High-resolution mm interferometry and the search for massive protostellar disks: the case of Cep-A HW2

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Abstract The direct detection of accretion onto massive protostars through rotating disks constitutes an important tile in the massive-star-formation-theory mosaic. This task is however observationally very challenging. A very interesting example is Cepheus A HW2. The properties of the molecular emission around this YSO seems to suggest the presence of a massive rotating disk (cf. Patel et al. in Nature 437:109, 2005). We have carried out sub-arcsec-resolution PdBI observations of high-density and shock tracers such as SO\(_2\), SiO, CH\(_3\)CN, and CH\(_3\)OH towards the center of the outflow. A detailed analysis of the spatial distribution and of the velocity field traced by all observed species leads us to conclude that, on a \(\sim 700\) AU scale, the Cep-A “disk” is actually the result of the superposition of multiple hot-core-type objects, at least one of them ejecting an outflow at a small angle with respect to the line of sight. Together with the well-known large-scale outflow ejected by HW2, this setup makes for a very complex spatial and kinematic picture.

Keywords High-mass star formation · Millimeter-wavelength radioastronomy · Millimeter interferometry · High-mass disks

1 Introduction

Several theories are being considered to explain the formation of massive \((M \geq 8\ M_\odot)\) stars, which can be roughly grouped into accretion-driven and coalescence-driven models (cf. Stahler et al. 2000). In the latter case, high-mass stars would form by merging of two or more lower-mass objects, making the presence of stable massive accretion disks around the protostar very unlikely. However, only models based on disk-protostar interactions are capable of explaining the existence of jets and outflows: hence, the high incidence, in large samples of massive YSOs, of long, collimated outflows (cf. Beuther et al. 2002) has been interpreted as indirect evidence for the existence of high-mass disks.

It is undoubted that the direct detection of accretion onto massive protostars through rotating disks constitutes an important tile in the massive-star-formation-theory mosaic. From an observational point of view, this task is mainly made difficult by two factors: (i) massive star-forming regions typically are far away, a few kpc on average, making the direct observation of small-scale structure such as disks virtually impossible with current instruments; and (ii), massive stars form in clusters, making the surrounding region extremely complex, both spatially and kinematically.

Although claims of the existence of rotating disks around massive protostars have become popular in the literature, to our knowledge only the case for IRAS 20126+4104 has been convincingly made (cf. Cesaroni et al. 1997, 2005; Zhang et al. 1998; Edris et al. 2005; Sridharan et al. 2005). Cepheus A is also considered a very promising candidate for the detection of a massive disk. Its well-studied bipolar outflow (cf. Gómez et al. 1999, hereafter G99, and references therein) is thought to be powered by the radio-continuum source HW2 \((\sim 10^4\ L_\odot)\), Rodríguez et al. 1994). The distribution of H\(_2\)O masers (Torrelles et al. 1996, hereafter T96) and of the
SiO emission (G99) around HW2, both oriented perpendicularly with respect to the direction of the flow, have been interpreted as strongly supporting the existence of accretion shocks onto a rotating and contracting molecular disk of \( \sim 700 \) AU diameter, centered on HW2, with the outflow being triggered by the interaction between such disk and HW2 itself. The relative small distance of this region from the Sun (\( \sim 725 \) pc, Johnson 1957) could allow such rotating object to be resolved with interferometric techniques. However, the G99 data did not have enough spatial and spectral resolution to establish a kinematical proof of a disk, and the water masers in T96 share the ambiguity of most similar studies about what the masers actually trace. Based on SMA observations of CH$_3$CN and dust emission, Patel et al. (2005) have recently claimed the presence of an 8 $M_{\odot}$ rotating disk, accreting onto HW2, and extending for about 330 AU around the protostar. Our PdBI observations do not support this interpretation: our conclusion is that, on the 1” scale, the Cep-A “disk” is actually the superposition of at least three different hot-core-type sources, at least one of them being the exciting source for a second molecular outflow.

### 2 Observations

In 2003 and 2004, with the Plateau de Bure Interferometer in AB (extended) configuration, we have carried out observations of high-density and shock tracers, such as SO$_2$, SiO, CH$_3$CN, CH$_3$OH, H$_2^{15}$O and HDO towards the HW2 position ($\alpha_{2000} = 22$ h 56 m 17.9 s, $\delta_{2000} = +62^\circ 01^\prime 49.6''$). High-spectral-resolution correlator units were employed to achieve a channel width of up to $\sim 0.3$ km s$^{-1}$. A list of some of the observed transitions and beam sizes can be found in Table 1.

### 3 Results

Figure 1 (upper panel) shows the inner $\sim 2800$ AU of the Cep-A HW2 star-forming region. The peak of the 241 GHz dust emission (grey scale) coincides with the HW2 position and with the center of the large-scale outflow. The integrated CH$_3$CN emission is also centered on HW2 (contours), and somewhat elongated almost perpendicularly to the direction of the large-scale outflow.

