THE CIRCUMSTELLAR STRUCTURE AND EXCITATION EFFECTS AROUND THE MASSIVE PROTOPARST CEPHEUS A HW 2

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ABSTRACT

We report SMA 335 GHz continuum observations with angular resolution of \( \sim 0.3" \), together with VLA ammonia observations with \( \sim 1" \) resolution toward Cep A HW 2. We find that the flattened disk structure of the dust emission observed by Patel et al. is preserved at the 0.3" scale, showing an elongated structure of \( \sim 0.6" \) size (450 AU) peaking on HW 2. In addition, two ammonia cores are observed, one associated with a hot core previously reported and an elongated core with a double peak separated by \( \sim 1.3" \), with signs of heating at the inner edges of the gas facing HW 2. The double-peaked ammonia structure, as well as the double-peaked CH3CN structure reported previously (and proposed to be two independent hot cores), surround both the dust emission as well as the double-peaked SO2 disk structure found by Jiménez-Serra et al. All these results argue against the interpretation of the elongated dust-gas structure as due to a chance superposition of different cores; instead, they imply that it is physically related to the central massive object within a “disk-protostar-jet” system.

Subject headings: ISM: individual (Cepheus A) — ISM: jets and outflows — stars: formation

1. INTRODUCTION

HW 2 is the brightest of the radio continuum objects detected in the star-forming region of Cepheus A (725 pc distance; Johnson 1957) harboring a massive young star (probably a B0.5 zero-age main-sequence star; Hughes & Wouterloot 1984; Garay et al. 1996). This object, in addition to the strong radio continuum emission seen at \( \lambda \) cm, is also related to well-known signatures typical of young massive stars, such as bright masers and intense magnetic fields (e.g., Torrelles et al. 1996, 2001; Minier et al. 2000; Gallimore et al. 2003; Niezuraweska et al. 2004; Bartkiewicz et al. 2005; Vlemmings et al. 2006; Patel et al. 2007). However, what makes this a unique object is its association with similar phenomena as has been observed toward low-mass young stellar objects. The HW 2 radio continuum jet detected at the base (\( \sim 1" \)) appears to be driving the more extended (\( \sim 1" \)) bipolar molecular outflow seen in HCO+ (Rodríguez et al. 1994; Gómez et al. 1999). Especially remarkable are the large proper motions observed in the two main components of the HW 2 radio jet, moving away at \( \sim 500 \) km s\(^{-1}\) from the central source in nearly opposite directions and parallel to the HCO+ bipolar outflow (Curiel et al. 2006). These observations strongly support theoretical models of high-mass star formation through an accretion disk (McKee & Tan 2003; De Buizer et al. 2005; Beltrán et al. 2006; Banerjee & Pudritz 2007), with the ejection of bipolar outflows sharing similar characteristics with the star formation process of low-mass stars (Shu et al. 1987). This is in contrast to models requiring merging of low-mass stars (Bonnell & Bate 2005) where collimated jets are not expected.

The detection of a rotating disk of dust and molecular gas of \( \sim 330 \) AU radius oriented perpendicular to, and spatially coincident with, the HW 2 radio jet has been reported through Submillimeter Array (SMA) observations with an angular resolution of \( \sim 0.75" \) (Patel et al. 2005). Those results gave additional support to the picture that during the formation of this massive object a “disk-protostar-jet” system has been formed. Moreover, Jiménez-Serra et al. (2007), through a detailed analysis of Very Large Array (VLA) and Plateau de Bure Interferometer (PdBI) subarcsecond (\( \sim 0.3"-0.6" \) \( \lambda \) mm observations, have resolved for the first time the hot gas surrounding HW 2. They find that the radiation from HW 2 could be photoevaporating the disk and that the disk does not appear to be rotating with a Keplerian law due to the extreme youth of the object. The size and kinematics of the SO2 disk inferred by Jiménez-Serra et al. is consistent with the conclusions of Patel et al. However, an alternative interpretation is that the disk structure and kinematics observed are due to the superposition on the plane of the sky of independent hot cores (Comito et al. 2007; Brogan et al. 2007). Here we report new SMA continuum observations and VLA NH3(3, 3) and NH3(4, 4) observations, both with very high angular resolution, giving further support to the circumstellar disk interpretation.

