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H_2CO MAPS OF HIGH-DENSITY MOLECULAR FRAGMENTS 3′ NORTH OF ORION-KL

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ABSTRACT

VLA maps of OMC-N, the molecular region 3′ north of Orion-KL in the 2 cm *K*-doublet line of formaldehyde, resolve this region into six high-density fragments having radial velocities ranging from 9 to 10 km s^{-1} and FWHP of 0.4 to 5 km s^{-1}. Virial estimates give H_2 densities ranging from 8×10^5 cm^{-3} to 3×10^7 cm^{-3} and masses from 1 $M_\odot$ to 150 $M_\odot$. There is good agreement between the positions of two of these fragments and the clumps detected in the $(J, K) = (2, 2)$ line of ammonia, but there is no hint of the rotation reported. On scales of 2′, four of the regions fall along a line with the same position angle found from lower resolution maps of ammonia and CO; on scales of ~20″ this alignment breaks down. The origin and evolution of these fragments is discussed.

Subject headings: interstellar: abundances — interstellar: molecules

I. INTRODUCTION

The molecular region 3′ north of Orion-KL is one of only five sources in the galaxy which show emission in the $J_{K_a K_c} = 2_{12}–2_{11}$ *K*-doublet line of H_2CO at 2 cm (see Bastien *et al.* 1985). Emission in this line is caused by quenching the Townes-Cheung (1969) mechanism which lowers the excitation temperatures of *K*-doublet transitions below 2.7 K. The H_2 densities required for this quenching process are about 10^6 cm^{-3}. In contrast to Orion-KL, this region, which we will refer to as OMC-N, has a rather low kinetic temperature, 30 K, and line widths which are only barely supersonic (Batrla *et al.* 1983). Since the Orion molecular cloud is an ongoing site of O–B star formation, it is likely that the formation of massive stars may be underway in OMC-N, but that no O stars have yet formed. Thus a high-resolution study of OMC-N would provide information about the initial conditions required for more massive stars to form. A 14″ resolution map in the metastable lines of NH_3 made by Harris *et al.* (1983) with the Very Large Array (VLA) showed that 27% of the ammonia emission was formed in two small clumps, each of which appears to be rotating with a period of 30,000 yr. Since the metastable ammonia lines are thermalized at 10^4 cm^{-3}, this line emission may arise from regions of only moderate density. The 2 cm line of formaldehyde is emitted only by the highest density molecular gas; in order to determine the spatial size and location of the highest density material on a 12″.5 ($=10^{17}$ cm) scale, we mapped OMC-N.

II. OBSERVATIONS

The data were taken using the Very Large Array (VLA) of the National Radio Astronomy Observatory[1] in the D-array configuration on 1986 February 2. Twenty-five antennas and 32 spectral channels were used. The total bandwidth was 16 km s^{-1}. The analyzing band was centered at a local standard of rest (LSR) velocity of 10 km s^{-1}. The line rest frequency of 14.488420 GHz was taken from Lovas (1986). The data were online Hanning smoothed to give a velocity resolution of 0.5 km s^{-1}. In our observing procedure, the phase calibrator was 0500 + 019, and the primary calibration source was 3C 286, which was assumed to have a flux density of 3.53 Jy. An 8 hr synthesis was carried out. The phase center for the observations was R.A.(1950) = $05^h32^m48^s.0$, Decl.(1950) = −05°21′00″0 (1950.0). The phase calibrator was observed for 7 minutes, and then the Orion region for 15 minutes. This procedure was repeated until the sources set. The initial calibration and editing of the data were carried out at the VLA site. Subsequent reductions were made using the Astronomical Imaging Processing system (AIPS) software package. After editing, the (UV)-plane data were given natural weighting, convolved with a 15 kilolambda Gaussian taper, and Fourier transformed to produce images. The synthesized beamwidth was a circular Gaussian of FWHP 12″.5. The maps were not corrected for the response of the 3′.3 (FWHP) primary beam of the VLA antennas.

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

III. RESULTS

A continuum map was formed by averaging eight spectral line channels at either end of the band. After cleaning this map, we found one significant continuum feature. This will be discussed in § IV. Spectral line maps were formed by subtracting the continuum map from the remaining 16 maps in the center of the band. The rms noise in each difference (i.e., line minus continuum) channel is 5 mJy $beam^{-1}$ ($=0.18$ K, main beam brightness temperature).

