ARCSSECOND IMAGES OF CH$_3$CN TOWARD W75N

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ABSTRACT

CH$_3$CN ($J = 6$–$5$) was observed with a resolution of $2''$ toward W75N using the BIMA interferometer. Two continuum sources were detected at 3 mm and designated MM1 and MM2 in previous studies. Alignment of the two continuum sources with the outflow axis from MM1 suggests that these continuum sources may be the result of the outflow interacting with the interstellar medium. MM1 is coincident with compact CH$_3$CN emission. CH$_3$CN was not detected toward MM2. The distribution of optical depth ($\tau_L$) is derived. An excitation analysis was not done because of large-line optical depths.

Subject headings: ISM: clouds — ISM: individual (W75N) — ISM: molecules — radio continuum: ISM

1. INTRODUCTION

Hot cores in molecular clouds have a characteristic diameter of $\sim$0.1 pc, a density $\geq$10$^6$ cm$^{-3}$, and a temperature $\sim$100 K. Those hot cores that are luminous in the far-IR ($L_{\text{FIR}} > 10^4 L_{\odot}$) but have no free-free radio emission are thought to be precursors to ultracompact (UC) H ii regions (Kurtz et al. 2000 and references therein). They are found in regions of massive star formation, often offset from UC H ii regions (Hunter et al. 2000). Hot cores are principally studied through their molecular line emission and millimeter-submillimeter continuum emission. Hofner et al. (1996) observed the UC H ii region complex G9.62+0.19 and found that CH$_3$CN emission is centered on the youngest, densest component in this complex. This component also drives an energetic molecular outflow (Hofner et al. 1996) and has weak ($<$1 mJy) radio continuum emission at centimeter wavelengths (Testi et al. 2000). Based on observations of G9.62+0.19, Hofner et al. (1996) postulated that CH$_3$CN emission might be a tracer of UC H ii precursors.

Wilner et al. (2001) used CH$_3$CN ($J = 12$–$11$) observations of W49N to estimate the timescale for hot core evolution; they concluded that hot cores, which precede the UC H ii stage, have lifetimes less than or equal to UC H ii regions. Zhang et al. (1998) observed many molecular lines, including CH$_3$CN ($J = 8$–$7$), toward W51 and concluded from line asymmetries that CH$_3$CN was tracing infalling material. These studies found that CH$_3$CN tends to be (1) tightly confined ($\sim$10$^4$–$10^5$ AU), (2) associated with regions of massive star formation, and (3) optically thick in millimeter-wave transitions. Watt & Mundy (1999) observed CH$_3$CN ($J = 6$–$5$) toward four massive star formation regions (two detections, two nondetections). Based on emission morphology, excitation analysis, and chemical models by Millar, Macdonald, & Gibb (1997), Watt & Mundy (1999) concluded that the hot core near G34.26+0.15, traced by CH$_3$CN emission, was probably externally heated. In contrast to typical results from the observations cited above, they found no significant dust emission at 3 mm. Based on single-dish detection and interferometer nondetection, they also concluded that the CH$_3$CN emission toward G11.94–0.62 has an extent of $\sim$50,000 AU.

A CH$_3$CN ($J = 12$–$11$) survey was undertaken using the 10 m Heinrich Hertz Submillimeter Telescope (SMT) toward 48 known massive star formation regions to determine the fraction with detectable CH$_3$CN emission (Pankonin et al. 2001). Forty-six percent of the regions surveyed were detected in CH$_3$CN emission. Because the angular resolution was $\sim$30', they were unable to determine if CH$_3$CN originates from UC H ii regions or from neighboring sites of even younger precursors of UC H ii regions. Pankonin et al. (2001) found beam-averaged rotation temperatures and column densities to be consistent with internal heating, presumably from embedded protostars or the ionizing stars of the UC H ii regions. They argued that beam dilution allowed only lower limits for CH$_3$CN column densities.

An investigation in the lines of CH$_3$CN ($J = 6$–$5$) using interferometric resolution toward W75N is presented here to better determine the properties of this source and to establish how important resolution effects may be in the analysis of CH$_3$CN line emission. W75N was selected because it is a relatively nearby region of massive star formation region with strong CH$_3$CN emission, and there are few previous observations of the hot core in this object.

