G24.78+0.08: A cluster of high-mass (proto)stars

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Abstract. We present the results of high angular resolution observations at millimeter wavelengths of the high-mass star forming region G24.78+0.08, where a cluster of four young stellar objects is detected. We discuss evidence for these to be high-mass (proto)stars in different evolutionary phases. One of the sources is detected only in the continuum at 2 and 2.6 mm and we suggest it may represent a good candidate of a high-mass protostar.

Key words. stars: formation – radio lines: ISM – ISM: jets and outflows – ISM: individual objects: G24.78+0.08

1. Introduction

High-mass stars are usually defined as stars with mass above ~8 M☉: for zero-age main sequence (ZAMS) objects, this corresponds to a luminosity ≥ 5×10⁴ L☉ and a spectral type earlier than B3. Such a definition is based on a basic theoretical result (Palla & Stahler 1993): unlike their low-mass equivalents, protostars with masses above 8 M☉ are expected to evolve on timescales much shorter than those relevant to accretion. As a consequence, they reach the ZAMS still deeply embedded in their parental clouds. Consequently, the dusty parental cocoon makes difficult to observe the newly born stars which can be studied only in the IR or at longer wavelengths. Moreover, massive stars form in clusters, which not only complicates the studies of each single young stellar object (YSO), but also profoundly affects the surrounding environment: copious production of Lyman continuum photons eventually leads to the destruction of the parental cloud thus making impossible to trace back the formation process.

Notwithstanding these difficulties, in recent years much progress has been done to identify earlier and earlier stages in the evolution of massive stars (see e.g. Kurtz et al. 2000). This eventually resulted in a scenario according to which high-mass star formation would proceed in dense, massive cores, with W3(OH) (Turner & Welch 1984), whereas W3(H2O) group in G24.78+0.08 with the isolated H2O group in G24.78+0.08. To this purpose, both OH and H2O masers, whereas the other, offset by ~8” to the NE, contains only H2O masers. Both groups are embedded in a ~0.5 pc clump traced by the ammonia emission. This situation resembles very closely that of the W3(H2O)/W3(OH) system, where a high-mass YSO has been found in association with W3(H2O) (Turner & Welch 1984), whereas W3(OH) coincides with an UC Hα region created by an early-type star. We have hence decided to search for a possible source associated with the isolated H2O group in G24.78+0.08. To this purpose, we have studied the continuum and line emission from this region at various wavelengths. The basic results are illustrated in the following, while a more detailed description is postponed to a subsequent paper.

2. Observations

In 1998–2002, we carried out continuum emission imaging using the Nobeyama Millimeter Array (NMA) at 2 mm, the Plateau de Bure interferometer (PdBI) at 2.6 mm, and
3. Results and discussion

Our main findings are illustrated in Figs. 1 and 2. The former shows the maps of the continuum emission from 2 to 7 mm and the integrated intensity map of the CH$_3$CN(8–7) line for CTC. Also shown are the positions of the OH and H$_2$O maser spots from Forster & Caswell (1999) and those of the CH$_3$OH masers from Walsh et al. (1998). The most important result is the detection of four separate sources, which are best seen in the 2 mm continuum map: these have been identified with letters A to D. Of these, A and B were already detected by CTC and are associated with two compact H$_2$ regions (see also Forster & Caswell 2000). Source C is seen in the mm continuum and CH$_3$CN line maps; this confirms our expectation that the H$_2$O masers to the NE were associated with a compact molecular core. A surprising result is the detection at 2 and 2.6 mm of a continuum peak, D, to the NW of the UC H$_2$ region in A. This must trace a compact dusty core, which is not detected in any of the molecular lines observed; such a lack of line emission may be indicative of molecular depletion and hence high density and low temperature.

Figure 2 presents maps of the blue- and red-shifted emission in the wings of the $^{12}$CO(1–0) line: these reveal two bipolar outflows centred on A and C. It is thus likely that one of the flows originates from the early-type star ionising the UC H$_2$ region in A, while the other may be powered by a deeply embedded YSO in C. The parameters of the outflow can be derived as usual by integrating the emission under the line wings and assuming an age equal to the kinematical time scale ($2 \times 10^4$ yr) given by the ratio between the size of the lobes (0.45 pc) and the maximum velocity reached in the flow (20 km s$^{-1}$): we find very similar values for both outflows, corresponding to masses.
of \( \sim 10 \, M_\odot \), mechanical luminosities of \( \sim 10 \, L_\odot \), and mass loss rates of \( \sim 5 \times 10^{-4} \, M_\odot \, \text{yr}^{-1} \). Such values are to be taken as lower limits, as the \(^{12}\text{CO}\,(1\rightarrow 0)\) line may be optically thick and the lobes might extend over a larger region than that imaged by the interferometer. Also, correcting for the (unknown) inclination of the outflow axis would increase the real velocity and hence the mass loss rate and mechanical luminosity. We conclude that the values quoted above are typical of high-mass stars, as one can see e.g. from Table 1 of Churchwell (1997).

Finally, it is worth noting that the two outflow axes are parallel to the direction outlined by the maser spots: this result leads support to the belief that \( \text{H}_2\text{O} \) masers could be strongly associated with outflows (see Felli et al. 1992), as already pointed out by CTC.

Three cores (A, C, D) and two compact H\( \text{ii} \) regions (A and B) are seen towards G24.78. The letters identify each spectrum according to the notation in Fig. 1. The lines are fits to the data obtained according to the model described in the text and for the parameters listed in Table 1.

