans, and Knapp did not detect the 2 cm H_2CO line in either absorption or emission. In both clouds, with increasing distance from the core the 2 mm emission strength decreases while the 2 cm absorption strength increases, forming a ring of strong 2 cm absorption around the dense core (Loren *et al.* 1980*b*). The 2 cm line occurs in absorption at low densities but goes into emission at very high core densities.

II. OBSERVATIONS

The 2 cm H_2CO line was observed with the NRAO[5] 43 m antenna at Green Bank, West Virginia. The beam size was 2′ at 14.49 GHz, and a velocity resolution of 0.27 km s^{-1} was used. Corrections have been made for changes in beam efficiency due to gravitation deformation (Loren, Evans, and Knapp 1979; Brown 1979). Three H_2CO lines from 137.5 to 145 GHz (Table 1) were observed with the Millimeter Wave Observatory[6] 4.9 m antenna at Fort Davis, Texas. The beam size at 140.8 GHz was 1′.8, and data with velocity resolutions of 0.53 km s^{-1} and 0.13 km s^{-1} were obtained.

Using two different antennas with similar beam sizes at their corresponding frequencies allows regions of the same projected area to be compared; observing two transitions that arise from the same state ensures that both lines are excited at the same density.

In Figure 1*a* the 2 cm H_2CO emission line toward the ρ Oph B dense core is compared to the corresponding 2 mm emission line. The differences between the two profiles are attributed to high optical depth in the 2 mm transition (Sandqvist and Bernes 1980). The optically

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TABLE 1

H_2CO EMISSION TOWARD ρ OPHIUCHI B

Position[a]	ON (1)	2E (2)	2 N–2 E (3)
2 cm = $J_{K_{-1}K_1} = 2_{12}–2_{11}$ at 14.5 GHz			
T_A(2 cm)	+0.12	+0.06	+0.11
V_{LSR}(km s^{-1})	3.6	3.7	3.3
ΔV(km s^{-1})	0.9	1.2	0.7
rms	0.025	0.027	0.027
T_A(2 cm)/η	+0.39	+0.20	+0.36
2 mm = $J_{K_{-1}K_1} = 2_{12}–1_{11}$ at 140.8 GHz			
T_A*(2 mm)	1.8	1.7	1.0
V_{LSR}	3.2	3.2	3.8
ΔV	1.0	1.9	1.5
T_R(2 mm)	2.1	2.0	1.2
$H^{13}CO$ = $J_{K_{-1}K_1} = 2_{12}–1_{11}$ at 137.5 GHz			
T_A*($H_2{}^{13}CO$)	0.4	...	...
V_{LSR}	3.0[b]	...	...
ΔV	3.4[b]	...	...
para-H^2CO = $J_{K_{-1}K_1} = 2_{02}–1_{01}$ at 145.6 GHz			
T_A*(para-H_2CO)	1.2	...	...
V_{LSR}	3.5	...	...
ΔV	1.9	...	...
T_A*(CO)	23.2	26.0	26.2

[a] Offset positions relative to ρ Oph B: $\alpha(1950) = 16^h24^m09^s$; $\delta(1950) = -24°21'49''$.

[b] 250 kHz filters used, all other 2 mm data used 62.5 kHz filters.

thin 2 cm line peaks at a velocity of 3.6 km s^{-1} where a dip occurs in the 2 mm line profile. The 2 mm profile resembles the optically thick self-reversals of CO and ^{13}CO that occur over much of the ρ Oph cloud (Lada and Wilking 1980). If the 2 mm line is self-reversed, use of its peak intensity may result in an incorrect density estimate.

To verify that self-absorption occurs we observed the 137.5 GHz ortho-H_2 ^{13}CO($J_{K_{-1}K_1} = 2_{12}–1_{11}$) and the 145.6 GHz para-H_2CO ($J_{K_{-1}K_1} = 2_{02}–1_{01}$) lines (Table 1). Both of these line profiles (Figs. 1*c* and 1*b*) resemble the optically thin 2 cm line rather than the 2 mm H_2CO line, supporting the suggestion of the high optical depth of the latter transition. The line profile of the 2 mm line and its weakness relative to the less abundant para-H_2CO suggest that absorption of radiation near the center of the 2 mm line is occurring as a result of a region of lower excitation temperature along the line of sight.