Figure 1 contains the map produced by cleaning the spectral line emission summed over the radial velocity range 8.0–11.5 km s^{-1}. The map was cleaned with 800 iterations and a loop gain of 0.1. This reduced the negative contours appreciably, but did not change the positive features located within 2′ of the map center. The rms noise in this map is 2 mJy $beam^{-1}$ ($=0.08$ K main beam brightness temperature). At this noise level, there is no significant absorption in the formaldehyde line. In Figure 1 there are six regions with emission peaks at the second

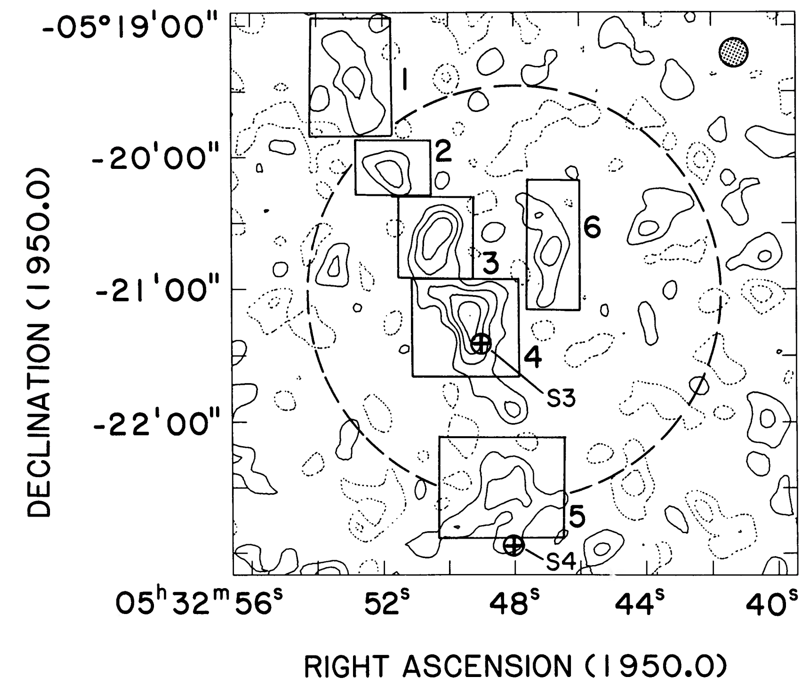

FIG. 1.—Map of the emission from the 2_{11}–2_{12} line of H_2CO at 2 cm, summed over the radial velocity range 8–11.5 km s^{-1}. Heavy dashed circle shows the FWHP of the individual antennas of the VLA. Boxes around the emission regions show where integrations were performed to produce the spectra in Fig. 2. Numbers identify the regions. Circled crosses show the location of clouds S3 and S4, mapped in this line with a 1′ beam by Bastien *et al.* (1985). The contours are 20%, 40%, 60%, 80%, and 100% of 115.4 mJy $beam^{-1}$ km s^{-1} (=4.32 K km s^{-1}, integrated main beam brightness temperature). Dashed contours represent the corresponding negative values.

contour or higher which extend over more than two to three beamwidths at the lowest contour; these are numbered for identification. The shape of region 5 differs in the cleaned and dirty maps. This is located toward the southern edge of the map where the cleaning process must correct for effects near the half-power point of the primary beam of the 25 m telescopes affecting the shape of the contours. Thus the angular size and shape of this region are more uncertain than the others. Also, the noise in Figure 1 is not uniform across the field, since we have plotted emission beyond the FWHP of the primary beam (the FWHP beam circle is shown dashed).

The cross and circle symbols labeled S3 and S4 mark the location of the two clouds estimated from 1′ resolution maps of the 2 cm line by Bastien *et al.* (1985). Summed over a 1′ square region centered on S3, more than 80% of the single-dish line flux density is in our VLA map. Considering the uncertainties in both results, we conclude that our VLA map contains all of the formaldehyde line intensity measured with a single dish. A comparison with S4 is more difficult because of the lower signal-to-noise ratio and corrections for the primary beamsize of the VLA antennas, but it appears that all of the line intensity measured with the 100 m telescope toward S4 is present in our VLA map also.

