Circumbinary Molecular Rings Around Young Stars in Orion

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ABSTRACT

We present high angular resolution 1.3 mm continuum, methyl cyanide molecular line, and 7 mm continuum observations made with the Submillimeter Array and the Very Large Array, toward the most highly obscured and southern part of the massive star forming region OMC1S located behind the Orion Nebula. We find two flattened and rotating molecular structures with sizes of a few hundred astronomical units suggestive of circumbinary molecular rings produced by the presence of two stars with very compact circumstellar disks with sizes and separations of about 50 AU, associated with the young stellar objects 139-409 and 134-411. Furthermore, these two circumbinary rotating rings are related to two compact and bright hot molecular cores. The dynamic mass of the binary systems obtained from our data are $\geq 4 M_\odot$ for 139-409 and $\geq 0.5 M_\odot$ for 134-411. This result supports the idea that intermediate-mass stars will form through circumbinary disks and jets/outflows, as the low mass stars do. Furthermore, when intermediate-mass stars are in multiple systems they seem to form a circumbinary ring similar to those seen in young, multiple low-mass systems (e.g., GG Tau and UY Aur).

Key words. stars: pre-main sequence – ISM: jets and outflows – ISM: individual: (Orion-S, OMC1-S, Orion South, M42) – ISM: Molecules, Radio Lines – ISM: Circumstellar Disks – ISM: Binary stars – ISM: Circumbinary Disks –

1. Introduction

About thirty years ago a new major puzzle emerged in the field of stellar astrophysics: How do massive stars form?, where massive stars are those with more than 10 $M_\odot$ (Kahn 1974; Larson & Starrfield 1971; Yorke & Kruegel 1977). It was believed that the powerful radiation fields and stellar winds produced at the very beginning of their lives will inhibit accretion of material limiting their mass growth to about 10 $M_\odot$. In the two last decades, several alternatives have been proposed to solve this puzzle. Among the most important are the formation of massive stars through dense disks and jets/outflows (Nakano 1989; Jijina & Adams 1996), in very dense and turbulent cores (McKee & Tan 2002), through the merging of smaller stars (Bonnell et al. 1998), and through ionized accretion flows that forms an ionized disk or torus around a group of stars (Sollins et al. 2005; Keto & Wood 2006). Discriminating between these alternatives remains an observational challenge (Cesarini et al. 2007).

OMC1S or Orion-S is the “twin” dusty massive molecular core of the Orion BN-KL core. It is located almost at the same angular distance from the “Trapezium” as Orion BN-KL ($\sim 1'$), but to the southwest of the former. We adopt a distance of 460 pc to the Orion Nebula (Bally et al. 2000). The OMC1S region has a mass of about 100 $M_\odot$ similar to that reported for BN-KL (Mezger et al. 1990), but with a bolometric luminosity of $\sim 10^4 L_\odot$, which is a factor of 10 less (Mezger et al. 1990; Drapatz et al. 1983). This difference in luminosity might be attributed to OMC1S being less evolved than Orion BN-KL, as inferred if one compares the molecular line emission from both regions (McMullin et al. 1993). With time, the massive stars forming in OMC1S might reach their final masses and shine with much larger luminosity than now. This possible evolutionary scheme has been also suggested to be taking place in the NGC6334I region (Rodríguez, Zapata & Ho 2007).

In this letter we report for the first time the possible presence of two circumbinary molecular rotating rings located in the OMC1S region with sizes of a few hundred Astronomical Units (AU) around two very compact circumstellar disks and that are associated with intermediate-mass (proto)stars.

2. Observations

The observations were made with the Submillimeter Array (SMA\textsuperscript{1} and the Very Large Array (VLA\textsuperscript{2} during 2004 September 2 and November 10, respectively.

