UNVEILING THE MAIN HEATING SOURCES IN THE CEPHEUS A HW2 REGION

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ABSTRACT

We present high angular resolution Plateau de Bure Interferometer images (beam of \(\sim 0.3\)′′) of the \(J = 27 \rightarrow 26\) line from several vibrational levels (\(v_f = 1\) and \(v_g = 1\)) of HC\(_3\)N toward Cepheus A HW2. These images reveal the two main heating sources in the cluster: one centered in the disk collimating the HW2 radio jet (the HW2 disk), and the other associated with a hot core 0′′3 northeast HW2 (the HC). This is the first time that vibrationally excited emission of HC\(_3\)N is spatially resolved in a disk. The kinematics of this emission shows that the HW2 disk rotates following a Keplerian law. We derive the temperature profiles in the two objects from the excitation of HC\(_3\)N along the HW2 disk and the HC. These profiles reveal that both objects are centrally heated and show temperature gradients. The inner and hotter regions have temperatures of 350 ± 30 K and 270 ± 20 K for the HW2 disk and the HC, respectively. In the cooler and outer regions, the temperature drops to 250 ± 30 K in the HW2 disk, and to 220 ± 15 K in the HC. The estimated luminosity of the heating source of the HW2 disk is \(\sim 2.2 \times 10^4\) \(L_\odot\), and \(\sim 3000\) \(L_\odot\) for the HC. The most massive protostar in the HW2 region is the powering source of the HW2 radio jet. We discuss the formation of multiple systems in this cluster. The proximity of the HC to HW2 suggests that these sources likely form a binary system of B stars, explaining the observed precession of the HW2 radio jet.

Key words: ISM: individual (Cepheus A) – ISM: molecules – stars: formation – stars: formation

1. INTRODUCTION

Cepheus A East, located at 700 pc (Reid et al. 2009) and with an IR luminosity of \(\sim 2.5 \times 10^4\) \(L_\odot\) (Evans et al. 1981), is a very active star-forming region with signposts of massive star formation (see, e.g., Hughes & Wouterloot 1984). The brightest radio continuum source is the thermal radio jet HW2 (Rodríguez et al. 1994), which powers the northeast–southwest outflow seen in CO and HCO\(^+\) (Narayanan & Walker 1996; Gómez et al. 1999).

Interferometric images of the molecular emission toward HW2 have revealed a very complex picture of the surroundings of the radio jet suggesting the presence of a cluster. Martín-Pintado et al. (2005), Patel et al. (2005), Brogan et al. (2007), and Comito et al. (2007) proposed that the number of sources in the HW2 system could be as many as five. Later, the higher angular resolution observations of Jiménez-Serra et al. (2007) showed that the molecular gas around HW2 is resolved, at least, into a disk centered at the radio jet (the HW2 disk), and an independent hot core located at \(\sim 0.4′′\) east HW2 (the HC).

Brogan et al. (2007) reported vibrationally excited emission of HC\(_3\)N (hereafter HC\(_3\)N\(^+\)), previously detected by Martín-Pintado et al. (2005), arising from an unresolved condensation (\(\leq 1′′\); HW2-NE) located at the same position as the HC. The vibrational states of this molecule are excited mainly by IR radiation re-emitted by dust at \(\lesssim 50\) \(\mu m\). The determination of the size of the emitting region and of the excitation temperature of HC\(_3\)N provides a good estimate of the luminosity of the heating object (de Vicente et al. 2000). Brogan et al. (2007) derived a temperature of 312 K for the HW2-NE/HC source. Assuming a size of \(\sim 0.6′′\) for this object (Martín-Pintado et al. 2005), the expected IR luminosity is \(\sim 2 \times 10^4\) \(L_\odot\). Since this luminosity is similar to that measured in HW2, and since the resolution of the Brogan et al. (2007) images is not high enough to discriminate between the HC and the HW2 source as the main heating source, the question remains whether HW2 or the HC is the most luminous source in the HW2 cluster.

