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PROTOSTELLAR CONDENSATIONS WITHIN THE ORION RIDGE

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ABSTRACT

Aperture synthesis observations of the CS $J = 2 \rightarrow 1$ line and 95 GHz continuum emission from a $2' \times 3'$ region around IRC2 in the OMC-1 molecular cloud have been obtained at $7''.5$ resolution with the OVRO millimeter interferometer. These observations reveal four distinct condensations within the OMC-1 molecular ridge. The condensations lie along the edge of the bright central part of the H II region, M42, suggesting that they may have been formed as a result of shock compression driven by the H II region. Their masses and densities, $M \approx 50 M_{\odot}$ and $n \approx 10^6$ – 10^7 cm^{-3} , suggest that the condensations will undergo further massive star formation on a short time scale ($\sim 2 \times 10^4 \text{ yr}$).

Subject headings: interstellar: molecules — nebulae: Orion Nebula — stars: formation

I. INTRODUCTION

At the core of the Orion molecular cloud, OMC-1, there exists a great diversity of phenomena: two luminous infrared sources, BN and IRC2, both of which probably formed in the last 10^4 yr ; an extensive network of shock fronts where stellar winds from one or both of these stars impinge on the ambient cloud; an active H II–H₂ interface region; and neutral condensations without internal heat sources, probably on the verge of collapse (cf. Glassgold, Huggins, and Schucking 1982). Since all these phenomena occur within the inner $1'$ of OMC-1, their relationship and interactions have remained vague due to the inadequate angular resolution of molecular line observations. Recently, interferometric studies of OMC-1 have been done in the millimeter emission lines of SO, SiO, CO, HCO⁺, and HCN (Plambeck *et al.* 1982; Wright *et al.* 1983; Masson *et al.* 1984; Vogel *et al.* 1984; Vogel *et al.* 1985) and in the 2.6–3 mm continuum (Masson *et al.* 1985; Wright and Vogel 1985). These observations particularly emphasized the high-velocity outflow gas and the structure close to IRC2 due to the chemical selectivity of the chosen molecules and the limited field of view. The CO interferometry was mostly confined to study of the high-velocity outflow because of the high CO opacity in the ambient cloud at the center of mass velocity.

In this *Letter*, we report high-resolution interferometer observations of the CS $J = 2 \rightarrow 1$ line and 95 GHz continuum emission from the central $2' \times 3'$ ($\Delta\alpha, \Delta\delta$) region of OMC-1. The present observations were specifically designed to probe the densest gas in the cloud core independent of shock processing. The CS molecule is chemically robust yet requires densities greater than 10^4 cm^{-3} to excite appreciable emission in the $J = 2 \rightarrow 1$ transition. The 95 GHz continuum emission has two origins: free-free emission and thermal emission from dust grains. The former process dominates in the area of the strong ionization fronts of M42, the latter in the densest neutral condensations of molecular gas. The dust emission

provides a reliable picture of the column density enhancements in the neutral cloud since the continuum emission at 95 GHz is optically thin and only linearly dependent on the dust temperature.

II. OBSERVATIONS

The CS $J = 2 \rightarrow 1$ transition (97.981 GHz) and the continuum flux at 95.3 and 98.0 GHz were observed toward 10 fields surrounding IRC2 using Owens Valley Radio Observatory (OVRO) Millimeter-Wave Interferometer. The line data were obtained with 32 1 MHz (3.06 km s^{-1}) channels; the continuum channel bandwidth was 250 MHz. The fields were arranged in a hexagonal pattern with a spacing of $42''$ between beam centers. Since the primary beam width (FWHM) of the OVRO 10.4 m dishes is $80''$ at 98.0 GHz, the individual fields of view overlap, allowing verification of individual features from field to field. The area covered by the 10 fields is outlined by the heavy dashed line in Figure 1*a* (Plate L3).

The data were obtained from 1985 January to April in six configurations of the three-element interferometer with physical baselines ranging from 20 to 60 m east-west and from 10 to 80 m north-south. The resulting synthesized beam width was approximately $7''.5$ (FWHM). The observations of the individual fields were interleaved to assure the best possible registration from field to field. The absolute flux scale was established from observations of W3(OH) (4.0 Jy) obtained during each track. The estimated error in the absolute flux scale is 20%; the absolute positional accuracy is estimated to be $\pm 1''$.