Like other molecular tracers (cf. Comito et al. 2007; Schilke et al. 2007), CH$_3$CN displays two different velocity components, centered at $\sim -5$ and $\sim -10$ km s$^{-1}$ respectively. The solid contours in Fig. 1, lower panel, show the emission of the CH$_3$CN(12-11) transition, integrated between $-7$ and $-3$ km s$^{-1}$, whereas the emission in the range between $-11.5$ and $-7.5$ km s$^{-1}$ is represented by the dashed contours (see Sect. 3.2).

### Table 1 Summary of observed transitions

| Transition      | Frequency (GHz) | HPBW     |
|-----------------|-----------------|----------|
| SiO(2-1)        | 87              | 2” × 1”6 |
| HCN(1-0)        | 89              | 1”9 × 1”8 |
| H$_2^{15}$O(3,1-2,0) | 203         | 1”7 × 0”8 |
| SO$_2$(12-11)   | 203             | 1”7 × 0”8 |
| $^{13}$CO(2-1)  | 220             | 0”9 × 0”7 |
| CH$_3$CN(12-11) | 220             | 0”9 × 0”7 |
| CH$_3$OH(5-4)   | 241             | 0”7 × 0”6 |
| HDO(2,1-2,1)    | 241             | 0”7 × 0”6 |

SiO peaks about 0.3 eastwards of HW2, close to the peak of the $-10$ km s$^{-1}$ CH$_3$CN component. A more detailed discussion on this transition can be found in Sect. 3.1.

In what follows, we will discuss in more detail the analysis of the CH$_3$CN and SiO transitions. Analysis and discussion on the other observed lines will be published in Comito et al. (2007) and Schilke et al. (2007).

### 3.1 SiO

In spite of the relatively low spatial resolution achieved in the imaging of the 89 GHz SiO line, this transition is the key to understand the dataset. Our data confirm that the spatial distribution of this shock tracer is mainly concentrated in the HW2 region (its presence in the large-scale outflow is limited to a few bullets at large distances from the center), although not centered on the HW2 position. This does indeed suggest that shock processes are taking place in the (projected) immediate vicinities of HW2. However, if the SiO emission were arising from accretion shocks onto a rotating disk (as proposed by G99), we would expect to observe a similar velocity structure to that observed for the other molecular tracers peaking around HW2. Instead, SiO seems to be tracing a completely different kinematic structure: unlike any other line in our dataset, the (2-1) line has a velocity spread of $\sim 30$ km s$^{-1}$ at the zero-flux level ($\sim 15$ km s$^{-1}$ FWHM). A mass of about 90 $M_{\odot}$ would be required to produce such large line width in a gravitationally bound environment (assuming virial equilibrium, and that the emission arises in a region of $\sim 350$ AU radius). This value is about one order of magnitude larger than the estimated mass of HW2, which is expected to be a B0.5 star once in ZAMS (Rodriguez et al. 1994).

We carried out a two-dimensional Gaussian fit of the SiO(2-1) spatial distribution for every spectral channel, thus deriving a distribution of the centroids of SiO emission as a function of velocity. As shown in Fig. 1, lower panel, the centroid positions occupy a well-defined two-lobed area, centered about 0.3 eastwards of HW2 and of the dust continuum emission peak. Although the error on every single
Fig. 1 Upper and lower panel: the levels of grey represent the dust emission at 241 GHz. Lowest level is $3.3 \, \text{mJy/beam or } 2\sigma$, highest is $22\sigma$. The HW2 position is indicated by the white star. The solid, crossing lines show the direction of the large-scale outflow, inferred from our PdBI HCN and $^{13}$CO data. The contours trace the CH$_3$CN emission at 220 GHz, and in the top left corner, the HPBW for the dust (grey foreground) and CH$_3$CN (black background ellipse) are shown.

Upper panel: the integrated emission of the CH$_3$CN(12$^3_3$-11$^3_3$) is shown by solid contours. Lower panel: here the $\sim -5$ and $\sim -10 \, \text{km s}^{-1}$ velocity components of CH$_3$CN(12$^3_3$-11$^3_3$) are plotted separately (solid and dashed contours respectively). The dots show the centroid positions for SiO(2-1), blue-shifted on the left, red-shifted on the right lobe. The yellow star between the SiO lobes points to the position of the Martín-Pintado hot-core.

The centroid position is large (up to 30%), as a whole their distribution describes a very clear velocity trend, with all the emission at $v_{\text{lsr}} < -10 \, \text{km s}^{-1}$ clustering in the left lobe, and all the emission at $v_{\text{lsr}} > -10 \, \text{km s}^{-1}$ clustering in the right lobe. This result suggests that a second molecular outflow is being ejected in the HW2 region, at a small angle with respect to the line of sight. Our interpretation is supported by the recent discovery of an intermediate-mass protostar, surrounded by a hot molecular core (Martin-Pintado et al. 2005), at a position which matches perfectly the inferred center position of the SiO outflow (Fig. 1, lower panel), hence a very likely candidate to be its powering engine.

