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VLA OBSERVATIONS OF FORMALDEHYDE EMISSION FROM RHO OPHIUCHI B

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ABSTRACT

The $2_{11}–2_{12}$ H_2CO *K*-doublet emission source in the ρ Ophiuchi B cloud core has been observed with an angular resolution of 10″. The core contains 1–4 $M_\odot$ of dense $[n(H_2) \approx 4–5 \times 10^6\ cm^{-3}]$ molecular gas within a region 0.05 × 0.02 pc in spatial extent. Maps with spectral resolution of 0.25 km s^{-1} exhibit structure on size scales approximately the same as the Jeans length, ~ 0.01 pc. Systematic variations in the positions of the peak line intensities with velocity suggest that the core may be comprised of at least two small rotating fragments. These fragments contain masses typical of low-mass stars and have densities and linear sizes expected of protostars.

Subject headings: interstellar: molecules — radio sources: lines — stars: formation

I. INTRODUCTION

The ρ Ophiuchi dark cloud has been proposed as the site of an embedded rich open cluster still in the process of formation (Wilking and Lada 1983). The proximity of this cloud (160 pc: Bertiau 1958; Whittet 1974) and its overall evolutionary state make it an excellent object in which to study the details of low-mass star formation.

One region of particular interest is the dense core ρ Oph B, where Loren *et al.* (1980) discovered emission from the $2_{11}–2_{12}$ line of H_2CO. This *K*-doublet transition at 2 cm is usually seen in absorption, even against the microwave background, and is seen in emission in only four sources. Excitation calculations (Garrison *et al.* 1975) demonstrate that H_2 densities of ~ 10^6 cm^{-3} or greater are required to drive this line into emission. A cloud of this density would have a free-fall collapse time of $\lesssim 4 \times 10^4$ yr, making it a likely site for the formation of new stars. Martín-Pintado *et al.* (1983, hereafter MWGH) mapped the 2 cm H_2CO emission in ρ Oph B with 1′ resolution and found that the emission peaks along a ridge 0.15 × 0.03 pc in linear size. The linear extent and inferred mass of this dense core exceed the Jeans length and Jeans mass, suggesting the possibility of additional structure on smaller spatial scales. In order to study the physical and dynamical state of this region and its relationship to the star formation process, we have made high spatial resolution (10″) aperture synthesis observations in the 2 cm H_2CO transition.

II. OBSERVATIONS

Observations of the $2_{11}–2_{12}$ *K*-doublet transition of H_2CO at 14488.479 MHz were made on 1984 July 3 using the NRAO[4] Very Large Array in the C/D hybrid (long north arm) configuration. Twenty-three antennas were used with spacings between 45 and 1,755 m from the array center. A total observing bandwidth of 781 kHz was divided into 32 spectral line channels. On-line Hanning smoothing was used, yielding a frequency resolution and channel spacing of 12.2 kHz, or 0.253 km s^{-1}. The nominal observing frequency was readjusted hourly to maintain a center channel LSR velocity of 3.60 km s^{-1} ± 0.05 km s^{-1}. The flux density scale was established by observing 3C 286 (assumed flux density 3.53 Jy). During the 8 hr observing session, ρ Oph B was observed at an antenna pointing and phase center position of $\alpha(1950) = 16^h24^m10^s$, $\delta(1950) = -24°22'42''$ for 10 minute periods and alternated with 5 minute observations of NRAO 530. The weather varied from broken clouds at the beginning of the session to clear weather during the last 5 hr. The derived flux density of NRAO 530 was 5.86 Jy.

The data were calibrated in the normal manner using NRAO 530 to determine the antenna gains and phases. Maps of each spectral channel were made using a cell size of 2″, with natural weighting and a Gaussian taper of 15 kλ applied to the *u-v* plane data. The raw maps of the on-line channels contained an underlying ripple pattern which could not be removed by any of the CLEANing techniques we applied. Because the ripple is not present in the off-line maps, we do not believe it is due to any instrumental effect. We attribute the ripple to flux from an extended region which is resolved out on all but the shortest spacings. In order to produce reliable maps of the small-scale structure of the source, we have removed the ripple by applying a minimum *u-v* spacing cutoff of 2kλ to the data. The resulting synthesized beam size was 12″.8 × 10″.0, p.a. 7°. No correction was made for primary beam taper (3′.5 HPBW) across the field of view. Channels 4–8 and 24–28 were averaged to form a continuum map. No continuum sources were found in the field to a limit of 5 mJy. The typical RMS noise in a single channel CLEANed map was 9.5 mJy per CLEAN beam area, corresponding to a main beam brightness temperature of 0.44 K.