The SMA was in its extended configuration, which includes 21 independent baselines ranging in projected length from 16 to 180 m. The phase reference center of the observations was R.A. = 05°35'14'', decl. = -05°24'00'' (J2000.0). The receivers were tuned at a frequency of 230.534 GHz in the upper sideband (USB), while the lower sideband (LSB) was centered at 220.53 GHz. The CH$_3$CN[12$\nu$-11$\nu$] transition was detected in

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Fig. 1. SMA 1.3 mm continuum color image of the southern most region of OMC1S (from Zapata et al. 2005), overlaying on the CH$_3$CN[12-11] integrated molecular emission of the hot molecular cores 139-409 and 134-411 (white contours). The contours of the CH$_3$CN[12-11] integrated molecular emission are -5, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 times 120 mJy beam$^{-1}$ km s$^{-1}$, the rms noise of the image. The integration is over a velocity range of -5 to +17 km s$^{-1}$. The millimeter sources 139-409, 134-411, 132-413, 135-409 and 137-408 were reported for the first time by Zapata et al. (2005). The synthesized beam of the CH$_3$CN image is 1.13$''$ x 0.93$''$ with a P.A. = -73$^\circ$ and it is shown in the upper left corner. The scale bar indicates the 1.3 mm continuum emission in mJy beam$^{-1}$. The yellow rhombi indicate the positions of the 7 mm continuum compact radio binaries. The green rhombus and triangle denote the position of the source FIR 4 (Mezger et al. 1990) and the millimeter source CS 3 (Mundy et al. 1986), respectively. The blue and red crosses indicate the position of the blue- and red-shifted H$_2$O maser spots, respectively, reported by Gaume et al. (1998). Note that the masers associated with the hot molecular core (134-411) show a large velocity gradient, going from -20 to +45 km s$^{-1}$. The green `X' symbols indicate the position of the 3 mm BIMA continuum sources reported by Eisner & Carpenter (2006). In the left bottom and right upper corners we show the 7 mm continuum compact radio binaries located on the centers of the hot cores 139-409 and 134-411. The scale bar indicates the 7 mm continuum emission in 10$^{-3}$ mJy beam$^{-1}$ on both images. In the left bottom corner box the contours are -2, 2, 3, 4, 5, 6, 7, 8, 9 times 0.15 mJy beam$^{-1}$, the rms noise of the image. In the right upper corner box the contours are -2, 2, 3, 4, 5, 6, 7, 8, 9 times 0.15 mJy beam$^{-1}$, the rms noise of the image. The synthesized beam is shown in the bottom left corner of each box. The sizes of these boxes are 0.6$''$ x 0.6$''$.

3. Results and Discussion

3.1. 1 mm Continuum and Molecular Emission

In Figure[1] we have overlayed the SMA 1.3 mm continuum image from Zapata et al. (2005), with the integrated CH$_3$CN[12-11] emission in the southern, most obscured part of OMC1S. Furthermore, we have also included on this image the positions of the water maser spots from Gaume et al. (1998), the positions of the strong 3 mm continuum and FIR sources located here (Mezger et al. 1990, Mundy et al. 1986, Eisner and Carpenter 2006), and the positions of the 7 mm binary systems associated with the sources 139-409 and 134-411.

In this image, we can see five 1.3 mm continuum sources (139-409, 137-408, 136-409, 134-411, and 132-413), but with only two sources (139-409 and 134-411) showing very compact CH$_3$CN[12-11] emission. Some of these continuum sources (139-409, 137-408, 134-411 and 132-413) are the 1.3 mm counterparts of the 3.6 cm, 1.3 cm and 3 mm sources reported by Eisner & Carpenter (2006) and Zapata et al. (2004a, 2004b) and which are interpreted as UC HII regions, ionized thermal jets and/or massive circumstellar disks. The 139-409 and 134-411 sources show strong compact molecular emission also in different lines (e.g. series of CH$_3$CN, CH$_3$OH, SO$_2$, $^{34}$SO, H$_2$CO, etc), and are thus related with two bright, very compact hot molecu-
lar cores associated with intermediate-mass stars (Zapata et al., in prep.).

The CH$_3$CN[12$+_{-1}$11$_{-4}$] line molecular emission associated with the source 139-409 has a deconvolved size of 0$'$.64 ± 0$'$.03 × 0$'$.45 ± 0$'$.04 (or 294 AU ± 14 AU × 207 AU ± 18 AU) with a P.A.of 87° ± 7°, while the molecular emission associated with the source 134-411 has dimensions of 0$'$.36 ± 0$'$.07 × ≤ 0$'$.33 (or 166 AU ± 32 AU x ≤ 151 AU) with a P.A.of 116° ± 10°.