We present high angular resolution Plateau de Bure Interferometer (PdBI) images (beam of \(\sim 0.3′′\)) of the \(J = 27 \rightarrow 26\) rotational lines in the \(v_f = 1\) and \(v_g = 1\) vibrational levels of HC\(_3\)N, toward the Cepheus A HW2 region. The HW2 disk and the HC are centrally heated by two massive protostars. The central source of the HW2 disk is the most luminous object in the cluster.

2. OBSERVATIONS AND RESULTS

The \(J = 27 \rightarrow 26\) \(v_f = 1\) and \(v_g = 1\) transitions (\(E_u/k = 487\) K), and the \(v_g = 1\) and \(1\) \(f\) transitions (\(E_u/k = 883\) K) were observed simultaneously with the PdBI in the A configuration. The correlator setup provided spectral resolutions of \(\sim 80\) and 160 kHz, i.e., \(\sim 0.1–0.2\) km s\(^{-1}\) at 246 GHz. The synthesized beam size was \(0′′39 \times 0′′28\) with a position angle (P.A.) of 85°. We used 3C454.3 (17 Jy) and 3C273 (11 Jy) as bandpass calibrators; MWC349 (1.3 Jy) as flux density calibrator; and 1928+738 (0.8 Jy) and 0212+735 (0.7 Jy) as phase calibrators.

\(^7\) The \(v_f = 1\) and \(v_g = 1\) vibrational levels correspond to the bending modes of the C–C=C and C≡C–C bonds.

\(^8\) Based on observations carried out with the IRAM Plateau de Bure Interferometer. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).
Calibration, continuum subtraction, imaging, and cleaning were done with the GILDAS package.\footnote{See http://www.iram.fr/IRAMFR/GILDAS.}

The four HC\textsubscript{3}N\textsuperscript{+} $v_7 = 1_e$ and $v_6 = 1_f$ transitions were detected toward HW2. In Figure 1, we show the integrated intensity maps of the $v_7 = 1_e$ (contours) and $v_6 = 1_f$ (grayscale and thin contours) line emission observed toward the HC ($-11$ to $-9$ km s$^{-1}$; upper panel) and the HW2 disk ($-7$ to $-3$ km s$^{-1}$; lower panel). For the HC, the first contour and step level are 30 (3$\sigma$) and 50 mJy km s$^{-1}$ for the $v_7 = 1_e$ map, and 10 (2$\sigma$) and 20 mJy km s$^{-1}$ for the $v_6 = 1_f$ image. For the HW2 disk, the first contour and step level are 12 (2$\sigma$) and 12 mJy km s$^{-1}$ for the $v_7 = 1_e$ emission, and 6 (1$\sigma$) and 6 mJy km s$^{-1}$ for the $v_6 = 1_f$ line. Negative contours correspond to the 3$\sigma$ level. The central coordinates are $\alpha(2000) = 22^h56^m17^s98$ and $\delta(2000) = +62^\circ01'49''55'$. Filled cross shows the expected location of HW2 (Curiel et al. 2006). The dashed lines and filled circles indicate the direction and positions at which the HC\textsubscript{3}N\textsuperscript{+} excitation is calculated (Section 3). Beam size is shown at the lower left corner. The spectra of the $v_7 = 1_e$ and $v_6 = 1_f$ lines toward the positions of the HC and the HW2 source are reported in the inner panels at the lower right corner. We also show the location of the HC (filled diamond), SMA1 and SMA2 (filled squares; Brogan et al. 2007), HC2 and HC3 (filled triangles; Comito et al. 2007), and R5 (filled star; Torrelles et al. 2001) in the lower panel of this figure.