In Figure 2 we show spectra for these regions obtained by integrating the 10 spectral channels over the areas enclosed by boxes. The result for region 2 is barely significant; the signal-to-noise ratios for regions 1 and 5 are degraded because these are located toward the edges of the primary beam, but even so these spectra have good signal-to-noise ratios.

We have made use of the "Toolbox" spectral line reduction package of the MPIfR to fit Gaussians to the profiles. The line parameters are given in Table 1. For regions 2 and 5, the errors in the fit results are large, and values of the line width and radial velocities are only qualitative. We have also applied the two-dimensional Gaussian fit routine in AIPS to the spatial distribution of the line emission, in order to estimate the angular size and position of each maximum. In most cases the fitted results were obtained from the data plotted in Figure 1. The 1 σ uncertainties were obtained from the fitting program. In order to estimate the peak line temperatures, we have applied two-dimensional fits to the spectral channels containing the maximum intensities. The results from fits to individual velocity channels show a somewhat different peak position and generally smaller source size than that listed in Table 1, but the noise in these narrow channels is larger. However, there is some evidence for significant changes in the positions of maxima with velocity.

Our data are consistent with a systematic velocity change of less than 1 km s^{-1} over the region mapped. The best evidence for this is contained in our channel maps for the most intense line, in region 4. In Figure 3 we plot the spatial distribution of the 80% peak contour for the spectral line channels between 9 and 11 km s^{-1}. These contours do show a shift parallel to the major axis of the fragment, with lower velocity toward the north. However, since the 9.5 km s^{-1} contour has a larger spatial extent than adjacent channels, the velocity pattern does not correspond to any simple rotational motion. It should be noted that the VLA map of this region in the $(J, K) = (2, 2)$ line of NH_3 by Harris *et al.* (1983) showed a systematic variation in the positions of the maxima in a direction at nearly right angles to that shown in Figure 3.

IV. DISCUSSION

A 2′ resolution map in the 2_{12}–1_{11}, 2 mm rotational transition of H_2CO was made by Kutner, Evans, and Tucker (1976). In contrast to maps of the 2 cm *K*-doublet line, the 2

