HOT GAS AND DUST IN A PROTOSTELLAR CLUSTER NEAR W3(OH)

FRIEDRICH WYROWSKI,1,2 PETER SCHILKE,1 C. MALCOLM WALMSLEY,3 AND KARL M. MENTEN1

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ABSTRACT

We used the IRAM interferometer to obtain subarcsecond resolution observations of the high-mass star-forming region W3(OH) and its surroundings at a frequency of 220 GHz. With the improved angular resolution, we distinguish three peaks in the thermal dust continuum emission originating from the hot core region ≈6" (0.06 pc) east of W3(OH). The dust emission peaks are coincident with known radio continuum sources, one of which is of nonthermal nature. The latter source is also at the center of expansion of a powerful bipolar outflow observed in H$_2$O maser emission. We determine the hot core mass to be 15 $M_\odot$ based on the integrated dust continuum emission. Simultaneously, many molecular lines are detected, allowing the analysis of the temperature structure and the distribution of complex organic molecules in the hot core. From HNCO lines spanning a wide range of excitation, two 200 K temperature peaks are found coincident with dust continuum emission peaks, suggesting embedded heating sources within them.

Subject headings: ISM: individual (W3(OH)) — ISM: molecules — radio continuum: ISM — stars: formation — techniques: interferometric

1. INTRODUCTION

The archetypical ultracompact (UC) H II region W3(OH) has been the topic of numerous studies targeted at understanding the phenomena involved in the formation of massive stars and the interaction of these objects with their environment. In particular, interferometric observations at radio and millimeter wavelengths have revealed an ever more detailed picture of the dense gas associated with W3(OH) (e.g., Baudry et al. 1993; Bloemhof, Reid, & Moran 1992; Reid et al. 1995; Turner & Welch 1984; Wilner, Welch, & Forster 1995; Wink et al. 1994; Wyrowski et al. 1997).

The observations suggest that there are several sites of very recent and ongoing star formation: the most prominent of these are the UC H II region itself, which is ionized by a young O star, and a region showing hot molecular line and dust emission that is associated with strong water maser emission. The latter region is located at a projected distance of ≈0.06 pc to the east of the UC H II region, assuming a distance of 2.2 kpc for W3(OH). Most of the dense neutral gas in the W3(OH) complex appears to be associated with the H$_2$O maser “hot core” source, whereas the most luminous young star in the region seems to be the exciting star of the UC H II region.

There are several lines of evidence suggesting that there are one or more young stars embedded in the dense molecular gas near the H$_2$O maser source: Turner & Welch (1984) found a compact source of emission in the HCN $J = 1\rightarrow0$ transition toward the H$_2$O maser position [referred to as W3(OH)-TW hereafter]. The HCN line showed broad wings suggestive of mass loss from a young embedded star. Alcolea et al. (1992) measured the H$_2$O maser proper motions and found them to be consistent with a bipolar outflow along an east-west axis in the plane of the sky. Mauersberger et al. (1986a) and Mauersberger, Wilson, & Walmsley (1986b) used their ammonia observations to demonstrate the presence of dense, hot (greater than 160 K) gas close to the water masers, and this was confirmed by the studies of Wink et al. (1994) and Helmich et al. (1994). However, the most surprising result was perhaps that of Reid et al. (1995), who studied weak elongated centimeter continuum emission toward the TW source. They concluded that there was strong evidence for this being synchrotron emission from a “jetlike” structure aligned with the outflow indicated by the proper motions of the H$_2$O masers associated with W3(OH)-TW. Moreover, the synchrotron emission centroid was found to be coincident with the center of expansion of the H$_2$O outflow as determined by Alcolea et al. (1992). All of these facts suggest the presence of a relatively luminous embedded star that drives a collimated outflow.

In this Letter, we present sensitive, subarcsecond resolution interferometric observations of the W3(OH) complex at a frequency of 220 GHz; results from simultaneous observations at 107 GHz will be presented elsewhere. We find an excellent coincidence between the structures seen at millimeter wavelengths in thermal dust emission and those seen in nonthermal emission (see Wilner et al. 1999) at centimeter wavelengths.

2. OBSERVATIONS

Our observations were made with the five-element Plateau de Bure Interferometer in three configurations: B1-N13 on 1998 January 6/7, A1 on February 7, and B2 on February 17. The phase center was α(J2000) = 02°27′04″:284, δ(J2000) = +61°52′24″:55, which is between the positions of W3(OH) and W3(OH)-TW. The total observing time on source was 17.1 hr, covering a baseline range from 30 to 410 m. We used the dual-frequency receiver systems to simultaneously observe the CH$_3$OH $J = 3\rightarrow4$ “A” and C$^{13}$O ($J = 2\rightarrow1$) lines. Due to good winter weather conditions, the 220 GHz system temperature was in the range 200–400 K and the radio seeing on all days was better than 0.5″. On-source integrations of 20 minutes were interspersed with phase calibrator observations on the quasar 0224+671. For bandpass and flux density calibration, the sources 3C 454.3, 3C 273, and 3C 84 were used, and the absolute flux density scale was established by observing MWC 349, for which a flux density of 1.66 Jy was assumed at 220 GHz. From the day-to-day variance in W3(OH)’s continuum flux density, we estimate that our 220 GHz flux density scale is accurate to within 20%.