2. OBSERVATIONS AND RESULTS

2.1. SMA Continuum

The submillimeter continuum observations were carried out in two configurations of the SMA (Ho et al. 2004), the extended configuration with a maximum baseline length of 220 m, on 2004 August 30, and the very extended configuration with a maximum baseline length of 472 m, on 2005 November 4. We summarize here the observations of this latter date (see Patel et al. [2005, 2007] for the details on the observations in the extended configuration). We used a tuning of 331.1 GHz centered in the lower sideband (and 341.1 GHz centered in the upper sideband). The quasar BL Lac was observed for 5 minutes between every cycle of 10 minutes on the main source. The spectral bandpass was calibrated using observations of Mars, and absolute flux calibration
was done using the asteroid Ceres and the quasar 3C 111. Continuum data were obtained from the line-free regions of the spectral band of the two sidebands. Weather was excellent during the observations with relative humidity of ~20% and \( \tau_{225\text{GHz}} \approx 0.06 \) (~0.22 at 335 GHz), measured at the nearby Caltech Submillimeter Observatory. The track was ~8 hr long with an onsource integration time of ~4.2 hr. \( T_{\text{sys,DSB}} \) varied from 220 to 500 K. The visibility data were calibrated and mapped using the Berkeley Illinois Maryland Array’s Miriad package. We estimate an uncertainty of ~20% in the absolute flux scale in the SMA data and an uncertainty of ~0.1" in absolute astrometry. Final maps were obtained by combining the two configurations (extended-+ very extended) and the two sidebands. Two continuum sources are detected with a beam size of 0.37", one coincident with HW 2 (\( S_{225\text{GHz}} \approx 0.6 \text{ Jy beam}^{-1} \)) and another one with HW 3c (\( S_{225\text{GHz}} \approx 0.1 \text{ Jy beam}^{-1} \)), which is located ~3" south from HW 2. The continuum emission around HW 2 shows (Fig. 1) an elongated structure with a deconvolved size of \( \approx 0.62'' \times 0.35'' \) (450 \( \times \) 250 AU; P.A. \( \approx 120^\circ \)) and total flux density of \( \approx 2 \text{ Jy} \) (brightness temperature \( T_B \approx 100 \text{ K} \)) (similar to the flux density measured with a beam size of \( \approx 0.75'' \) by Patel et al. 2005). A weak feature (6 \( \sigma \) level, \( \sigma = 7 \text{ mJy beam}^{-1} \)) located ~1" north from the peak of the elongated structure is also observed. The implications of these high angular resolution continuum observations are discussed in § 3. An analysis of the SMA spectral line data combining the two configurations will be presented in a forthcoming paper by Patel et al.

2.2. VLA Ammonia

We have reanalyzed the \( \text{NH}_3(3, 3) \) and \( \text{NH}_3(4, 4) \) line data (1.3 \( \text{cm} \)) observed by Torrelles et al. (1999), who reported detection of the lower transition but nondetection of the higher one. These observations were carried out with the VLA of the NRAO\(^8\) in the C configuration and 4IF spectral line mode, allowing us to observe simultaneously the two transitions with a spectral resolution of \( \approx 0.6 \text{ km s}^{-1} \) and covering a velocity range of \( -30 \text{ km s}^{-1} \leq V_{\text{LSR}} \leq 8 \text{ km s}^{-1} \) (covering only the main hyperfine component of these transitions; see Ho & Townes 1983). More details of these observations are given in Torrelles et al. (1999). The recalibration of the observations was performed using the new recommended procedure of NRAO for reducing high-frequency VLA data. The continuum emission contribution from HW 2 to the spectral line data was subtracted. Emission from both transitions is detected in the velocity range from \( \approx -13.6 \text{ to } -2.6 \text{ km s}^{-1} \) with a beam size of \( \approx 1'' \). The integrated flux density images in this range are consistent with those reported by Torrelles et al. (1999) \( [\text{NH}_3(3, 3)] \) and Brogan et al. (2007) \( [\text{NH}_3(4, 4)] \), showing a more complex structure around HW 2. However, more simple structures are differentiated from integrated intensity maps made in two different velocity ranges, from \( -13.6 \text{ to } -8.1 \text{ km s}^{-1} \) and from \( -7.5 \text{ to } -2.6 \text{ km s}^{-1} \). In the former range of integration, a distinct spatially “isolated” ammonia core is identified in both transitions, spatially coinciding with the hot core reported by Martin-Pintado et al. (2005) in \( \text{SO}_2 \approx 0.5'' \) to the east of HW 2 (Fig. 2). This core is also seen in \( \text{CH}_3\text{CN} \) (Comito et al. 2007). On the other hand, an elongated core centered on HW 2 is distinguished in the \( -7.5 \text{ to } -2.6 \text{ km s}^{-1} \) range (more prominent in the \( \text{NH}_3(4, 4) \) transition; Fig. 2). This structure has a similar orientation as the \( \text{CH}_3\text{CN} \) and \( \text{SO}_2 \) structures reported by Patel et al. (2005) and Jiménez-Serra et al. (2007), respectively, within the same velocity range, although the ammonia structure is about 2 times larger (\( \approx 2'' \)). In addition, the ammonia emission in the \( -7.5 \text{ to } -2.6 \text{ km s}^{-1} \) range shows a velocity pattern that is roughly consistent with the pattern observed in \( \text{SO}_2 \) by Jiménez-Serra et al. (2007); that is, the gas of the