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III. RESULTS

Figure 1 shows the VLA line emission profile integrated over the central 64″ × 64″ area compared to the single-dish profile (1′ HPBW) obtained by MWGH at the same observing position. While the VLA radial velocities and line widths are in good agreement with MWGH, we recover only ~ 50% of the single-dish flux density in our VLA maps. Since the VLA maps contain no *u-v* coverage at spacings less than 2 kλ, this suggests that a significant portion of the single-dish flux density comes from a region whose brightness temperature is uniform on angular scales greater than 100″. In fact, unpublished data which we have obtained with the NRAO 43 m telescope at Green Bank suggest that the entire 8′ × 4′ emission region reported by Loren, Sandqvist, and Wootten (1983) may consist of two components—a low brightness temperature extended component and higher brightness temperature clumps such as we describe below. MWGH mapped a part of the overall emission region to identify and delineate the more compact structure. Thus their map does not contain information on the extended low-level emission which we believe is present.

We show in Figure 2*a* the spatial distribution of the H_2CO emission averaged over the velocity range 3.6–4.4 km s^{-1} (four channels). Because the maps are noise-limited, we have displayed contour intervals which are −3, 3, 4, 5, 6 times the RMS noise. The bulk of the emission is extended along a position angle of 161°, with a deconvolved size of ~ 63″ × 21″. In Figure 2*b* we compare the spectrally averaged VLA map to the single-dish map of MWGH. This comparison shows that the high brightness temperature emission region which we see with the VLA lies primarily in the northern extension of the MWGH map. We do detect in our VLA maps evidence for additional low-level emission coincident with the southeastern extension of the MWGH map. However, because the signal is only about twice the RMS noise, the position and extent of this emission is very poorly determined, and we do not include it on our final map. In Figure 2*c* we present a composite map constructed of representative contours from each of the single-channel maps whose spatially integrated flux density is greater than one-half the peak value. In this composite overlay, one can see a systematic variation in the spatial location of the emission peaks with velocity. The source appears to consist of at least two distinct components, each of which has a systematic velocity gradient, with velocity increasing from southeast to northwest. The two strongest components have been designated NW and SE for reference in the following discussion.

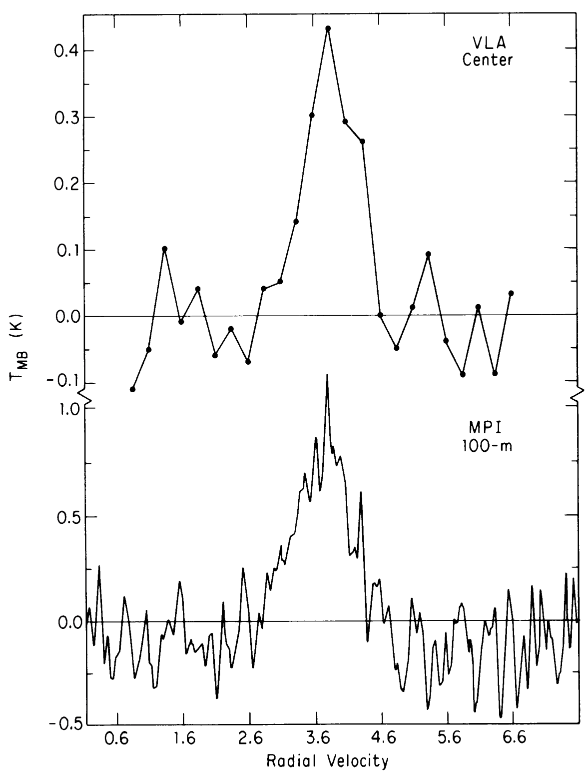

FIG. 1.—A comparison of the H_2CO 2_{11}–2_{12} emission spectra at the observing position $\alpha(1950) = 16^h24^m10^s$, $\delta(1950) = -24°22'42''$ obtained with the VLA (*above*) and the 100 m telescope of the MPI by MWGH (*below*). Temperatures are in units of main beam brightness temperature. At the line frequency of 14.48848 GHz, the angular resolution of the 100 m telescope is 60″ FWHP, while the VLA profile has been averaged over an area of 64″ × 64″. Radial velocities are given with respect to LSR.

IV. DISCUSSION

At the distance to the ρ Ophiuchi cloud of 160 pc (Bertiau 1958; Whittet 1974) the overall emission region detected with the VLA has a linear size of ~ 0.05 × 0.02 pc. If the line-of-sight distance through the source is comparable to these dimensions, the virial mass appropriate to the observed 1 km s^{-1} line width is 4 $M_\odot$ and the mean H_2 density is 5×10^6 cm^{-3}. The column density of molecular hydrogen is then 5×10^{23} cm^{-2}. For a gas-to-extinction ratio appropriate for the ρ Ophiuchi cloud (Whittet 1981), the visual extinction to the cloud center is ~ 250 mag. Assuming the 2_{11}–2_{12} emission is optically thin and that the millimeter rotational transitions are thermalized we obtain an ortho-H_2CO column density of 1.4×10^{14} cm^{-2} and an (ortho-H_2CO/H_2) ratio of 3×10^{-10}. The virial estimates could be in error by a large factor if the line-of-sight extent of the cloud is much larger or much smaller than we have assumed. However, the observed velocity structure, which we discuss below, makes this unlikely, so that the virial estimates should be accurate to a factor of 2–3.