Of the \( \lambda \approx 2 \, \text{mm} \) thermal emission from the dust, we estimated the emission measure (EM) of the H\( \text{ii} \) region and the mass of the cores in A and C: in the other cases only lower limits can be set. The fit parameters are given in Table 1. For core D we have assumed a maximum temperature equal to that of core C. Although such an assumption is arbitrary, it seems unlikely that the gas is hotter, otherwise one would expect to detect line emission from molecules evaporated from grain mantles: as discussed above, such emission is not seen at the same level as in A and C.

### Table 1. Parameters for the fits in Fig. 3. An electron temperature of \( 10^4 \, \text{K} \) and a distance of 7.7 kpc have been assumed.

<table>
<thead>
<tr>
<th>Source</th>
<th>( R_{\text{HII}} ) (pc)</th>
<th>( EM ) (pc , cm(^{-6} ))</th>
<th>( T_{\text{dust}} ) (K)</th>
<th>( M_{\text{core}} ) (( M_\odot ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.005(^{(*)})</td>
<td>2.10(^{9} )</td>
<td>90(^{(*)})</td>
<td>550</td>
</tr>
<tr>
<td>B</td>
<td>0.05(^{(*)})</td>
<td>6.5 \times 10^{6}</td>
<td>90(^{(*)})</td>
<td>\leq 40</td>
</tr>
<tr>
<td>C</td>
<td>\textless 0.005(^{(*)})</td>
<td>\textgreater 9 \times 10^{6}</td>
<td>30(^{(*)})</td>
<td>250</td>
</tr>
<tr>
<td>D</td>
<td>\textless 0.005(^{(*)})</td>
<td>\textless 7.5 \times 10^{6}</td>
<td>\textless 30(^{(*)})</td>
<td>\textgreater 100</td>
</tr>
</tbody>
</table>

\(^{(*)}\) Derived by CTC.

\(^{(*)}\) No \( T_{\text{dust}} \) estimate: same temperature as in A assumed.

\(^{(*)}\) Upper limit assumed equal to diameter of H\( \text{ii} \) region in A.

\(^{(*)}\) Assumed equal or less than the temperature of core C.

### Fig. 2. Overlay of the 2 mm continuum image (grey scale) with the outflow maps (contours) obtained by integrating the \(^{12}\text{CO}\,(1\rightarrow 0)\) line emission under the wings, from 90 to 105 km \, s\(^{-1} \) (full contours) and from 116 to 131 km \, s\(^{-1} \) (dashed contours). The cloud LSR velocity is \( \sim 111 \, \text{km} \, \text{s}^{-1} \). Contour levels correspond to 1.1, 1.4, and 1.7 Jy/beam (dashed contours) and 0.4, 0.6, 0.8, 1.2, and 1.6 Jy/beam (full contours). Symbols and letters have the same meaning as in Fig. 1.

### Fig. 3. Spectrum of the continuum emission of the four objects detected towards G24.78+0.08. The letters identify each spectrum according to the notation in Fig. 1. The lines are fits to the data obtained with the model described in the text and for the parameters listed in Table 1.

### 4. Nature of the sources and evolutionary sequence

In the light of the previous results, we can now discuss the nature of the four sources, whose properties are schematically summarised in Table 2.
Table 2: Characteristics of the four objects observed.

<table>
<thead>
<tr>
<th>YSO</th>
<th>D</th>
<th>C</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dusty Core (mm cont.)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Molecular Core (NH₃, CH₃CN)</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Bipolar Outflow (¹²CO)</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>H₂O masers</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>CH₃OH masers</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>OH masers</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>UC H₂ region (cm free-free)</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

destroying the densest portion of the molecular surroundings. The ionising star is hence relatively old, although less than \(10^5\) yr, the expected life time of UC H₂ regions (Wood & Churchwell 1989).

A The UC H₂ region is unresolved at 1.3 cm (CTC) and deeply embedded in a dense molecular core, as witnessed by the absorption detected in the NH₃(2, 2) and (3, 3) lines. The compactness of the ionised region, the temperature and mass of the surrounding core, the existence of a bipolar outflow, the strong emission in rare molecules such as CH₃CN, the presence of maser emission in various species all indicate that we are dealing with a young early-type ZAMS star strongly interacting with the surrounding environment and in an earlier evolutionary phase than the star in B.

C The basic difference with respect to A which suggests a younger age for C is represented by the absence of an UC H₂ region toward C even though the large mass of the molecular core, the outflow parameters, and the detection of hot core species such as CH₃CN are all typical of high-mass YSOs. This conclusion is also supported by the fact that C, unlike A, harbours only H₂O maser emission: the common belief is that H₂O masers should appear at a very early stage of the evolution of a high-mass star, which also suggests that C is younger than A. Further evidence in favour of C being associated with massive YSOs is represented by the large mass of the core, \(~250 M_☉\). In fact, such a mass is comparable to that of cores hosting high-mass YSOs (see Table 1 of Kurtz et al. 2000); moreover, it is contained in 0.07 pc and is \(~6\) times greater than that (40 \(M_☉\) over 0.2 pc) of the low-mass star forming clumps observed by Testi et al. (1998) in the Serpens region. Therefore, it is unlikely that we are observing a low-mass star forming core.

D This is the most intriguing object, as it is traced only by the millimeter continuum emission and is not detected in any molecular species (CO, CH₃CN, NH₃). One cannot rule out the possibility that this is a quiescent core without star formation. However, this is hard to believe given the large value of the mass, \(>100 M_☉\); as already discussed for C, values such large are not appropriate for low-mass star forming cores.

In conclusion, we have detected a cluster containing at least 4 high-mass YSOs, in different evolutionary phases. More precisely, the ages of these YSOs are likely to be in the order \(t_B > t_A > t_C > t_D\). We suggest that core D represents an excellent candidate for a high-mass protostar.

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References