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Fig. 2.—Contour maps of the integrated flux density ammonia emission of the (3, 3) and (4, 4) inversion transition lines for different velocity ranges in km s$^{-1}$ (indicated in the figures). Contour levels are 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 $\times$ 14 mJy beam$^{-1}$ km s$^{-1}$. Beam size $\sim$1.1$''$ is indicated in the lower right panel. The cross indicates the position of HW 2 (Curiel et al. 2006). The accuracy in the relative position of the (4, 4) and (3, 3) ammonia emission is estimated to be $\sim$0.05$''$.

The northwestern part of the elongated structure appears to be redshifted with respect to the southeastern part. However, the signal-to-noise ratio (S/N) of the individual ammonia velocity channels is not good enough (S/N $\leq$ 5–6 $\sigma$) to make a detailed kinematical comparison, even more considering the different angular resolution of both observations (NH$_3$ and SO$_2$).

An additional relevant result is obtained when a spatial comparison of the (4, 4) and (3, 3) ammonia emission is made, given that their flux density ratio is sensitive to the rotational temperature describing the population of these two rotational states (Ho & Townes 1983). In fact, from Figure 2 we see that in the −13.6 to $\sim$−8.1 km s$^{-1}$ range the (4, 4) and (3, 3) peaks of the ammonia clumps do not coincide but are separated by 0.2$''$, with the (4, 4) peak being closer to HW 2, suggesting external heating by the massive protostar. A relative spatial displacement between the (4, 4) and (3, 3) emission is also observed in the elongated structure ($\sim$−7.5 to $\sim$−2.6 km s$^{-1}$ range), with the two (4, 4) peaks separated by 1.2$''$ and being closer to HW 2 than the corresponding (3, 3) ammonia peaks that are separated by 1.4$''$, suggesting that the inner edges of the elongated structure facing HW 2 is being heated by the massive protostar. This relative spatial displacement is significant considering that the accuracy in the relative position of the (4, 4) and (3, 3) ammonia emission is estimated to be $\sim$0.05$''$. From the (4, 4) to (3, 3) ratios ($\geq$0.4, obtained from the spectra), assuming optically thin emission, we estimate overall rotational temperatures $T$$_R$ (4, 4; 3, 3) $\approx$ 160 K for the elongated structure. These temperatures are consistent with those obtained by Martín-Pintado et al. (2005) through SO$_2$ observations and with the brightness dust temperature of $\sim$100 K (§ 2.1).

3. DISCUSSION

Our new high angular resolution SMA observations show that the flattened disklike structure of the dust emission observed previously by Patel et al. (2005) is still preserved at $\sim$0.3$''$ scale, with a single continuum peak on HW 2. In fact, the dust continuum peak coincides in absolute position within 0.07$''$ with the HW 2 position estimated at centimeter wavelengths by Curiel et al. (2006). In addition, this elongated structure is similar in size and orientation to the molecular SO$_2$ disk structure detected by Jiménez-Serra et al. (2007; see Fig. 1), but with the dust continuum peaking in between the two peaks of the SO$_2$ structure. Both the dust continuum and SO$_2$ structures are engulfed by the elongated double-peaked ammonia structure, as well as by the double-peaked CH$_3$CN structure detected at 230 GHz with arcsecond resolution (proposed to be delineating two hot cores, HC2 and HC3; Comito et al. 2007; see Fig. 1). Our results argue against the interpretation that the elongated structure observed perpendicular to the HW 2 jet and proposed to be a disk by Patel et al. (2005) is due to a chance superposition of different hot cores (HC 2 and HC 3), given that they have an angular separation ($\sim$1$''$) that is significantly larger than the size of the elongated dust continuum structure ($\sim$0.6$''$). Furthermore, the fact that a main single continuum peak on HW 2 is observed gives additional evidence that the observed dust continuum emission distribution is dominated by the gas directly associated with HW 2. We note that notwithstanding the importance of chemistry, with molecules being enhanced and depleted depending on the physical conditions, dust emission is much less affected by such chemical effects and hence is a more reliable indicator of the structure of material in the immediate vicinity of HW 2. We would like to emphasize, however, that we are not discarding the presence of multiple hot cores in the immediate vicinity of HW 2. Furthermore, these hot cores seem to be necessary to explain the observed chemical inhomogeneities in the region (Comito et al. 2007; Brogan et al. 2007). However, what we find here is that the SMA dust disk structure is not made up of these reported hot cores.