We have applied a Large Velocity Gradient (LVG) approximation to a homogeneous spherical cloud model to calculate the photon trapping in the $\Delta J = 1$ mm rotational lines. In our model we take the kinetic temperature to be 18 K (Zeng, Batrla, and Wilson 1984) and assume a velocity gradient of 20 km s^{-1} pc^{-1}, consistent with the observed spatial extent and line width. The collisional transition rates are those of Green *et al.* (1978). While the single line transition which we measure cannot uniquely constrain the model input parameters, we do reproduce the observed line intensity for an assumed H_2 density of 5×10^6 cm^{-3} and an (ortho-H_2CO/H_2) ratio of 3×10^{-10}. Although the LVG assumption is clearly inconsistent with the observed velocity structure

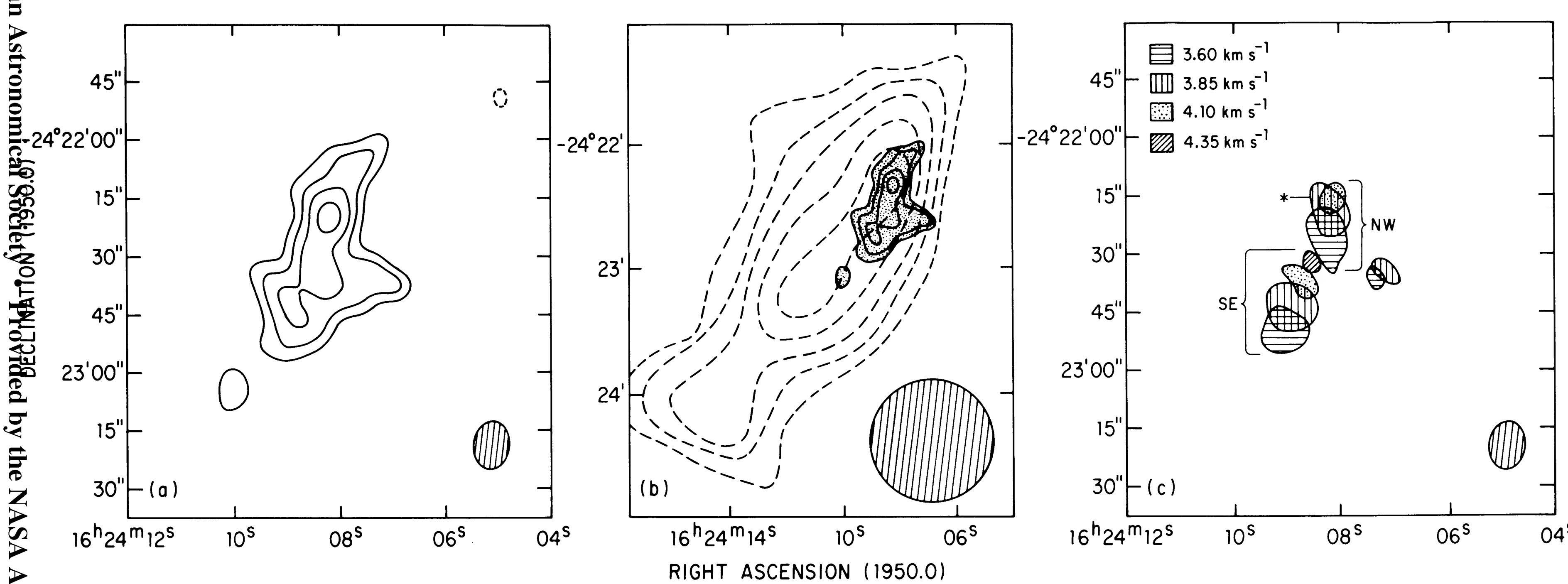

FIG. 2.—(*a*) The spatial distribution of H_2CO emission averaged over the velocity range 3.6–4.4 km s^{-1} LSR (four channels). Contour intervals are −0.8, 0.8, 1.1, 1.3, 1.6 K main beam brightness temperature, corresponding to flux densities of −17.1, 17.1, 22.8, 28.5, and 34.2 mJy per beam. (*b*) A comparison of the averaged VLA map from Fig. 2*a* (*solid contours*) with the single-dish map of MWGH (*dashed contours*). The MWGH map shows the main beam brightness temperature integrated over the line profile, with contour intervals of 0.24, 0.36, 0.48, 0.60, and 0.72 K km s^{-1}. The 60" MPI beam size is shown. (*c*) A composite overlay of representative contours taken from the individual channel maps. Contours are T_{MB} = 1.8 K, with the exception of the contour marked with the *, which is T_{MB} = 2.2 K. Contours are labeled with their respective LSR velocities. The contour positions show a systematic variation with Doppler velocity. The center-to-center channel spacing and the velocity resolution are 0.253 km s^{-1}. The contours have been grouped as components NW and SE for the discussion in the text.