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany.
2 Department of Astronomy, University of Maryland, College Park, MD 20742-2421.
3 Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy.
The data were processed using the GILDAS software package. To remove the effects of short-term atmospheric fluctuations on the interferometer phases, phase corrections derived from 220 GHz total power measurements were applied to the 107 and 220 GHz data (see Bremer, Guilloteau, & Lucas 1996). Then, correcting for phase drifts on long timescales was done in the standard manner by observing a calibrator source. The phase solutions for the 107 GHz data were subtracted, appropriately scaled, from the 220 GHz data. The rms noise of the fits to the residual 220 GHz phase was found to be only 10' on average. After gridding and fast Fourier transform of the $uv$-data, a 220 GHz beam size of 0'83 $\times$ 0'55 (FWHM) was determined for natural weighting with a position angle of 100'. From all correlator units, spectral line data cubes were built and checked for frequency ranges free of line emission in order to produce a continuum map. All data were deconvolved using the CLEAN algorithm, and the resulting dynamical range-limited rms noise in the 220 GHz continuum maps is 20 mJy.

3. RESULTS

3.1. 220 GHz Continuum Measurements

In Figure 1, we present our 220 GHz continuum map of W3(OH) superposed upon the 8 GHz VLA map of Wilner et al. (1999). For a better comparison with the latter, our 220 GHz map was restored with a circular beam of 0'5 diameter (FWHM) and is thus slightly superresolved. On both maps, the main features are the UC H II region to the west and the water maser source 6" to the east. We checked the alignment of the maps by computing their correlation and found them to coincide within 0'05. Toward the H II region, the main emission mechanism even at 220 GHz is free-free emission from the ionized gas. In fact, in agreement with the measurements of Wyrowski et al. (1997), we observe an integrated flux density of $3.1 \pm 0.5$ Jy at 220 GHz toward the H II region as compared to a value of $3.0 \pm 0.15$ Jy at 107 GHz. Combining the 3 mm measurements with results from the literature allows us to extrapolate the flux density to 220 GHz assuming optically thin free-free emission, and we find $3.0 \pm 0.3$ Jy. This value is consistent with the actually measured flux density at 220 GHz, and we place a conservative upper limit of 0.5 Jy on any contribution from emission from dust associated with the UC H II region.

Most strikingly, Figure 1 reveals the small-scale spatial coincidence of dust emission features (shown in gray scale) with radio continuum sources detected toward the TW object in the 3.6 cm map of Wilner et al. (1999; contours). As seen in Figure 1 (inset), the easternmost component A is coincident with the centroid of the elongated structure seen with the VLA. There is also a rough correspondence between components B and C of the 220 GHz map with features seen at 3.6 cm. In particular, it seems clear that dust emission source A is associated with the nonthermal radio source detected at centimeter wavelengths.

We note here that there is also evidence in Figure 1 for extended emission surrounding components A, B, and C. Our observations are not sensitive to structures extended over size...
TABLE 1
CONTINUUM PEAK POSITIONS AT 1.3 MM AND THEIR CORRESPONDING CONTINUUM FLUXES AND ROTATIONAL TEMPERATURES TOWARD W3(OH)-TW

| Position | α (J2000) | δ (J2000) | S_{220 GHz} (mJy beam^{-1}) | T_{rot}(HNCO) (K) |
|----------|-----------|-----------|----------------------------|------------------|
| A        | 02 27 04.71 | 61 52 24.6 | 185                         | 200 ± 40         |
| B        | 02 27 04.60 | 61 52 24.8 | 145                         | 150 ± 15         |
| C        | 02 27 04.52 | 61 52 24.7 | 150                         | 190 ± 15         |

Note.—Units of right ascension are given in hours, minutes, and seconds, and units of declination are given in degrees, arcminutes, and arcseconds.

...scales larger than about 5', and hence it is likely that we are missing flux. We consider therefore that the total integrated flux density measured toward the water maser position (1.6 Jy from Fig. 1) is a lower limit. Estimates of the integrated fluxes in components A, B, and C are rendered difficult due to both the presence of the extended emission and blending obvious on Figure 1. Consequently, we only quote peak flux densities of components A, B, and C measured in our 0.5 beam in Table 1.

3.2. Line Measurements near 220 GHz

Compared to previous, similar observations, our data have much-improved sensitivity and angular resolution and thus allow a new discussion of the molecular line emission distribution in the W3(OH) region. The observations discussed in Wyrowski (1997) clearly showed that there is a dichotomy between oxygen-containing molecules related to methanol (essentially methyl formate and dimethyl ether) and nitrogen-containing species such as ethyl and vinyl cyanide. The former are seen both toward the UC H ii region and the water masers, whereas the latter are only seen toward the water masers. This is shown with improved angular resolution in Figure 2, in which we compare naturally weighted integrated intensity maps of lines detected near 220 GHz from a variety of species. We note in particular the fact that the 24-23 transition of CH$_3$CH$_2$CN and the 24-23 transition of HC$_3$N (respectively 135 and 772 K above ground) peak precisely in the direction of continuum component C and are not detected toward the H ii region. In contrast, the transitions which we detect from CH$_3$OH, HCOOCH$_3$, and H$_2$CO are seen both toward the ionized gas and toward the water maser concentration. The similarity of the intensity distributions in all three cases suggests a chemical link between these molecules as indeed discussed by Blake et al. (1987) in the context of Orion. Finally, we note the curious behavior of the 22-21 transition of SO$_2$ which, in contrast to, e.g., CH$_3$OH, is seen toward the eastern rather than the western border of the H ii region.