Since the other high-density regions of 2 cm H_2CO emission, OMC-1 and OMC-2, are known to be associated with enhanced T_A*(CO), IR sources, H_2O masers, etc., it might be expected that ρ Oph B would also be associated with some signposts of star formation. The 2 cm H_2CO emission occurs at three adjacent beam positions in ρ Oph B, shown on a map of T_A*(CO) in Figure 2. This differs from the CO map by Encrenaz, Falgarone, and Lucas (1975) in two aspects. First, our map is of peak T_A*(CO) rather than integrated line intensity. Second, the lines were observed with a fourfold increase of velocity resolution, which is important in sources with narrow lines like ρ Oph. Toward ρ Oph B modest enhancement—T_A*(CO) $\sim$ 26 K—is seen, indicating heating sources might be present. Surprisingly, Figure 2 shows that no near- or far-infrared or radio continuum sources lie within the region of 2 cm H_2CO emission, although several unusual infrared sources (E31, E32, E33, and VS26) lie just to the southeast. The most interesting of these, E32, is extended at 1.6 and 2.2 μm (Elias 1978) and may contribute to the observed CO heating. Vrba *et al.* (1975) estimate $A_v \sim$ 14–40 mag toward these infrared sources. Large A_v is also indicated by the large strength of the observed 3.1 μm ice band feature (Harris, Woolf, and Rieke 1978). High column densities also occur 5′ W–4′ S of ρ Oph B where Lada and Wilking (1980) estimate A_v W 100 mag because of the presence of ^{13}CO self-absorption. The J = 2–1 ^{13}CO line profiles toward ρ Oph A also show evidence of self-absorption (Loren *et al.* 1980*a*).

Often regions of star formation have enhanced emission in the wings of the CO lines. In the region near ρ Oph B the CO line profiles have enhanced low-velocity wings (Fig. 2) which may reflect cloud motions associated with an early stage of star formation.

Wootten and Loren (1980) find that the J = 2–1 DCO^+ intensities toward ρ Oph B are stronger (1.5–2.0 K) than in any other known source (cf. Wootten, Loren, and Snell 1980). The abundance of a deuterated molecule depends strongly on kinetic temperature (Snell and Wootten 1979). Hot clouds like OMC-1 do not have detectable DCO^+ lines, while cold clouds like L134N have strong lines. The strong DCO^+ J = 2–1 lines toward ρ Oph B indicate the presence of a *cold* core rather than a warm core. This cold core may contribute to the self-absorption of the CO, ^{13}CO, and H_2CO lines. This supposition is in accord with the results of Lada and Wilking (1980) which require a large column of cold dust ($T_D \sim$ 14 K) between the observer and the warm CO.

III. DENSITY TOWARD ρ OPHIUCHI B

The self-reversal of the 2 mm H_2CO line and the possibility that the dense core is colder than the observed T_A*(CO) would appear to make the density determination in ρ Oph B quite uncertain. If no self-absorption occurs, the observed radiation temperature $T_R(2\ \text{mm}) = T_A^*/\eta = 2.1$ K. If self-absorption reduces T_R (2 mm) then the para-H_2CO can be used to estimate its intensity; assuming an ortho/para abundance ratio of 3 and a ratio of line strengths of 1.5/2.0 gives T_R (2 mm) = 3.2 K. For a warm cloud core (T_K = 30 K) and T_R (2 mm) in the range from 2.1 to 3.2 K, spherical large-velocity gradient models show the 2 cm line is still weakly in absorption even at densities of $n = 10^6$ cm^{-3} (Snell 1979). The 2 cm line occurs more strongly in absorption at lower densities. A lower T_K does not substantially alter this situation—the core density must still be at least 10^6 cm^{-3} to drive the 2 cm line into emission.

The size of the 2 cm emission region in Figure 2 is $\sim 3' \times 4'$ or 0.13×0.17 pc at 150 pc. If the line-of-sight dimension is similar, the density of 10^6 cm^{-3} implies a column density of 4–5.3 $\times 10^{23}$ cm^{-2} or an $A_v \sim 160$–210 mag if $N = 2.5 \times 10^{21} A_v$. The core density and size indicate a core mass of 100 $M_\odot$, far in excess of the masses found in other cold cloud cores (Snell 1979) but similar to those found in warmer star formation regions. The cold temperatures and high mass concentration suggest that ρ Oph B represents a cloud at an earlier stage of star formation than either OMC-1 or OMC-2.

If self-absorption of the 2 mm H_2CO line occurs toward cold clouds like ρ Oph B or L134N (Snell 1979; Langer *et al.* 1979) one should examine whether high 2 mm H_2CO optical depth affects the determination of density toward warm clouds like OMC-1 or OMC-2. With an analysis similar to that used above the para-H_2CO intensity toward OMC-1 (Scholtes, unpublished data) can be used to estimate T_R (2 mm)