The four HC\textsubscript{3}N\textsuperscript{+} $v_7 = 1_e$ and $v_6 = 1_f$ spectra observed toward the HC and the HW2 source. In agreement with the SO\textsubscript{2} images of Jiménez-Serra et al. (2007), the HC\textsubscript{3}N\textsuperscript{+} emission is resolved into two main molecular condensations: one centered at the HC, and the other associated with the protostellar disk around the HW2 jet, the HW2 disk. For completeness, we show in Figure 1 (lower panel) the location of sources SMA1, SMA2 (filled squares; Brogan et al. 2007), HC2, HC3 (filled triangles; Comito et al. 2007), and R5 (filled star; Torrelles et al. 2001) also reported in the region.

2.1. The Hot Core (HC)

The HC\textsubscript{3}N\textsuperscript{+} emission from $-11$ to $-9$ km s$^{-1}$ (upper panel, Figure 1) is relatively compact and mainly arises from the HC. The central radial velocity of this condensation is $v_{LSR} = -10$ km s$^{-1}$, and its peak emission is located at $\sim 0^\circ3$ northeast HW2. This position is similar to that reported by Martín-Pintado et al. (2005) for the HC, and consistent with the location of the HW2-NE source (Brogan et al. 2007). The deconvolved size of the $v_7 = 1_e$ line emission is $0^\prime4 \times 0^\prime7$ (270 AU $\times 480$ AU), and for the $v_6 = 1_f$ line, $0^\prime25 \times 0^\prime4$ (170 AU $\times 270$ AU). The HC is likely the powering source of the small-scale SiO outflow reported by Comito et al. (2007) toward HW2.

2.2. The HW2 Disk

From $-7$ to $-3$ km s$^{-1}$, the HC\textsubscript{3}N\textsuperscript{+} emission shows an elongated structure centered on HW2 that resembles the SO\textsubscript{2} disk reported by Jiménez-Serra et al. (2007). To our knowledge, this is the first time that high-excitation HC\textsubscript{3}N\textsuperscript{+} lines are spatially resolved toward a protostellar disk. The HW2 disk is centered at $v_{LSR} = -5$ km s$^{-1}$, which gives a velocity difference between the HC and this object of $\sim 5$ km s$^{-1}$. This difference has also been observed in the circumstellar molecular gas around HW2 at larger scales (Codella et al. 2006).

While the HC\textsubscript{3}N\textsuperscript{+} $v_7 = 1_e$ emission arises from all along the disk (deconvolved size of $1^\prime4 \times 0^\prime18$, 950 AU $\times 120$ AU), the $v_6 = 1_f$ line is restricted to the inner and hotter regions closer to the HW2 source (size of $\lesssim 0^\prime18 \times 0^\prime4$, $\lesssim 120 \times 270$ AU). The orientation of the $v_7 = 1_e$ and $v_6 = 1_f$ line emission (P.A. $\simeq 115^\circ$) is roughly perpendicular to the HW2 jet (P.A. $\simeq 46^\circ$; Rodríguez et al. 1994). This orientation, although not exactly the same, is similar to that seen in SO\textsubscript{2}, CH\textsubscript{3}CN, and NH\textsubscript{3} for the same velocity range (Torrelles et al. 2007). We note that Brogan et al. (2007) reported larger differences in the disk orientation for different molecular tracers. However, their molecular emission images were obtained for a larger velocity range from $\sim -13$ to 0 km s$^{-1}$. In any case, the discrepancies in the disk orientation could be produced by either chemical or excitation effects.

The integrated intensity maps of the $v_7 = 1_e$ line for the velocity intervals of Jiménez-Serra et al. (2007) are shown in Figure 2. The kinematics of this emission are similar to those observed from SO\textsubscript{2} for the HW2 disk. The redshifted HC\textsubscript{3}N\textsuperscript{+} emission is brighter toward the northwest of HW2, and progressively moves to the southeast for blueshifted velocities. The HC\textsubscript{3}N\textsuperscript{+} emission at $v_{LSR} = -7.9$ km s$^{-1}$ is clearly dominated by the HC. The velocity difference between the northwest and the southeast part of the HW2 disk is $\sim 5$ km s$^{-1}$ over a projected distance of $\sim 1000$ AU.