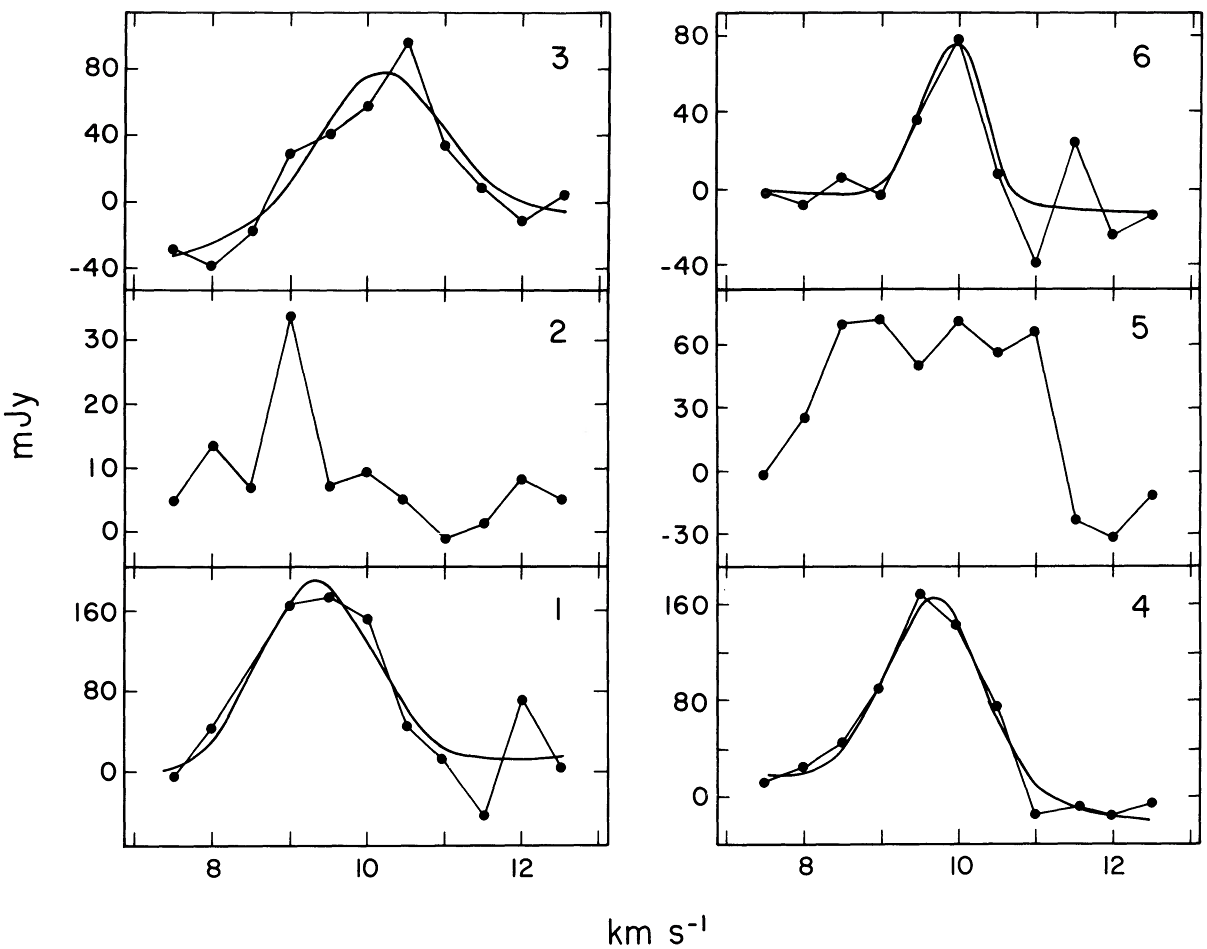

FIG. 2.—Straight lines connecting the dots are spectra obtained by integrating over the boxed regions in Fig. 1. Smooth curves are the Gaussian fits for these results. For regions 2 and 5, the errors in the fit results were large, and the line parameters were estimated. The fit results are collected in Table 1.

TABLE 1
PARAMETERS OF THE FRAGMENTS

Region (1)	Position: R.A. 05^h32^m (2)	Position: Decl.(1950) $-05°$ (3)	Deconvolved Max, Min Angular Sizes (arcsec) (4)	P.A. of Major Axis (5)	Line Width (km s^{-1}) (6)	Radial Velocity (km s^{-1}) (7)	Geometric Mean Linear Radius (pc) (8)	Peak Line Temperature (K) (9)	Virial Estimates: Mass ($M_\odot$) (10)	Virial Estimates: H_2 Density (cm^{-3}) (11)
1.........	$52^s.9 \pm 0^s.1$	$19'26'' \pm 2''$	46 ± 4 6 ± 2	$23° \pm 9°$	1.8 ± 0.5	9.3 ± 0.2	2.0E-02	0.23 ± 0.04	15	1E07
2.........	51.7 ± 0.1	$20'04'' \pm 2''$	18 <6	50	$<0.4(?)$	10.0(?)	<1.3E-02	~ 0.2	<1	>8E05
3.........	50.4 ± 0.1	$20'35'' \pm 2''$	31 ± 2 9 ± 2	170 ± 10	1.9 ± 0.4	10.2 ± 0.1	2.0E-02	0.47 ± 0.07	12	7E06
4.........	49.3 ± 0.1	$21'12'' \pm 1''$	33 ± 2 15 ± 1	20 ± 5	1.4 ± 0.1	9.7 ± 0.1	2.7E-02	0.48 ± 0.03	12	3E06
5.........	48.2 ± 0.2	$22'32'' \pm 3''$	29 ± 5 22 ± 2	150	4.6	9.1	3.1E-02	~ 0.2	160	3E07
6.........	46.8 ± 0.6	$20'42'' \pm 2''$	38 <6	10 ± 10	0.8 ± 0.2	9.9 ± 0.2	<1.2E-02	0.36 ± 0.09	<3	<3E06