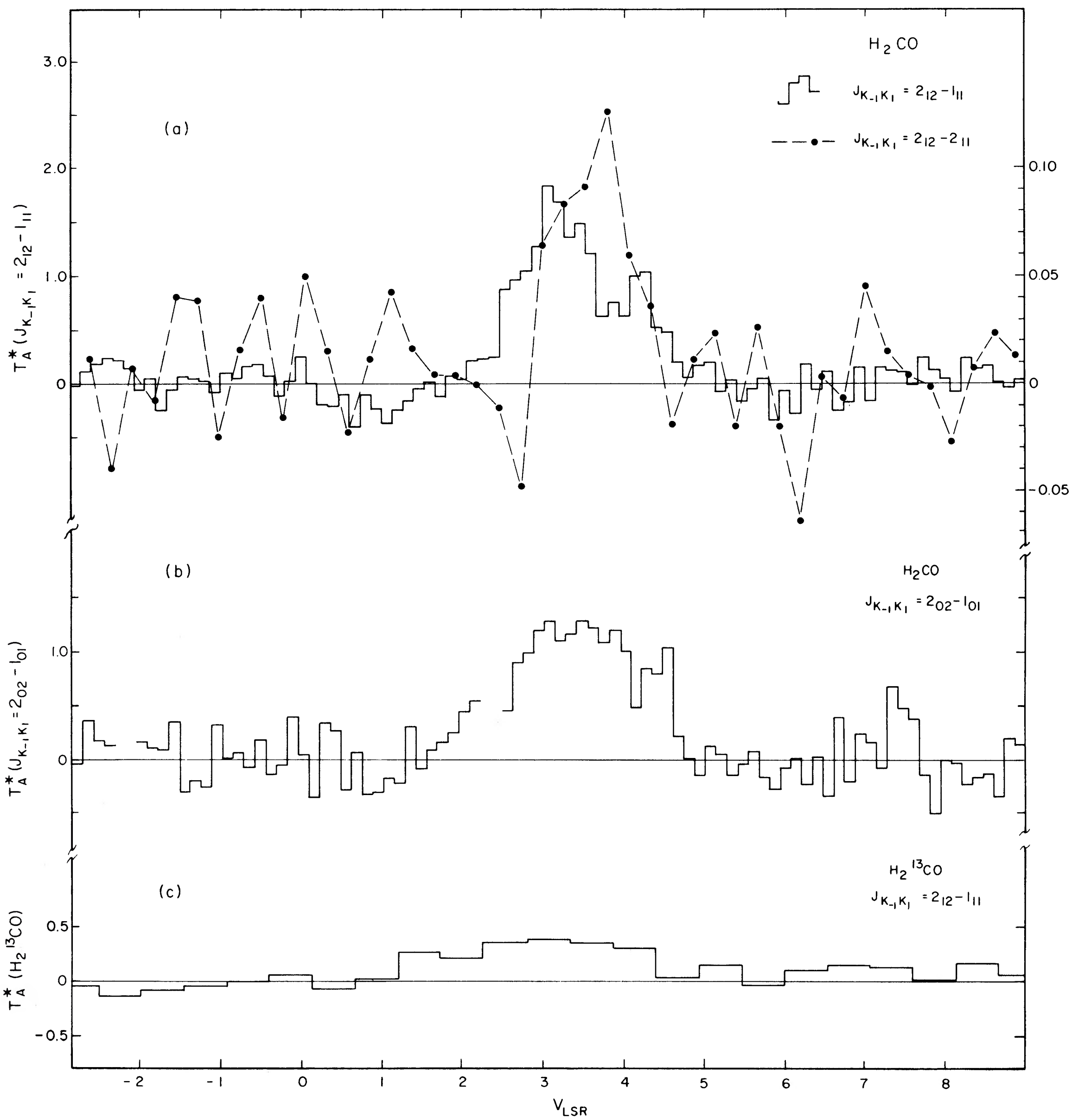

FIG. 1.—H_2CO line profiles toward $\alpha(1950) = 16^h24^m09^s$ and $\delta(1950) = -24°21'49''$. (*a*) The dashed-dot curve is the 2 cm ($J_{K_{-1}K_1} = 2_{12}$–2_{11}) line usually seen in absorption. The histogram is the 2 mm ortho-H_2CO line ($J_{K_{-1}K_1} = 2_{12}$–1_{11}). (*b*) The para-H_2CO line ($J_{K_{-1}K_1} = 2_{02}$–1_{01}). (*c*) The ortho-$H_2{}^{13}CO$ 2 mm line ($J_{K_{-1}K_1} = 2_{12}$–1_{11}).

in the optically thin limit. We find that T_R (2 mm) could be at most a factor of 2 larger than observed. As a result the T_R (2 mm) used to estimate the OMC-1 density may be underestimated. Even a small uncertainty in T_R (2 mm) for OMC-1 results in large errors in the density determination since lines of constant T_A (2 cm)/η and T_R (2 mm) are virtually parallel in the log $X(H_2CO)$ versus log n plane when the 2 cm line goes into emission. It is possible that these high optical depth effects, rather than pronounced clumping, may account for the weakness of the 2 mm H_2CO line in OMC-1 relative to that expected from the intensities of other H_2CO transitions (Evans, Plambeck, and Davis 1979).