In Figure 3, we show the $P$--$V$ diagram of the $v_7 = 1_e$ emission along the HW2 disk, after smoothing the data to a velocity resolution of 0.76 km s$^{-1}$. We also superpose the Keplerian rotation velocity curve for a star of $18 M_\odot$, a disk size...
of $\sim1000$ AU, and an inclination angle of the disk axis with respect to the line of sight of $\sim62^\circ$ (Patel et al. 2005). Although the morphology of the HC$_3$N$^*$ emission is very complex, the agreement of the data with Keplerian rotation (thick gray line) is particularly good for the redshifted part of the HW2 disk. The blueshifted part is contaminated by emission from the HC and shocked gas (Jiménez-Serra et al. 2007). Therefore, the HW2 disk seems to rotate following a Keplerian law. The central mass of $18M_\odot$, a disk size of $\sim1000$ AU, and an inclination angle of $62^\circ$, is also shown (thick gray line).

In contrast with the HW2 disk scenario, Brogan et al. (2007) reported chemical differences within the molecular structure around HW2 at $\sim1''$--$2''$ scales. These authors proposed that this feature could be instead due to the superposition of two independent objects in the plane of the sky. Although this possibility cannot be ruled out, there are several observational evidences that favor the disk scenario: (1) HC$_3$N$^*$ (this work), SO$_2$, and NH$_3$ (Jiménez-Serra et al. 2007; Torrelles et al. 2007) show a continuous structure whose kinematics are consistent with Keplerian rotation; (2) the observed HC$_3$N$^*$ peaks do not seem to coincide with SMA1, HC2, HC3, or R5; for SMA2, this source falls $\sim0.25$ northwest the redshifted HC$_3$N$^*$ peak (we note that the uncertainty in absolute position is $\leqslant0.1''$); (3) the dust continuum emission delineates a similar structure to that seen in HC$_3$N$^*$, SO$_2$, or NH$_3$ (Torrelles et al. 2007); and (4) the spatial distribution of the H$_2$O and CH$_3$OH masers (Torrelles et al. 1996; Sugiyama et al. 2007) is consistent with the presence of a disk with radius $\sim600$--$700$ AU. Therefore, we propose that the observed chemical differences within the HW2 disk could be produced by different external physical conditions, or by the presence of other hot core sources in the vicinity of HW2.

3. TEMPERATURE PROFILES AND HC$_3$N COLUMN DENSITIES

We can combine the $v_6 = 1$ and the $v_7 = 1$ lines of HC$_3$N to derive the excitation temperature of the hot gas along the HC and the HW2 disk (Figure 1) by means of Boltzmann diagrams. These diagrams assume LTE and optically thin emission. In case the $v_7$ lines were moderately optically thick, the derived excitation temperatures should be considered as upper limits.

Figure 4 shows the radial profile of the excitation temperatures of HC$_3$N toward the HC (filled triangles) and the HW2 disk (filled circles). The errors associated with these temperatures are $\leqslant12\%$. For the HC, the temperature profile is centrally peaked with a maximum value of $270 \pm 20$ K, and drops to excitation temperatures of $\leqslant225$ K within the inner $0.15''$. This is consistent with the idea that the HC is internally heated by an IR source (see Figure 3 of de Vicente et al. 2002), and suggests that the hot gas is highly concentrated around the protostar. The temperature of $270$ K is larger than that derived by Martín-Pintado et al. (2005, $\sim160$ K) from single-dish HC$_3$N data, but lower than that calculated by Brogan et al. (2007, $\sim312$ K). In the former, dilution effects could account for the temperature discrepancies. In the latter, the excitation temperature of $\sim312$ K is only an upper limit, since the low lying HC$_3$N$^*$ lines are likely optically thick (Brogan et al. 2007).