We also detected the $K_a$ = 0, 2, 3, and 4 components of the $J$ = 10–9 HNCO transitions at excitations of 50–750 K above ground. The relative populations of these levels is thought to be determined by a combination of collisions and radiative transitions induced by the FIR radiation field within the hot cores (Churchwell et al. 1986). We have attempted to use the relative intensities of these lines as a “thermometer” measuring the temperature of the hot core by assuming, first, that all transitions are optically thin (which is justified by the fact that the $K_a = 0$ line has a brightness temperature of less than 20 K) and, second, that the level populations are maintained by the radiation temperature of the dust. Since the dust is optically thick at the HNCO FIR pump wavelengths of 50–330 μm, the

![Fig. 2. Integrated intensity maps (contours, velocity windows of 10–20 km s$^{-1}$) of the principal species detected in the 220 GHz band: (from the top) CH$_3$CH$_2$CN 24, $v_2$=23, $v_1$=2, 24–23, CH$_3$OH $5_1$–$4_2$, HCOOCH$_3$, $18_1$–$17_1$, H$_2$CO $9_1$–$8_2$, and SO$_2$ $22_1$–$21_2$ superposed on the 220 GHz continuum (see Fig. 1) in gray scale. Contour units are steps of 20% of the peak emission. The continuum peaks A, B, and C (Fig. 1) are marked by triangles. Position offsets are relative to the phase center position given in § 2.](image-url)
radiation temperature equals the dust temperature. We thus estimate rotational temperatures as a function of position over the water maser source. In practice, the derived level column densities are consistent with a single rotational temperature at each point and allow us (assuming LTE) to infer the dust (and gas) temperature. The resulting temperature map is shown in Figure 3, where one sees that there are two 200 K peaks roughly coincident with our continuum peaks A and C. Between these there is a “plateau” where the temperature is of order 150 K. We interpret this as evidence that there are two energy sources (young proto-B stars) embedded in the molecular gas whose positions are roughly defined by the temperature peaks and which are responsible for the centimeter emission.

Moreover, we can use the temperature distribution thus derived to deduce the dust and, thus, the hydrogen column density distribution from our continuum map. The resulting hydrogen column density map is also shown in Figure 3, in which the resulting gas distribution appears to be single-peaked and extended with dimensions of 0.02 × 0.01 pc. Using the formula given by Mezger, Wink, & Zylka (1990), we calculate a total mass of 15 $M_\odot$ for this structure. Thus, the triple-peaked appearance of our continuum map (Fig. 1) is caused by an interplay of the temperature and column density distributions. This interpretation is supported by our C$^{18}$O (2–1) integrated intensity distribution (Fig. 3), which has the same general form as our hydrogen column density map but is more sensitive to cooler material further from the embedded stars.

4. DISCUSSION AND CONCLUSIONS

Our new 220 GHz interferometer data suggest the presence of two embedded young stars lying slightly offset from the center of the gas clump associated with the water maser complex close to W3(OH). The mass of high-temperature gas in the region is of order 15 $M_\odot$, although our C$^{18}$O map makes it clear that there is more cooler gas at larger distances from the protostars. The luminosity of the hypothesized embedded stars coincident with positions A and C can be crudely inferred from the observed temperature distribution (Fig. 3) by applying the Stefan-Boltzmann law. This way we find $3 \times 10^4 L_\odot$ for the gas clump with a factor of 3 uncertainty due to temperature errors. This (Panagia 1973) suggests embedded B0 stars. It is of course likely that there are other lower mass objects associated with the complex, and it is possible that there is more mass in stars than in gas.

Finally, we note that perhaps the most remarkable result of this study has been the coincidence of continuum source A with the “synchrotron jet” of Wilner et al. (1999). What is the significance of this? It seems reasonable that the dense hot core gas plays a role in confining the “jet.” The magnetic pressure of the medium in which the relativistic electrons radiate $B^2/(8\pi) \sim 4 \times 10^{-6}$ ergs cm$^{-3}$; Reid et al. 1995] is of the same order as the thermal pressure in the molecular gas for a density of $10^7$ cm$^{-3}$, and thus such confinement seems feasible. The origin of the relativistic electrons is unclear, but there are analogous cases known. An example is the jet in Cepheus A (Garay et al. 1996), whose radio emission is thought to be produced in shocks resulting from the interaction of the jet with the confining medium. The explanation in the case of W3(OH) may be similar.

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![Figure 3](image-url)