2. OBSERVATIONS

Observations of W75N were obtained with the BIMA millimeter interferometer (Welch et al. 1996) on 1999 October 8, 11, and 12 and 2000 April 30 in the C configuration and on 1999 October 14 in the B configuration. Baselines ranged from 180 m to 60 m. The phase calibrator, 2025+337 (J2000), was observed approximately every 25 minutes. Our primary flux density calibrator was Mars, whose integrated flux density was 40 Jy on 1999 October 10.
TABLE 1

| Measurement                        | Result       |
|-----------------------------------|--------------|
| Source                            | W75N         |
| Phase center                      |              |
| Right ascension (J2000)           | 20$^{h}$38$^{m}$36$^{s}$6 |
| Declination (J2000)               | 42$^{o}$37$^{s}$32$^{"}$ |
| Transitions                       | CH$_3$CN ($J$=6–5) $K$=0–4 |
| Center rest frequency (GHz)       | 110.3701     |
| Spectral resolution (km s$^{-1}$) | 1.1          |
| Continuum bandwidth (MHz)         | 200          |
| Antenna HPBW (arcsec)             | 96           |
| Synthesized HPBW (arcsec)         | 2.5 x 2.2    |
| Synthesized beam position angle    | 21$^\circ$ east of north |
| T$_{\text{brightness}}$ [K / (Jy beam$^{-1}$)] | 18.2         |
| Maximum spatial scale (arcsec)    | 60           |
| rms$_{\text{beam}}$ (mJy beam$^{-1}$) | 136          |
| rms$_{\text{east}}$ (mJy beam$^{-1}$) | 4.2          |
| Flux calibrator                   |              |
| Mars (1999 Oct 10) (Jy)           | 40 $\pm$ 8   |
| Phase calibrator                  |              |
| 2025+337 (1999 Oct 8–12) (Jy)     | 2.3 $\pm$ 0.4 |

Flux calibration is accurate to 20%. The phase calibrator 2025+337 was found to have a flux density of 2.29 Jy, which is within the range of previous measurements (Welch et al. 1996). All data editing and reduction were performed using the MIRIAD package (Sault, Teuben, & Wright 1995). Narrow channel observations were obtained covering the frequency range 110.3485 to 110.3916 GHz covering the CH$_3$CN $J$=6–5 $K$=0–4 emission lines. These windows were not wide enough to observe the nearby CH$_3$CN transitions. Continuum subtraction was performed using two 100 MHz windows. These two windows were inspected and found to be free of lines. All maps were made using natural weighting. The correlator setup, rms noise, and beam sizes are summarized in Table 1.

3. RESULTS: CONTINUUM AND CH$_3$CN LINE EMISSION

3.1. MM1

Our 3 mm continuum image is shown in Figure 1 in both contours and gray scale. The line emission integrated over the $K = 0$–4 components is shown in Figure 2 as contours superposed on the 3 mm continuum shown in gray scale. The CH$_3$CN ($J$=6–5) spectrum integrated over a 4$''$ $\times$ 4$''$ area centered on MM1 is shown in Figure 3. The line emission is confined to MM1. As traced by CH$_3$CN, MM1 is one of the most compact hot cores yet observed ($\theta_{\text{deconvolved}} = 5.0'' $ x $ 1.5'' = 10,000$ AU $\times$ 3000 AU). The distribution of line emission is slightly elliptical, with a deconvolved major-to-minor axis ratio of 3.4 and a position angle 24° $\pm$ 10° west of north, determined by a least-squares two-dimensional Gaussian fit to the line emission. The individual K components were imaged separately and found to be indistinguishable from the integrated line emission. The MM1 continuum emission is also elongated with a position angle 24° west of north but a deconvolved axis ratio of 1.6. MM1 has a peak 3 mm continuum flux density of 80 $\pm$ 16 mJy beam$^{-1}$ and integrated continuum flux density of 390 $\pm$ 80 mJy (integrated over 200 arcsec$^2$). The results of our analysis are given in Table 2.