From the $v_7 = 1$ integrated line flux ($\sim0.7$ Jy km s$^{-1}$), and assuming a temperature of $\sim220$ K, the derived HC$_3$N column...
density in the HC is of \(\sim 10^{16} \text{ cm}^{-2}\). The partition function of the 
HC3N \(v_1\) level has been calculated from the one in the ground
vibrational state, but multiplied by \(\sim 0.3\). This corresponds to
the factor \(e^{\frac{1}{2}(290 \text{ K}/220 \text{ K})}\), where 290 K is the energy of
the fundamental rotational level in the \(v_1\) state and 220 K is
the derived excitation temperature. If we consider an HC3N abundance
of \(\sim 10^{-8}\) (as for the Orion hot core; de Vicente et al. 2002), the estimated H2 column density is \(\sim 10^{24} \text{ cm}^{-2}\).
Assuming a size of \(\sim 0.5''\), this leads to a circumstellar mass of
\(\sim 0.6 M_\odot\) for the HC, which is consistent with that derived by
Martín-Pintado et al. (2005) from SO2.

For the HW2 disk, the maximum excitation of HC3N is found at \(\sim 0.2''\) northwest and southwest of the radio jet (350 \(\pm 40\) and 365 \(\pm 25\) K, respectively), suggesting that the hot
gas is distributed in an inner disk of radius \(\sim 0.2''\) (140 AU; as
estimated from Figure 4). Outside this disk, the temperature
falls by more than 100 K. From the \(v_7 = 1\) integrated line flux
\(\sim 0.4\) Jy km s\(^{-1}\) and, assuming a temperature of \(\sim 250\) K, the
derived column density of HC3N is \(\sim 3 \times 10^{16} \text{ cm}^{-2}\). By using
Equation (2) of Jiménez-Serra et al. (2007), and assuming an
HC3N abundance of \(\sim 3 \times 10^{-10}\) to \(10^{-9}\), the estimated mass
for the HW2 disk is \(\sim 0.4\)–1 \(M_\odot\). This mass is similar to that
obtained by Patel et al. (2005), Jiménez-Serra et al. (2007), and
Torrelles et al. (2007).

4. ON THE HEATING OF THE HC AND THE HW2 DISK

In the case of radiative excitation, the HC3N gas temperatures are a
good estimate of the dust temperatures because the continuum
emission of the HC and the HW2 disk at 20 and
45 \(\mu\)m is likely optically thick. If we assume an H2 column density of \(\sim 10^{25} \text{ cm}^{-2}\), a gas-to-dust mass ratio of 100, and dust opacities of 3560 and 1810 \(\text{cm}^2\ \text{g}^{-1}\) at 20 and 45 \(\mu\)m for both objects (Ossenkopf & Henning 1994), the derived optical
depths are \(\gg 60\). This explains the large obscuration seen toward
HW2 at 24.5 \(\mu\)m by de Wit et al. (2009). Since gas and dust are
thermally coupled, we can then estimate the IR luminosity of the
central source by using the Stefan–Boltzmann law (de Vicente et al. 2000).
From the \(v_7 = 1\) emission size \(\sim 0.5''\), and considering spherical symmetry for the HC, we derive an IR luminosity of \(\sim 3000 L_\odot\) for a dust temperature of \(220\) K. This
luminosity, which is consistent with that obtained by Martin-
Pintado et al. (2005), would correspond to a zero-age main
sequence (ZAMS) B2-type star \((\sim 10 M_\odot); Panagia 1973\).

If we now consider an edge-on disk geometry with radius
475 AU and height 120 AU for the HW2 disk, we estimate an
IR luminosity of \(2.2 \times 10^4 L_\odot\) for a dust temperature of \(250\) K.
This is consistent with a ZAMS B0 star of \(\sim 18 M_\odot\) for the HW2
source (Panagia 1973).