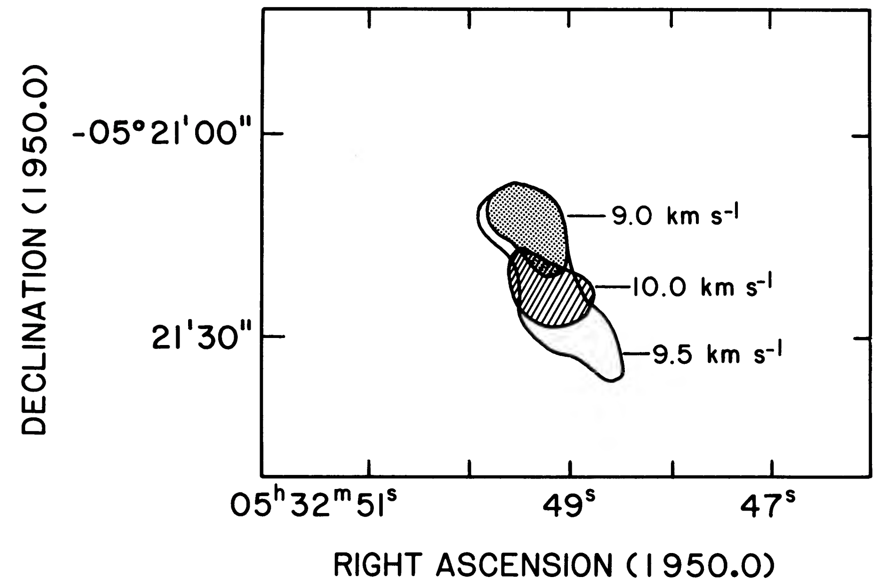

FIG. 3.—The spatial distribution of the 80% contours from the individual channel maps for region 4 (see Fig. 1). The velocity resolution of each channel is 0.5 km s^{-1}.

mm map is very extended. This implies that the 2 mm line is optically thick and is probably emitted from regions with densities of 10^4 cm^{-3} or more (for excitation discussions, see Garrison *et al.* 1975; Green *et al.* 1978; and the appendix in Bastien *et al.* 1985). Since OMC-N probably has a wide range of H_2 densities, combining the VLA data with this map does not lead to a better constraint on the H_2 density.

Using the deconvolved line widths and geometric mean source sizes collected in Table 1, we have obtained the virial masses and H_2 densities listed in Table 1. These were calculated assuming uniform density spherical regions (see appendix of Batrla *et al.* 1983 for formulae). The errors in the mass determinations are at best 20%. The H_2 densities depend critically on the sizes and are thus only rough estimates. However, these agree with the expectation that the formaldehyde emission arises in regions with H_2 densities of 10^6 cm^{-3} or more. The most massive fragment is region 5, but the unusual line shape indicates that there may be an interaction of some sort, and the linewidth for this region may not represent gravitational equilibrium alone. There is a continuum feature about 17″ NE of region 5. This feature is extended NW to SE, with a FWHP of about 60″ × 40″; the peak main beam brightness temperature is about 0.2 K. The continuum source might be a part of the Orion nebula. If region 5 and this continuum emission are associated, the molecular gas might be compressed by the expansion of the H II region. If so, the densest part would be located toward the front of the molecular region.

From the NH_3 measurements, the kinetic temperature of these regions is about 30 K. Using the linewidths in Table 1, we find that the gas is moving at more than twice the sound speed. Without an energy input such motions will decay in less than one crossing time, 10^5 yr. This time scale is shorter than free-fall times for H_2 densities of 10^5 cm^{-3}. In order to maintain such motions, sources of energy are needed. Either stars which have already formed in these regions, or shock waves from the expansion of Orion A into the molecular cloud could provide the input.