The CH$_3$CN[12$+_{-1}$11$_{-4}$] molecular emission shows a total velocity shift of 5 km s$^{-1}$ for the object 139-409 and of 2.5 km s$^{-1}$ for the object 134-411 and if one assumes that this molecular gas is rotating in a Keplerian way and uses the deconvolved sizes of the molecular structures presented above, we calculated a lower limit for the mass of the central objects shown in Table 1. Since these are lower limits, we think that the binaries at the center of these circumstellar disks are formed by intermediate-mass stars. The velocity gradients in both objects were determined from a simultaneous Gaussian fitting to the CH$_3$CN transition. The blue circles and red crosses indicate the position of the blue- and red-shifted H$_2$O masers, as in Figure 2).

3.2. 7 mm Continuum Emission

The sources 139-409 and 134-411 in the 7 mm continuum observations were resolved into two compact binary systems with separations and sizes of about 50 AU (see Figure 1) that are interpreted as very compact circumstellar disks. The small size of these disks might be explained as tidally truncated disks as those observed in the L1551 IRS5 system (Rodríguez et al. 1998). In the case of 134-411 the orientation of the H$_2$O masers is very close to that observed for the circumstellar molecular disk (see Figure 2), suggesting that maybe these masers are either associated with it. However, the velocity gradient observed in the masers is too large to be explained in terms of Keplerian rotation.

From the millimeter observations of Zapata et al. (2005) and the 7 mm continuum observations presented here, we calculate that the sources 139-409 and 134-411 have average spectral indices of 2.6 ± 0.3 and 2.7 ± 0.3, respectively. We then suggest that at 7 and 1.3 mm we are observing optically thin dust emission with a dust mass opacity coefficient that varies with frequency as $k \propto \nu^{0.6}$ and $k \propto \nu^{0.7}$ (suggesting grain growth). With this information we can estimate the enclosed masses of the 7 mm sources. Assuming optically thin, isothermal dust emission and a gas-to-dust ratio of 100 (Sodroski et al. 1997) and an adopted value of $k_{1,3mm} = 1.5$ cm$^2$ g$^{-1}$ (and then $\kappa_{7mm}$ equal to 0.46 for 139-409 and 0.54 cm$^2$ g$^{-1}$ for 134-411), and a typical dust temperature value of 100 K, we derive total enclosed masses for those putative circumstellar disks that are shown in Table 1. From the results of this Table we conclude that the masses of these systems are dominated by the stellar components, with the disks contributing with masses of order 0.1 $M_\odot$. We also note that the mass associated with the circumbinary disks is comparable with that associated with the circumstellar disks (see Table 1).

3.3. Two Circumbinary Molecular Rings?

Since the CH$_3$CN molecule is a high-density tracer (Cesaroni et al. 1999), the elongated structures traced by this molecule in

Table 1. Physical Parameters of the Circumbinary Rings

| Name       | R.A.  | Dec.  | Deconv. Radius | Rot. Vel. | Mass          |
|------------|-------|-------|----------------|-----------|---------------|
|            | [J2000] | [J2000] | [AU]           | [km s$^{-1}$] | [M$_{\odot}$] |
| 139-409    | 05 35 13.912 | -05 24 09.40 | 147 ± 7   | 5       | ≤ 0.4 (0.08) |
| 134-411    | 05 35 13.394 | -05 24 11.15 | 83 ± 16  | 2.5     | >0.5 (0.12)  |

The Circumstellar Disks

| Name       | R.A.  | Dec.  | Flux Density | Undeconv. Radius | Mass of the Gas$^a$ |
|------------|-------|-------|-------------|------------------|---------------------|
|            | [J2000] | [J2000] | [mJy]       | [AU]             | [M$_{\odot}$]       |
| 139-409a   | 05 35 13.928 | -05 24 09.41 | 2.5 ± 0.3 | 25 | 0.05 |
| 139-409b   | 05 35 13.933 | -05 24 09.47 | 3.2 ± 0.5 | 20 | 0.06 |
| 134-411a   | 05 35 13.406 | -05 24 11.33 | 3.3 ± 0.5 | 25 | 0.06 |
| 134-411b   | 05 35 13.412 | -05 24 11.22 | 3.2 ± 0.5 | 25 | 0.06 |