5. DISCUSSION

The high-angular resolution HC3N\(^*\) images toward Cepheus
A HW2 have shown that this multiple system contains two
massive protostars. The powering source of the HW2 disk stands out among them with an IR luminosity of \(2.2 \times 10^4 L_\odot\). The number of ionizing photons for a B0 star, as inferred from the heating \((\sim 10^{37} \text{ s}^{-1}; Panagia 1973)\), is similar to that estimated by Hughes et al. (1995) from the radio continuum emission of the
HW2 radio jet \((\gg 5 \times 10^{46} \text{ s}^{-1})\). This indicates that the HW2 source is the most massive protostar in the region.

The mass of the HW2 disk, as derived from HC3N, is relatively high \((\sim 0.4\)–1 \(M_\odot)\) suggesting that this object is
at an early stage of evolution. The dynamical age of the CO/HCO\(^+\) outflow \((\sim 5 \times 10^4 \text{ yr}; Narayanan & Walker 1996)\) is short compared to the lifetime of a photoevaporating disk for a \(\sim 18 M_\odot\) star \((\lesssim 10^5 \text{ yr}; Gorti & Hollenbach 2009)\), suggesting that the HW2 disk probably constitutes the most massive disk
associated with B stars detected so far (Fuente et al. 2003). The
differences observed within the HW2 disk (Brogan et al. 2007) could be due to different external physical conditions or to other hot core sources present within this multiple system.

The derived temperature profile for the HC indicates that this object is centrally heated by a protostar with an IR luminosity of \(\sim 3000 L_\odot\). External heating of the HC would require luminosities of \(\gtrsim 10^5 L_\odot\) for the HW2 source as pointed out by Martin-Pintado et al. (2005). Shock heating could not account for the luminosity of the HC since the mechanical luminosity of the outflows in the region is only \(\sim 40 L_\odot\)
(Narayanan & Walker 1996). Therefore, the HC hosts a massive
protostar. Since this object has not yet ionized its surroundings,
the HC is at an earlier stage of evolution than the HW2 source.

Massive stars are usually found in binary systems (Mason et al. 1998). The proximity of the HC to HW2 \((\sim 200 \text{ AU})\) could be interpreted as a binary system. Coeval formation is likely the main mechanism for the formation of low-mass
T-Tauri binaries (Ghez et al. 1997). However, the orbits of these
stars are preferentially aligned with the circumstellar disks of
the primary stars (Jensen et al. 2004), which contrasts with the
non-coplanarity of the HC/HW2 disk system. Alternatively, the
HC could have formed after the fragmentation of the HW2 disk
(Krumholz et al. 2009), but this would require disk-to-total
stellar mass ratios of \(\sim 0.1\)–0.2, i.e., factors of 3 and 6 larger
than that observed in HW2 \((\sim 0.03)\).

As shown by Cunningham et al. (2009), the capture of a massive
companion (the HC) by the HW2 disk/protostar system in an
eccentric orbit could explain the observed precession of
the HW2 jet. If we assume an averaged orbital period of
\(\sim 3700 \text{ yr}\) for the binary (Figure 7 in Cunningham et al. 2009),
the expected mass enclosed within the system would be \(\sim 25 M_\odot\)
for a velocity difference of 5 \(\text{ km s}^{-1}\) and an inclination angle
of 62\(^\circ\). This mass is similar to the sum of the masses of the HC
and the HW2 source as derived from HC3N\(^*\).

Finally, we cannot rule out the idea that the formation of HW2 has
triggered the formation of the HC and other objects in the region.
Cepheus A HW2 therefore would resemble the case of
SgrB2, where previous episodes of star formation triggered the
formation of new clusters of massive hot cores (de Vicente et al. 2000).

In summary, we report the detection of HC3N\(^*\) emission toward
the HC and the HW2 disk in Cepheus A HW2. The HC3N\(^*\) images show that these objects are centrally heated by massive
protostars \((18 \text{ and } 10 M_\odot\) for the HW2 source and the
HC, respectively). Since they appear to be very close \(200 \text{ AU}\),
we propose that these objects form a binary system of massive
stars.

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