Previous observations with the VLA show that three compact centimeter continuum sources lie within the central region of MM1 (Hunter et al. 1994 at 1.3 and 3.6 cm; Torrelles et al. 1997 at 1.3 cm). Those observations had beam sizes $\sim$0.1, which permitted them to resolve the centimeter sources (see Fig. 1; each VLA source is represented by a white plus sign). The position angle of the outflow is not well determined.

Black line: CO and cm-radio continuum outflow orientation is indicated (Davis et al. 1998a; Torrelles et al. 1997). Upper left corner: Synthesized HPBW. The origin of the outflow is not well determined.
white X). The sources lie roughly along the millimeter continuum major axis of MM1. The millimeter continuum and CH$_3$CN major axes are both perpendicular to the MM1 outflow axis (discussed below). This alignment is suggestive of an oblate cloud core, although the millimeter and CH$_3$CN morphology could also result from the alignment of the three compact VLA continuum sources. MM1 and MM2 were not detected by the MSX satellite (Mill et al. 1994) between 8 and 21 $\mu$m. Modeling the emission as thermal dust emission at $T = 35$ K (see § 3.4.2), we estimate that expected flux densities ($S_v < 1$ mJy) are below the MSX detection limits ($S_v > 100$ mJy).

### 3.2. MM2

A second millimeter continuum source, MM2, was found $\approx 5''$ to the southwest of MM1. MM2 has a peak 3 mm continuum flux density of $45 \pm 9$ mJy beam$^{-1}$ and an integrated continuum flux density of $200 \pm 40$ mJy. MM2 was not detected at centimeter wavelengths, indicating that its millimeter emission is probably due to dust. Previous submillimeter observations do not have the spatial resolution to distinguish between MM1 and MM2 (Hunter et al. 2000).

MM2 was also not detected via K-band photometry by Moore et al. (1988, 1991) or MSX (8–21 $\mu$m). Absence of emission at $K$ band is probably due to intrinsically weak emission, although high optical depth may also be important at $\lambda \leq 2$ $\mu$m. We are unable to distinguish between four possible explanations of these observations: (1) MM2 is heated by a prototypical O star that has not formed a detectable H II region because of infall, (2) MM2 is heated by a nonionizing star, (3) MM2 is heated by internal shocks, probably associated with the outflow from MM1, or (4) MM2 is heated externally, probably by the three centimeter components of MM1.

### 3.3. Outflow

A bipolar outflow has been detected toward MM1 in CO ($J = 3–2$; Davis, Smith, & Moriarty-Schieven 1998a; Hunter et al. 1994), CO ($J = 2–1$; Davis et al. 1998b), and in the centimeter radio continuum (Torrelles et al. 1997); all of whom find that the outflow position angle is 66° east of north (Figs. 1 and 2, black line). The outflow source has not been clearly determined. The outflow axis is perpendicular to the millimeter continuum and CH$_3$CN major axis. The centimeter continuum is likely produced by free-free emission, which, assuming the source is optically thin, would not be detectable at 3 mm. H$_2$O and OH masers have also been measured along the outflow axis, although no significant velocity gradient was measured (Hunter et al. 1994; Torrelles et al. 1997). Some of the assumptions on which the excitation analysis was based included the outflow from MM1 relative to MM2. Using flux density measurements at 1 mm (230 GHz) and 3 mm (90 GHz) of Shepherd (2001), the spectral indices of MM2 and MM3 are 3.1 and 1.8, respectively. Comparing Shepherd’s measurements with those in this study, we estimate the error in the spectral index of MM2 to be large, $\sim 1$. The alignment of MM2 and MM3 suggests that they are associated with the outflow from MM1. In this scenario and based on its spectral index, emission from MM2 and MM3 could originate from either shock-heated dust or shock-ionized optically thick gas in the outflow.

### 3.4. Analysis

#### 3.4.1. Boltzmann Analysis and Optical Depth

CH$_3$CN is a symmetric top molecule whose K components are closely spaced in frequency but have a wide range of excitation energies above ground. $J = 6–5$, $K = 0$ has an excitation energy of 13 K above ground, whereas the $K = 3$ transition, which is only 19 MHz lower in frequency, is 76 K above ground. Assuming the line emission from MM1 is optically thin, an excitation analysis based on the radiation transfer equation allows a determination of the rotation temperature ($T_{rot}$) and column density ($N_{col}$).