The interferometer data were processed using the NRAO AIPS package. All data were transformed to a common phase center and CLEANed maps of each field were made independently. The maps of the individual fields were then corrected for the primary beam response and summed pixel-by-pixel with each pixel in each field weighted proportional to the square of the primary beam response. The individual field

FIG. 1a

FIG. 1b

FIG. 1.—The image in Figs. 1a and 1b is a VLA 2 cm map of the M42 H II region obtained with the D array at VLA in 1985 December (MEM reconstructed with a $2''.5 \times 2''.1$ beam). The contours in Fig. 1a are the composite map of the 95 GHz continuum emission. The contour levels are ± 0.05 , ± 0.10 , ± 0.15 , ± 0.2 , ± 0.3 , ± 0.4 , ± 0.5 , ± 0.7 , and ± 0.9 Jy per beam. The broad dashed border encloses the region covered by the OVRO interferometer observations. The plus sign marks the position of IRc2. The contours in Fig. 1b show the integrated CS line flux. The contour levels are 5, 10, 20, 30, 50, 75, 100, 125, and 150 Jy per beam km s^{-1} .

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maps were cut off at 30% of the primary beam response, and only pixels with an accumulated primary beam response of $\geq 45\%$ were kept in the final map.

III. 95 GIGAHERTZ CONTINUUM EMISSION

The composite 95 GHz continuum map is shown superposed on a 2 cm VLA map of the H II region (M42) in Figure 1a. The apparent noise level in the composite map is dependent on position due to the primary beam corrections, the overlapping of fields, and small scale structure in the foreground H II region. In order to identify the H II region contributions to our 95 GHz map, we have produced a 2 cm map with the same UV coverage as the 95 GHz map. The features on the eastern half of the 95 GHz map and the feature 50'' south of IRC2 are found to correspond with H II region emission features. The origin of the emission in the three remaining continuum peaks is most probably warm dust since none of the peaks are coincident with compact 15 GHz sources stronger than 3 mJy (Moran *et al.* 1982; J. M. Moran, private communication) and molecular line emission can be ruled out as no strong molecular lines lie within the 250 MHz continuum band (cf. Masson *et al.* 1985; Wright and Vogel 1985).

The three major dust emission features in Figure 1a have been designated continuum source (CS) 1, 2, and 3; the position, size, peak flux density, and total flux for each are given in Table 1. CS1, located approximately 30'' northeast of IRC2, appears in the 400 μ m map by Keene, Hildebrand, and Whitcomb (1982, hereafter KHW) and the 1 mm continuum map by Schloerb, Snell, and Schwartz (1984) as a northeastern extension of the low level contours around IRC2. The 3 mm continuum map of Wright and Vogel (1985) also has a low-level feature at this position. The source centroid of CS2 is located approximately 2'' southwest of IRC2, roughly coincident with the NH₃ hot core detected by Pauls *et al.* (1983). CS3 is in the area of the southern peak in the 400 μ m map (KHW) and the NH₃ clump identified as S6 by Batrla *et al.* (1983).

Due to the uncertainty in the dust emissivity law, it is difficult to estimate the fraction of the total flux recovered by the interferometer observations. Based on the Schloerb, Snell, and Schwartz (1984) measurements at 1.3 mm, we estimate that 20%–50% of the dust emission is recovered. Since the H II region is the dominant source of emission at 3 mm, single-dish observations can not easily resolve this uncertainty in total flux from dust.

IV. CS LINE EMISSION

The CS line emission in the 1 MHz channels centered at 13.7, 10.6, 7.5, and 4.4 km s⁻¹ is shown in Figures 2a–2d, respectively, and the integrated line emission (2.9–15.2 km s⁻¹) is shown superposed on the 2 cm map in Figure 1b. Channels further from the 9.0 km s⁻¹ cloud velocity exhibit emission only in the region of CS2 (IRC2) which will be discussed in detail elsewhere (Scoville *et al.* 1986). The average noise level in the channel maps is ~ 0.4 Jy per beam so features with two or more contours represent $> 5 \sigma$ detections. The line maps show four major features which roughly lie along the projected edge of the H II region. Three of the emission regions are associated with dust emission peaks; the fourth region, designated as line source (LS) 1, is located 45'' south of CS2. For comparison, a single-dish map of the CS $J = 2 \rightarrow 1$ line with 1/3 resolution is shown in Figure 3a. Most of the single-dish flux is contained in a north-south ridge which is approximately $8' \times 2'$. The interferometer observations resolve out spatial scales $> 40''$ in this ridge leaving only the small-scale regions of enhanced and depressed emission. The negative features in the interferometer map are areas with less emission than the average within the field of view. The amount of line flux in the interferometer maps range from 10% to 20% of the single-dish flux.