The question arises as to the meaning of the double-peaked molecular structure observed in SO$_2$ (Jiménez-Serra et al.) inside of the double-peaked molecular structures observed in CH$_3$CN (Comito et al. 2007) and in NH$_3$ (this Letter), all these structures observed within the same integrated velocity range ($\sim$7.5 to $\sim$2.6 km s$^{-1}$; Fig. 1). As far as we know, this is the first time that this behavior has been observed and reported at (sub)arcsecond scale toward a high-mass star-forming region. As an open issue, we discuss here three different interpretations, not necessarily independent. The first one is that each of the different molecular peaks are tracing molecular fragments from the remnant of the parental core from which the central massive
object has been formed. The fact that all of them are almost aligned along the same axis, roughly perpendicular to the HW 2 jet, would favor this possibility. In addition, the observed heating of the gas facing HW 2 (§ 2.2) indicates a physical association of the large (2′) elongated molecular structure with the massive protostar, rather than a projection effect by the superposition in the plane of the sky of different molecular cores. A second possible explanation is that chemical and excitation effects produce different spatial molecular peaks for different molecular transitions. This could be consistent with the fact that SO₂ (observed closer to HW 2) emission traces regions with densities 2 orders of magnitude higher than the ammonia (van der Tak et al. 2007). This would also be consistent with the fact first noted by Jiménez-Serra et al. (2007) that the water masers reported by Torrelles et al. (1996) are distributed along the SO₂ emission (water masers arise in regions with very high densities, ~10⁸ cm⁻³; Elitzur 1989). A third possible explanation is that a more or less continuous structure but with chemical variations becomes denser and thinner as we probe closer to the protostar, giving rise to concentric flattened structures of similar shape and orientation. A beam-averaged radius of the structure growing with increasing beam size would then produce the concentric double-peaked structures. We hypothesize that this could be the case for HW 2, given that the angular separation of the two peaks of the different molecular structures found around HW 2 decreases with decreasing beam size (Fig. 3). This possible scenario might be tested by observing with the VLA the ammonia emission with higher angular resolution (~0.3′). If this scenario is correct, a smaller separation between the corresponding double ammonia peaks should be measured. On the contrary, if the spatial separation between the ammonia peaks does not change when observed with higher angular resolution, it would indicate that chemical and excitation effects are the dominant effects in producing the different double-peaked molecular structures.

The main heating mechanism of the gas around HW 2 can be explained via collisions with hot dust, which in turn is heated by the absorption of the radiation of this high-mass protostar (although a shock-heating contribution from the HW 2 wind and/or from the external material infalling into the disk is also expected). From Scoville & Kwan (1976) and Zhang et al. (2007), we find that the expected dust temperature at a distance of 0.3″ (220 AU) from HW 2 is $T_d \approx 100–180$ K (depending on the grain emissivity spectral index $\beta = 2$ to 1) for a source with a luminosity of $2.5 \times 10^4 L_\odot$ (Evans et al. 1981; Lenzen 1988). Since collisional coupling of the gas and dust is expected for densities $n(H_2) \approx 10^{3}$ cm⁻³ (Goldsmith & Langer 1978), a value consistent with the detection of NH₃, CH₃CN, and SO₂ emission, we conclude that molecular gas heating up to the observed temperatures and distances is possible. Comito et al. (2007) conclude that the millimeter/submillimeter portion of the continuum emission is optically thick. Therefore, to calculate the gas mass of the disk we follow the procedure outlined by Beuther et al. (2007), assuming optically thin emission and correct that through the opacity correction factor $C = (1/e^{-\tau})$, with $\tau$ the dust opacity. In this way we estimate the gas mass to be $(0.4–3) M_\odot$, assuming a gas to dust ratio of 100, temperature of ~160 K, and depending on the grain emissivity spectral index $\beta = 1$ to 2.

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