The pattern of K components were simultaneously fitted with Gaussian profiles. That is, we fixed the line separations and shifted the overall pattern to obtain a least-squares fit. We also forced each line to have the same FWHM, true if all emission lines originate in the same volume. Thus, we allowed only 6 free parameters at each position: one common width (FWHM), one pattern velocity, and four intensities ($T_A^*$). The Gaussians were fitted using a Levenberg-Marquardt least-squares minimization technique (Argonne National Labs Minipak Project 1980). We discarded fits to spectra at any position for which $T_A^* < 3\sigma$ for any single emission line.

Some of the assumptions on which the excitation analysis rests are not strictly true. Specifically, the ratios of K-com-
and a wide range of excitation energy will be required to provide enough constraints to justify such a model.

The CH$_3$CN emission observations toward W75N show some similarity to observations toward IRAS 20126+4104 (Cesaroni et al. 1999). That study concluded that CH$_3$CN was tracing an infalling accretion disk. The resemblance, however, is only strong enough to encourage further observations as described above.

3.4.2. Mass Estimate

We can also approximate the mass in MM1 and MM2 using the measured millimeter continuum. We estimate the free-free contribution to the 3 mm emission by extrapolating from observations at 1.3 cm (Torrelles et al. 1997) and 3.6 cm (Hunter et al. 1994). All three centimeter components of MM1 have rising spectra from 3.6 cm to 1.3 cm, indicating the sources are partly optically thick. Using the spectral index between 3.6 and 1.3 cm to estimate the flux density at 3 mm due to free-free emission would predict $\sim 100$ mJy. If the sources are optically thin shortward of 1.3 cm, however, we estimate the free-free component would be $\sim 20$ mJy at $\lambda = 3$ mm. Since we wish to obtain an upper mass limit (see below) and would prefer to overestimate the dust emission, we assume the free-free component of the 3 mm emission of MM1 is $\sim 20$ mJy. Assuming thermal dust emission accounts for the remaining 3 mm emission (370 mJy) and following the method of Hildebrand (1983), millimeter continuum emission is related to the total mass (gas + dust) according to

$$M_{\text{total}} \geq \frac{F_\nu D^2}{B_\nu(T_{\text{dust}}) \kappa_\nu},$$

where $D$ is the distance to the source, $F_\nu$ is the continuum flux density, $B_\nu$ is the Planck function at frequency $\nu$, and $\kappa_\nu$ is the opacity of dust at $\nu$. $M_{\text{total}}$ is given as a lower limit because the measured flux density may not represent the entire range of dust temperatures present. We assume a gas-to-dust ratio of 100 and thus $\kappa_\nu = 0.006(\nu/245 \text{ GHz})^{-1} \text{ cm}^2 \text{ g}^{-1}$ (Shepherd & Watson 2002). We assume a frequency index $\beta = 1.5$ (Shepherd 2001; Pollack et al. 1994) for the dust opacity. This result is sensitive to the assumed value of $T_{\text{dust}}$. If we use a lower limit for $T_{\text{dust}} = 10 \text{ K}$, however, the relationship above gives an upper mass limit of 440 $M_\odot$ for MM1 (see Table 2). If more than $\sim 500$ $M_\odot$ were present at any reasonable temperature, we would measure a greater flux density at 3 mm. Since typical values for the mass of clouds that give rise to O stars are $\gtrsim 1000$ $M_\odot$ (see Hunter et al. 2000), we conclude that W75N is unlikely to be forming an O star. This result is consistent with Hunter et al. (1994), who inferred the spectral types of the three centimeter sources comprising MM1 to be early B stars. Since Hunter et al. (1994) did not account for dust absorption or free-free self-absorption, however, the true spectral types may be earlier. The mass upper limit calculated for MM2 using the same method is reported in Table 2.