The major features in the CS channel maps constitute large increases in brightness temperature (T_b) over the mean value in the field. For our synthesized beam, 1 Jy per beam corresponds to 2.6 K of brightness temperature. The brightest CS

TABLE 1
SOURCE PARAMETERS

Quantity	CS1	CS2	CS3	LS1
Right ascension (1950) ^a	05 ^h 32 ^m 47 ^s .78	05 ^h 32 ^m 46 ^s .90	05 ^h 32 ^m 46 ^s .13	05 ^h 32 ^m 46 ^s .2
Declination (1950)	−5°24'00".2	−5°24'25".8	−5°26'01".7	−5°25'21".
Peak continuum flux (Jy per beam)	0.36	0.95	0.30	...
Total continuum flux (Jy)	0.6	2.3	0.6	...
Continuum source size (arcsec)	9 × 7	12.5 × 7	10 × 4	...
Peak T_b in CS $J = 2-1$ (K)	22	57	16	22
CS source size (arcsec)	16 × 7	12 × 8	30 × 16	24 × 14
Assumed dust temperature (K)	70	100	60	70
Peak $N(\text{H}_2)$ from continuum flux ^b (cm ⁻²)	1 × 10 ²⁴	2 × 10 ²⁴	1 × 10 ²⁴	...
Mass from continuum flux ^b ($M_\odot$)	45	125	54	...
Minimum $N(\text{CS})$ at peak (cm ⁻²)	1 × 10 ¹⁵	2 × 10 ¹⁶	6 × 10 ¹⁴	1 × 10 ¹⁵
Minimum mass from CS ^c ($M_\odot$)	6	80	12	12
Maximum virial mass ($M_\odot$)	35	...	135	54
Density range (cm ⁻³)	2–13 × 10 ⁶	3–6 × 10 ⁷	0.5–5 × 10 ⁶	0.8–4 × 10 ⁶
Jeans mass ($M_\odot$)	1.5–4	1–1.5	2–5	2.5–6

^a Continuum source position except for LS1.

^b Assumes λ^{-2} dust opacity law.

^c Assumes CS fractional abundance of 2.5×10^{-9} .

FIG. 2.—Figs. 2a–2d show the CS line emission in four of the OVRO interferometer 1 MHz (3.06 km s^{-1}) channels. The contour levels are ± 1 , ± 2 , ± 4 , 6, 10, 15, and 20 Jy per beam. One Jy per beam corresponds to 2.6 K. The plus sign marks the position of IRC2; the stars show the position of the Trapezium.

emission, associated with CS2, has $T_b \approx 57 \text{ K}$ while the other bright emission regions have $T_b = 15\text{--}20 \text{ K}$. These temperatures are actually minimum values for the true brightness temperatures of the regions because the smooth component of the emission has been resolved out and because part of the compact source emission may be absorbed by overlying gas. For comparison, single-dish measurements with $1/3$ resolution give an average brightness temperature of $\sim 15 \text{ K}$ along the ridge. Thus, the interferometer observations are revealing clumps which have a factor of 2–5 times more emission than average.

V. DISCUSSION

The OVRO interferometer observations provide significant constraints on the small-scale structure in OMC-1. Approximately 80% of the single-dish CS line flux from areas other than CS2 is resolved out in the interferometer line maps; this emission must be smoothly distributed across the sky on size scales less than $\sim 30''$. If clumps are responsible for the majority of the CS emission seen in the single-dish map, they must be numerous enough to produce an apparently smooth emission distribution. (An important caveat to this statement

is that the velocity resolution of our observations could be smearing out structure if the intrinsic line widths in clumps are $\ll 3 \text{ km s}^{-1}$.) The line flux detected by the interferometer mainly arises from a few discrete clumps which are $7''\text{--}20''$ in size. Since these clumps are generally also seen in dust continuum, they are most likely regions of increased gas density and column density.