IV. CONCLUSIONS

Observations of a 2 cm H_2CO emission line in the ρ Oph cloud have revealed a very dense cold core not associated with known signposts of star formation. The density of this region is $n \gtrsim 10^6$ cm^{-3}, and it has $A_v \approx 200$ mag and a total mass of 100 $M_\odot$ within a radius of 0.08 pc. The temperature of the region is low, probably $T_K \lesssim 20$ K. Higher temperatures deduced from the CO line probably originate in a less dense, warmer region on the far side of the cloud. The high core mass and the velocity structure in the CO line suggest that this region is a propitious site for future star formation, while its low temperature suggests a current lack of high-luminosity internal heating sources. Sensitive infrared, radio continuum and H_2O maser searches should reveal more fully the characteristics of this unusual massive cold cloud core and the extent of star formation within it.

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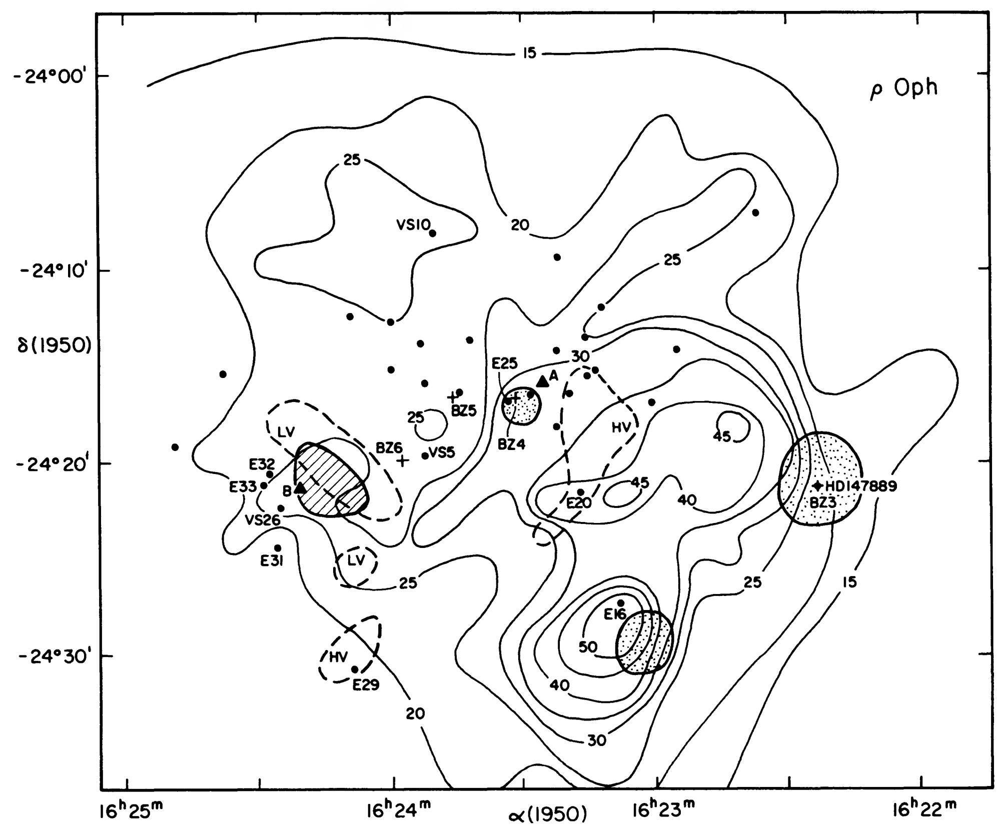

FIG. 2.—The solid contours correspond to peak T_A*(CO). Strong 2 cm H_2CO emission is indicated by the cross-hatching. Peak SO emission (Gottlieb *et al.* 1978) positions (*filled triangles*) are labeled A and B. Regions of enhanced CO line-wing emission are shown by the dashed contours (LV and HV to indicate which CO wing is more enhanced). Solid circles are infrared sources associated with the cloud, E denotes Elias (1978), and VS denotes Vrba *et al.* (1975). The crosses and BZ numbers are radio continuum sources (Brown and Zuckerman 1975). The stipled regions correspond to far-infrared emission (Fazio *et al.* 1976) and Harvey, Campbell, and Hoffman (1979). Extended near-infrared emission nebulae occur at E21, E29, and E32 (Elias 1978). Strong 3 μm ice absorption is seen toward E32, E33, and VS26 (Harris, Woolf, and Rieke 1978).

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