4. CONCLUSIONS

CH$_3$CN ($J = 6-5$) was observed toward W75N using the BIMA interferometer with $2''$ resolution. Five compact ($\sim 10,000$ AU) K components were detected ($K = 0-4$) toward the peak of MM1. CH$_3$CN emission is elongated with a deconvolved major-minor axis ratio of 3.4. The
major axis coincides with the alignment of three centimeter continuum sources reported previously with 0′′1 resolution VLA observations. Thus, the elongation is probably caused by multiple sources lying approximately along a straight line projected on the plane of the sky, although we cannot rule out CH$_3$CN tracing out an oblate cloud core. A bipolar outflow was previously detected toward MM1 in CO ($J = 1$–0, $J = 3$–2) and centimeter continuum. MM2 and MM3 (detected by Shepherd 2001) lie on opposite sides of MM1 along the outflow axis, indicating that they may be heated by shocks as the outflow interacts with the local interstellar medium.

Analysis of $K = 2$ and 3 emission lines indicates that CH$_3$CN ($J = 6$–$5$) is optically thick ($\tau_{\text{max}} \approx 8$). Thus, a radiative transfer/statistical equilibrium model that incorporates source kinematics and temperature and density gradients will be required to estimate $T_{\text{rot}}$ and $N_{\text{CH}_3\text{CN}}$. The results of this study support the previously observed pattern that CH$_3$CN in massive star formation regions tends to be compact ($\sim 10^4$–$10^5$ AU) and optically thick in millimeter-wave transitions.

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REFERENCES
Cesaroni, R., Felli, M., Jenness, T., Neri, R., Olmi, L., Robberto, M., Testi, L., & Walmsley, C. M. 1999, A&A, 345, 949
Davis, C. J., Moriarty-Schieven, G., Eistoffel, J., Hoare, M. G., & Ray, T. P. 1998b, AJ, 115, 1118
Davis, C. J., Smith, M. D., & Moriarty-Schieven, G. H. 1998a, MNRAS, 299, 825
Goldsmith, P. L., & Langer, W. D. 1999, ApJ, 517, 209
Hildebrand, R. H. 1983, QJRAS, 24, 267
Hofner, P., Kurtz, S., Churchwell, E., Walmsley, C. M., & Cesaroni, R. 1996, ApJ, 460, 359
Hunter, T. R., Churchwell, E., Watson, C., Cox, P., Benford, D. J., & Roellige, P. R. 2000, AJ, 119, 2711
Hunter, T. R., Taylor, G. B., Felli, M., & Tofani, G. 1994, A&A, 284, 215
Kurtz, S., Cesaroni, R., Churchwell, E., Hofner, P., & Walmsley, C. M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 299
Mill, J. M., O'Neil, R., Price, S. D., Remick, G., Uy, M., & Gaposchkin, E. M. 1994, J. Spacecraft & Rockets, 31, 900
Millar, T. J., Macdonald, G. H., & Gibb, A. G. 1997, A&A, 325, 1163
Moore, T. J. T., Mountain, C. M., Yamashita, T., & McLean, I. S. 1991, MNRAS, 248, 377
Moore, T. J. T., Mountain, C. M., Yamashita, T., & Selby, M. J. 1988, MNRAS, 234, 95
Pankonin, V., Churchwell, E., Watson, C., & Bieging, J. H. 2001, ApJ, 558, 194
Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., Roush, T., & Fong, W. 1994, ApJ, 421, 615
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco: ASP), 433
Shepherd, D. 2001, ApJ, 546, 345
Shepherd, D., & Watson, A. 2002, ApJ, 566, 966
Testi, L., Hofner, P., Kurtz, S., & Rupen, M. 2000, A&A, 359, L5
Torrelles, J. M., Gomez, J. F., Rodriguez, L. F., Ho, P. T. P., Curiel, S., & Vazquez, R. 1997, ApJ, 489, 744
Watt, S., & Mundy, L. G. 1999, ApJS, 125, 143
Welch, W. J., et al. 1996, PASP, 108, 93
Wilner, D. J., De Pree, C. G., Goss, W. M., & Welch, W. J. 2001, ApJ, 550, L81
Zhang, Q., Ho, P. T. P., & Ohashi, N. 1998, ApJ, 494, 636