Applying the relation between dust optical depth and column density of H_2 from Keene, Hildebrand, and Whitcomb (1982) to the 3′ resolution data of Smith *et al.* (1979) and taking the kinetic temperature to be 30 K, we obtain a total mass of 100 $M_\odot$ for the region centered on region 3. Excluding region 5, the total mass contained in dense fragments is 50 $M_\odot$, from Table 1. Batrla *et al.* (1983) found a similar percentage for this region; to the south in the KL nebula, all of the mass is contained in small fragments, while to the north of OMC-N, less that 30% of the neutral gas is present in small clumps. OMC-N is a prominent source of molecular ions, radicals, and very weak emission from the refractory species SiO has been reported (Turner and Thaddeus 1977; Guelin 1987; Ziurys and Friberg 1987). Maps in these species have a lower angular resolution, and the excitation and optical depth of many of these transitions is not yet determined. A more direct comparison can be made with the VLA map of Harris *et al.* (1983), made with a 14″ angular resolution in the (2, 2) line of NH_3. In Figure 4 we show an overlay of these two sets of data. Our regions 1 and 5 are located outside the primary beam of Harris *et al.* (1983). There is good agreement between the location of our peak 4 and the SE maximum in NH_3; the NW NH_3 peak coincides with region 6. The peak intensities of the SE and NW clumps are equal in NH_3, but differ by a factor of 2.5 in our formaldehyde map. The formaldehyde distribution in regions 3 and 4 (the SW NH_3 fragment) is clumpier and more extended along the major axis than in NH_3. More importantly, Harris *et al.* (1983) reported that in NH_3 the positions of both peaks moved to the NW with increasing velocity, and interpreted this as rotation about the major axis of the fragments. Such motions are not found in our data. These differences are caused at least in part by excitation and chemical effects. All of the single-dish line flux density is present in fragments, whereas 75% of the NH_3 emission arises from more extended material. Presumably the extended gas has a lower H_2 density. At such lower densities, the excitation temperature of the 2 cm line of H_2CO would be close to 2.7 K, and comparable to the noise. If on the average the NH_3 line emission arises from less dense gas, these motions may represent an intermediate stage in which the angular velocity increases because of the conservation of angular momentum. The 2 cm H_2CO line is emitted

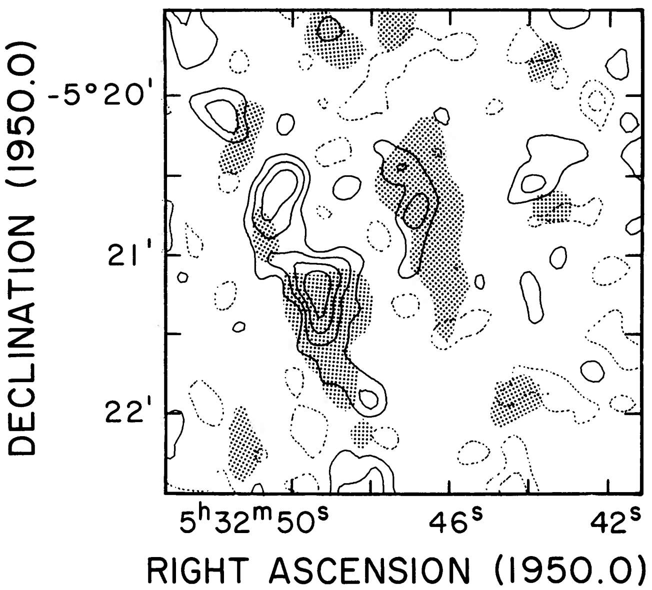

FIG. 4.—The shaded regions are the 20% contours of the VLA map of the $(J, K) = (2, 2)$ inversion line of NH_3 (Harris *et al.* 1983) overlaid on the central portion of Fig. 1.

from the highest density regions where we measure no rotation. Magnetic braking (see Mouschovias and Paleologou 1979; Gillis, Mestel, and Paris 1979) is a mechanism which would allow a transfer of angular momentum out of these dense regions and this would explain the low limits to velocity motions.

A line drawn through the maxima of regions 1 through 4 is inclined at 12° (E of N). This is nearly the angle found in resolution maps of NH_3 (Batrla *et al.* 1983) and CO maps (Kutner *et al.* 1977). Thus over a scale of 25′ ($=10^{19}$ cm or 3.7 pc at 500 pc) to 1′ ($=4.4 \times 10^{17}$ cm or 0.15 pc) the molecular material is aligned in the same direction. However, on a scale of 10″ to 20″, the directions of the major axes of individual fragments is less ordered: region 3 and the southern extension to region 4 as well as region 5 point in different directions (see col. [5] of Table 1). This indicates that the alignment mechanism breaks down on a scale of $\approx 20''$ or less ($=10^{17}$ cm or 0.036 pc). If magnetic fields cause the ordering, perhaps they are removed before this stage. This change of direction, as with the low observed rotational velocities, may be caused by magnetic braking.