The physical parameters for the condensations can be estimated in several ways. The mass in the continuum sources can be estimated from the flux by adopting dust temperatures from Werner (1982) and an optical depth to H_2 column density conversion factor based on the empirical calibration for $400 \mu\text{m}$ by KHW and a λ^{-2} dust emissivity law (Hildebrand 1983). The dust temperatures and derived masses for the three sources are given in Table 1. A $\lambda^{-1.3}$ emissivity law would result in masses a factor of 4 lower. An independent lower limit to the H_2 mass is obtained from the CS line emission using an assumed CS fractional abundance of 2.5×10^{-9} (Blake 1985) and an escape probability radiative transfer code to estimate the minimum CS column density, $N(\text{CS})$, consistent with the observed T_b at densities of $10^6\text{--}10^8 \text{ cm}^{-3}$. Lastly, an upper limit on the mass was derived for each

FIG. 3.—A single-dish map of the CS $J = 2 \rightarrow 1$ emission is shown in Fig. 3a. The data were obtained with an OVRO 10.4 m dish (FWHM = $1'3''$) with $1'$ spacing. The contours are main beam brightness temperature in steps of 2 K from 3 K to 15 K. The CS line emission, integrated from 3.9 to 12.1 km s^{-1} , is shown in Fig. 3b and compared with other observations in Figs. 3c and 3d. The contour levels for the CS emission are 5, 10, 20, 30, 50, 75, 100, 125, and 150 Jy km s^{-1} . The triangles in Fig. 3b mark the positions of the continuum sources. The thick contours in Figs 3c and 3d are the $400 \mu\text{m}$ emission (KHW) with contours at 10%, 20%, 40%, 60%, and 80% of the peak and the integrated NH_3 (1,1) brightness temperature (Batra *et al.* 1983) with contour levels of 5, 7, 9, 15, 25, 35, and 45 K km s^{-1} , respectively.

condensation assuming virial equilibrium with the observed line widths (FWHM), $\leq 6 \text{ km s}^{-1}$ in CS1 and LS1 and $\leq 9 \text{ km s}^{-1}$ for CS3, and the maximum size of the CS emission region. (The virial mass for CS2 was not calculated due to the outflow associated with IRc2.) The corresponding range in H_2 densities and Jeans masses are also given in Table 1.

A quantitative comparison of the present results with those of other studies in the region is complicated by the uncertainty in the dust emissivity law, the unmeasured short UV spacing flux, and the low spatial resolution of previous observations. Figure 3c shows a comparison of the integrated line emission map with the $400 \mu\text{m}$ map by KHW ($35''$ resolution). The $400 \mu\text{m}$ emission shows a north-south ridge, which is too wide to be detected in the present observations, and two peaks around the CS1–CS2 and CS3 positions. The authors estimate a mass of $50 M_\odot$ for the northern peak (roughly around IRc2), $60 M_\odot$ for the southern peak, and $250 M_\odot$ for the ridge structure. Figure 3d shows a NH_3 (1,1) map of the IRc2 region with $43''$ resolution (Batra *et al.* 1983). The NH_3 map has two distinct peaks which can be identified with CS1–CS2 and CS3. Batra

et al. (1983) estimate a mass of $50\text{--}100 M_\odot$ for the northern peak and $\sim 70 M_\odot$ for the southern peak. The VLA maps of NH_3 (Pauls *et al.* 1983) and 6 cm H_2CO (Johnston *et al.* 1983) show emission only from the CS2 condensation; the absorption in the 6 cm map occurs $\sim 10''$ west of CS3. Thus, qualitatively, our results are consistent with previous results. The condensation masses given in Table 1 are on the high end of previous estimates especially if a significant fraction of the continuum flux is being resolved out.

The four condensations isolated in the present observations clearly represent an advanced stage of concentration in the molecular gas within the OMC-1 molecular ridge. They are well in excess of their Jeans mass and, in a quiescent environment, would be expected to form stars with a free-fall collapse time of only $2 \times 10^4 \text{ yr}$ (for $n_{\text{H}_2} = 5 \times 10^6 \text{ cm}^{-3}$). CS1 is a newly identified condensation which has no known embedded IR sources or H II regions. The southernmost source, CS3, shows some of the signposts of massive star formation activity such as broad ($4\text{--}8 \text{ km s}^{-1}$) CS and NH_3 lines and thermal SiO emission (Ziurys, Friberg, and Irvine 1985) but, as yet,

there is no detectable compact H II region in the immediate area. The alignment of the condensations along the edge of the H II region suggests that the condensations, and perhaps the entire molecular ridge, are a result of compression by the high-pressure H II region.

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