3.2 CH$_3$CN

The upper panel of Fig. 1 shows the distribution of integrated intensity for the CH$_3$CN(12$^3_3$-11$^3_3$) line. Indeed, the dense molecular gas appears to be distributed around the HW2 position, and elongated in a direction roughly perpendicular to the projected direction of the large-scale outflow on the plane of the sky. From a morphological point of view, therefore, the data are very suggestive of the presence of a $\sim 300 \, \text{AU-radius}$ disk-like structure around HW2.

The kinematical picture is more complex. A position-velocity cut along the major axis of the elongated structure (indicated in Fig. 1 with a dashed line) reveals a velocity spread of about $6 \, \text{km s}^{-1}$ (see Fig. 2), also observed by Patel et al. (2005). However, the two intensity peaks along the axis share the same systemic velocity ($\sim -5 \, \text{km s}^{-1}$). The weaker, blue-shifted component of emission ($\sim -10 \, \text{km s}^{-1}$) appears to trace rather the outskirt of a physically separated component than a rotation-induced velocity gradient along the axis of the alleged “disk”. The peak of the $-10 \, \text{km s}^{-1}$ CH$_3$CN emission is spatially and kinematically close to the center of the small-scale SiO outflow (see Fig. 1, lower panel), it may therefore be associated to it and/or to its exciting source.

The CH$_3$CN integrated intensity is dominated by the two $-5 \, \text{km s}^{-1}$ peaks, which lie respectively about 0.6" to the northwest, and 0.5" to the southeast of the HW2 position. In
what follows, we will refer to them respectively as CH$_3$CN-NW and CH$_3$CN-SE. Figure 3 compares the spectra observed towards the two positions. It is clear that, in both cases, both the $-5$ and $-10$ km s$^{-1}$ components are present along the line of sight, although the contribution from the latter is more intense in the CH$_3$CN-SE region, i.e., close to the peak of the $-10$ km s$^{-1}$ SiO emission.

We have assumed LTE approximation to fit the physical parameters associated with the two different velocity components. All transitions in the spectrum are fitted simultaneously, in order to take line blending and optical depth effects properly into account (a detailed description of the method can be found in Comito et al. 2005). At $-5$ km s$^{-1}$, the line intensity ratios of the $k = 0$ through $k = 4$ transitions clearly indicate that these lines are optically thick towards both positions. The data at this velocity can only be reproduced by including a very compact, hot, dense object in the model. The emission centered at $-10$ km s$^{-1}$ can be modeled by a cooler, more extended component. The results of the fit, for the two positions, are summarized in Table 2.

### Table 2

| Source      | $v_{lsr}$ (km s$^{-1}$) | Source size (″) | N(CH$_3$CN) ($\text{cm}^{-2}$) | $T_{rot}$ (K) | $\Delta v$ (km s$^{-1}$) |
|-------------|------------------------|-----------------|-------------------------------|--------------|-------------------|
| CH$_3$CN-NW | $-4.5$                 | $0''3$          | $\sim 3 \times 10^{16}$      | 250          | 2.9               |
|             | $-8.9$                 | $1''$           | $\sim 8 \times 10^{14}$      | 150          | 4.0               |
| CH$_3$CN-SE | $-4.2$                 | $0''25$         | $\sim 3 \times 10^{16}$      | 250          | 3.2               |
|             | $-10.0$                | $0''45$         | $\sim 5 \times 10^{15}$      | 150          | 4.5               |

4 Discussion and open issues

The observed elongation of the molecular gas distribution around HW2, over a radius of $\sim 0''.5$ ($\sim 360$ AU), appears to be due to the projected superposition, on the plane of the sky, of at least two protostellar objects, of which at least one is triggering a molecular outflow at a small angle with respect to the line of sight (Sects. 3.1, 3.2). All lines in our dataset are consistent with this interpretation (cf. Comito et al. 2007). The observed chemical differentiation between clumps (cf. Brogan et al. 2007; Schilke et al. 2007; Comito et al. 2007) is a further indication of the unlikelihood of a rotating accretion disk over a $1''$ spatial extension. A rotating accretion disk around HW2 is likely to exist, but it must be searched for on a smaller scale.

A few questions are still unanswered: first of all, the nature of the CH$_3$CN-NW and CH$_3$CN-SE condensations remains to be understood. The analysis of the CH$_3$CN spectra (Sect. 3.2) seems to suggest the presence of internally heated compact hot-core-type objects. However, the dust emission at 1mm, which peaks unambiguously on the HW2 position and does not show any clumping, does not seem consistent with this picture.

Another open issue is the physical location of the $-10$ km s$^{-1}$ molecular component. Though it seems likely that the peak of CH$_3$CN emission is associated with the powering source of the small-scale SiO outflow, its connection to the somewhat more extended molecular emission at this systemic velocity (cf. Brogan et al. 2007) remains to be confirmed.

Although no follow-up studies will be possible from the Atacama site towards the Cep-A East cloud, over a few-hundred AU scale this source provides a very good template for the upcoming ALMA observations of high-mass star-forming regions: in fact, ALMA’s high spatial resolution will open a window on a new degree of complexity for massive star-forming regions, in which what currently is known as giant massive hot-core-type sources is likely to break up in a cluster of dozens of smaller sources.

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