The other four sources in our Galaxy observed in the 2 cm emission line of H_2CO show a bewildering variety of characteristics. This is due in part to limitations inherent in the observations, namely the large size of the telescope beam when expressed in parsecs and the low intensity of quasi-thermally excited emission lines. The source in W75 S (Johnston, Henkel, and Wilson 1984) has a filamentary structure similar to the fragments shown in Figure 1, but at 3 kpc, it is likely that a great deal of substructure is present. If the most nearby 2 cm H_2CO emission line source, ρ Oph B (Wadiak *et al.* 1985) were located at the distance of Orion, the two clumps which are resolved with a 12″.5 beam would appear to make up an elongated fragment. The emission from OMC-2 (Kutner, Evans, and Tucker 1976; Bastien *et al.* 1985) is very weak, and has an angular size smaller than 1′. The 2 cm line emission from Orion-KL itself is more intense than that for other sources, but the interactions with IR sources makes the dynamics complicated (Bastien *et al.* 1985; Johnston *et al.* 1983). The small clumps in ρ Oph B appear to be rotating with a period of 50,000 yr, but there is no hint of such motions in any of the other sources. Even though the beam size expressed in pc is 3 times smaller for ρ Oph B than OMC-N, we would have detected such motions. The presence or absence of rotation must be related to some intrinsic factor which allows the removal of angular momentum. One possibility is the degree of ionization in the molecular cloud.

In its general features a scenario for the development of Orion A and the OMC follows that proposed by Elmegreen and Lada (1977). However the scheme for OMC applies to at most a 3 to 4 pc region. The cylinder-like shape of the molecular region near Orion A must be caused by an alignment mechanism specific to the neutral material. The most obvious candidate is an aligned magnetic field, but a mechanism involving converging shock waves is also possible. The H_2 density in the OMC cloud would have been about 10^3 cm^{-3} initially. The formation of the exciting stars in Orion A might have been a chance event. Once this happened, however, the nearby molecular gas was heated and compressed. At the back face of Orion A, this compression raised the H_2 density by factors of 10 to 100. All of the 2 cm H_2CO emission is seen in projection within the continuum contours of Orion A (see, e.g., Wilson and Pauls 1984) giving some support for this notion. Additional evidence is given by the line shape observed for region 5, which is close to a continuum feature. In this picture, the high-density molecular gas is produced by the expansion of Orion A, and only lower density molecular gas is found to the north. Because the mass of the molecular cloud is much larger than that of the H II region, only the gas at a small depth into the molecular cloud would be compressed. The star formation, warm molecular gas, and high abundance of complex molecules would only be observed along the line of sight to Orion A, and these phenomena would occur near the front face of the molecular region. Although the chances for star formation are enhanced by the expansion of the H II region, the details of the collapse process are still unclear. The factors hindering collapse are angular momentum, turbulence, and magnetic fields. Angular momentum would have to be transferred to less dense gas by magnetic braking, and then the magnetic field itself would have to decease. Subsequently, supersonic turbulence would be dissipated in one crossing time, and there would be only thermal support of these fragments. At densities of 10^5 cm^{-3}, the free-fall time is 10^4 yr, and we may be observing the birth of the next set of stars in the Orion region.

V. CONCLUSIONS

Maps of the 2 cm line of formaldehyde in the OMC-N region with an angular resolution of 12″.5 show that the low-intensity extended emission seen with a 1′ beam breaks up into six elongated fragments. Line excitation studies and virial estimates show that the H_2 densities in these fragments are more than 10^5 cm^{-3}. The kinetic temperature of the fragments is about 30 K, and with one exception the line widths are only slightly supersonic. The combination of high density, small turbulence, and low kinetic temperature makes these fragments prime candidates for collapsing molecular clouds. The relative positions of these fragments follow the direction of the molecular line emission on a larger scale. This alignment may be caused by magnetic effects. On a 15″ scale ($=10^{17}$ cm), this alignment breaks down. Some of the fragments have also been detected in NH_3 and show rapid rotational motion. This is not present in our data. The excess angular momentum may have been removed from the dense gas by magnetic braking. The development of this region may have been strongly influenced by the expansion of Orion A into the molecular cloud. In this picture, all of the densest gas is located at the front face of the OMC region.

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