TABLE 1

TWO-COMPONENT ROTATIONAL MODEL

Parameter	SE	NW
R.A.(1950)	$16^h24^m08^s.9$	$16^h24^m08^s.2$
Decl.(1950)	$-24°22'41''$	$-24°22'18''$
Angular size	$29'' \times 18''$; pa 157°	$22'' \times 12''$; pa 174°
Linear size (pc)	0.023×0.014	0.017×0.009
v(rotational) (km s^{-1})	0.5/(sin i)	0.4/(sin i)
M(min)[a] ($M_{\odot}$)	0.7	0.3
$n(H_2)$ (min)[a]	3.2×10^6 cm^{-3}	3.9×10^6 cm^{-3}

[a] Minimum values are obtained on the assumption that the clouds are gravitationally bound and seen edge-on.

of the cloud, we expect that the uncertainties in the density and abundance estimates obtained with the LVG model will be of the same order or less than the uncertainties in our virial estimates (see, e.g., White 1977).

It is natural to interpret the velocity structure in the two components seen in Figure 2c as rotational motion. The observed velocity shifts across each of the two components correspond to velocity gradients of ~ 40 km s^{-1} pc^{-1}. These velocity gradients are at least an order of magnitude greater than any large-scale velocity gradients in this part of the ρ Oph cloud, as inferred from arc minute–resolution, single-dish observations in several molecular species. Thus it appears that these components may have spun up by conserving much of their original angular momentum during collapse. Lower mass limits for these components may be determined on the assumption that they are rotating, gravitationally bound spheroids seen edge-on. These masses are $M(\mathrm{SE}) \gtrsim 0.7\ M_{\odot}$ and $M(\mathrm{NW}) \gtrsim 0.3\ M_{\odot}$, implying minimum mean H_2 densities of 3.2×10^6 cm^{-3} and 3.9×10^6 cm^{-3}, respectively. Table 1 summarizes the observed and derived parameters of the two components for this model.

It is possible that the core may contain one or more undetected IR sources. In a completely sampled survey at 2 μm, Wilking and Lada (1983) detect no sources within the VLA emission region brighter than K = +12.0. However, given the high visual extinction which we obtain, the extinction towards the source center at 2 μm is 10–25 mag. While the absence of radio continuum emission (Falgarone and Gilmore 1981) would rule out the presence of massive ZAMS stars, the presence of one or more deeply embedded low-mass prestellar objects could explain the apparent modest temperature enhancement of this region above the typical cold cloud core temperature of $T_K \approx 10$ K.

There may be substantially more mass in the ρ Oph B core than that found in the two clumps. If the difference between the single-dish and VLA flux densities is due to a uniform brightness temperature region resolved out at the VLA spacings, its angular size must be $\gtrsim 100''$, corresponding to a linear size of $\gtrsim 0.08$ pc. Because the line is seen in emission, the density in this halo must be $\gtrsim 10^6$ cm^{-3}. A uniform spherical halo of this density and extent would contain at least 14 $M_{\odot}$ of gas. The single-dish intensity which is absent in the VLA maps corresponds to a line peak surface brightness of 0.5 K per beam area, or roughly one RMS. Therefore, some low-level structure below our detection limit could be present in the extended emission region.

V. CONCLUSIONS

Our VLA observations of ρ Oph B reveal a very dense core in a region devoid of any obvious evidence for recent star formation. This core exhibits a clumpy structure down to linear size scales equivalent to a Jeans length, indicating that fragmentation is occurring. The velocity structure of the two major components is suggestive of rotational motion with a velocity gradient much larger than that of the parent cloud, implying that much of the initial angular momentum has been conserved during collapse. The reasonable agreement between virial, rotational, and H_2CO excitation analyses indicate that the core region contains 1–4 $M_{\odot}$ of dense (4–5 $\times 10^6$ cm^{-3}) gas. Our derived parameters for the two major core components bear a striking resemblance to those used as the starting point in many stellar collapse calculations (see, e.g., Larson 1972). This similarity leads us to identify these components as low-mass protostars.

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