(a): The masses of the gas were obtained assuming a dust temperature value of 100 K, an adopted value of $k_{1,3mm} = 1.5$ cm$^2$ g$^{-1}$ (the average of the values of 1.0 cm$^2$ g$^{-1}$, valid for grains with thick dust mantles, and 2.0 cm$^2$ g$^{-1}$, valid for grains without mantles) and the flux densities at 1.3 mm of 180 mJy for 139-409 and of 270 mJy for 134-411.
This kind of structures appear to be tidally stimulated during the UY Aur (Guilloteau, Dutrey, & Simon 1999; Duvert et al. 1998). The horizontal lines indicate the position of the center of each source, while the vertical lines indicate the systemic velocity of the cloud. The systemic LSR radial velocity of the ambient molecular cloud is about 7 km s\(^{-1}\). Note the velocity gradients shown by the white lines. In the top image the contours are 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20, 22, and 24 times 120 mJy beam\(^{-1}\), the rms noise of the image. In the bottom image the contours are 2, 3, 4, 5, 6, 7, 8, 9, and 10 times 120 mJy beam\(^{-1}\), the rms noise of the image. Note that our spectral resolution is comparable with the linewidth of the CH/CN transition.

139-409 and 134-411 suggest two flattened circumbinary molecular rings observed in nearly edge-on. Moreover, the first moment of the CH\(_3CN\)[12-11] emission shows a total velocity gradient of about a few kilometers per second that seems to be aligned with the major axes of both structures, supporting also this interpretation (see Figure 2). We note that the two 7 mm sources are aligned along the velocity gradient in 139-409, but perpendicular to it in 134-411. One might speculate that the former ring is almost edge-on, whereas the latter could be significantly inclined with respect to the line of sight. In fact, if the binary system is coplanar with the ring and seen edge-on, the two stars must appear along the direction of the velocity gradient; instead, if the ring is inclined, the projections of the two stars on the plane of the sky may appear along any direction. The fact that the velocity gradient is much less in 134-411 than in 139-409 is consistent with this interpretation. Finally, in Figure 3 we show that the kinematics of the molecular gas in both cores, as computed along the major axes, seems to be consistent with a "rigid body law". This kinematic behavior also suggests that the molecular gas in both flattened structures seems to be only in a rotating ring.

Those molecular ring-shaped circumbinary structures have been also observed in low-mass young stars, e.g. GG Tau and UY Aur (Guilloteau, Dutrey, & Simon 1999; Duvert et al. 1998). This kind of structures appear to be tidally stimulated during the formation of binary or multiple systems of stars at its center. When a multiple system is formed the very compact circumstellar disks associated with the protostars clean its vicinity (or the innermost part of the large circumbinary disk) forming thus a circumbinary ring around them (Mathieu et al. 2000). This circumbinary ring might not transfer material to the compact circumstellar disks anymore, however, see Monin et al. (2006) for a more detail discussion of this phenomenon.

It is interesting to note that much larger molecular rotating structures have also been observed around multiple OB (proto)stars (Torrelles et al. 1983; Beltrán et al. 2005; Sollins et al. 2005). However, contrary to these circumbinary rings, these molecular structures (also known as "toroids") seem to be transient and in non-gravitational-equilibrium (Beltrán et al. 2005).

In conclusion, we interpret the flattened molecular structures associated with the sources 139-409 and 134-411 as two circumbinary rings around binary systems traced by very compact 7 mm circumstellar disks associated with young intermediate-mass (proto)stars. However, we believe that more observations with higher angular and spectral resolution are necessary to confirm our interpretation. Finally, this result supports also the idea that intermediate-mass stars form through circumstellar disks and jets/outflows, as the low mass stars do.

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