ARCSECOND SCALE KINEMATIC AND CHEMICAL COMPLEXITY IN CEPHEUS A-EAST

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ABSTRACT

We present results from SMA observations of the star forming region Cepheus A-East at ~ 340 GHz (875 μm) with 0''7 – 2'' resolution. At least four compact submm continuum sources have been detected, as well as a rich forest of hot core line emission. Two kinematically, chemically, and thermally distinct regions of molecular emission are present in the vicinity of the HW2 thermal jet, both spatially distinct from the submm counterpart to HW2. We propose that this emission is indicative of multiple protostars rather than a massive disk as reported by Patel et al. (2005).

Subject headings: ISM: individual (Cep A) — ISM: lines and bands — ISM: molecules

1. INTRODUCTION

The Cepheus A-East (hereafter CepA) star forming region lies at a distance D ~ 725 pc and has Lbol ~ 2.2 × 10⁶ L⊙, consistent with a cluster of B0.5 or later stars (Blaauw, Hiltner, & Johnson 1959; Sargent 1979; Mueller et al. 2002). At cm-wavelengths, CepA consists of several compact sources called HW1, HW2, ... HW9, which lie along a roughly inverted Y-like structure (e.g., Hughes & Wouterloot 1984; Garay et al. 1996). It is currently unclear how many of these compact ionized structures correspond to individual protostars. For example, much of the cm-wavelength emission from the HW2 region is due to a bipolar thermal jet rather than a Strömgren sphere (Rodríguez et al. 1994; Curiel et al. 2006).

A wide range of other signposts of on-going star formation have been observed in CepA including several outflow components (e.g. Codella et al. 2005, and references therein), however the locations of the powering sources remain uncertain. On smaller sizescales copious OH, H₂O, and CH₃OH maser emission has been detected toward several of the cm-wavelength sources (Vlemmings et al. 2006, and references therein). Patel et al. (2005) report the detection of a massive molecular gas and dust disk toward the HW2 source from Submillimeter Array⁴ (SMA) observations of methyl cyanide.

In this Letter, we present new and archival SMA 345 GHz observations toward CepA (including those of Patel et al. 2005, concentrating on the continuum data and the spatial, kinematic, and temperature information provided by the wealth of spectral lines; complete details of the spectral line results will be presented in a future paper. Our observations and results are presented in § 2 and are discussed in § 3.

2. OBSERVATIONS & RESULTS

The SMA observing parameters are provided in Table 1. The data were taken with a channel width of 0.8125 MHz (~ 0.7 km s⁻¹) except for the archival data which have 8 times poorer spectral resolution across most of the band (the CH₃CN (18–17) K=0-3 lines were observed with ~ 0.7 km s⁻¹ resolution). All five epochs employed seven antennas. The data were calibrated using the MIRIAD package. The quasars BL Lac and 3C 454.3 were used for phase calibration, 3C 454.3, Uranus, and Saturn were used for bandpass calibration. Comparison of the amplitude calibration (from the quasars) applied to Uranus vs. a model of its baseline dependent flux density suggests that the CepA amplitude calibration is accurate to within ~ 15%.

Table 1

| Date          | ν range (GHz) | tobs (hours) | USB/SSB (GHz) | Line Beam (″ × ″) |
|---------------|--------------|--------------|---------------|--------------------|
| 30 Aug 2004²  | 20-190       | 5.7          | 331.4/–       | 0.9 × 0.8 (77)     |
| 26 Sep. 18 Oct 2004 | 14-130   | 5.0          | 343.0333.0   | 1.9 × 1.2 (71)     |
| 05, 07 Oct 2005 | 10-80       | 4.1          | 346.636      | 2.0 × 1.9 (33)     |

²Approximate center frequency of 2 GHz wide sidebands.
³Synthesized beam and position angle of the USB line data.
⁴Archival Patel et al. (2005) data, only the upper sideband was analyzed.

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Contamination subtraction, imaging, deconvolution, and self-calibration were carried out in AIPS. After extracting the continuum using line-free channels in the ν-ν data, the continuum for each observation/sideband were separately self-calibrated; the derived phase and amplitude corrections were also applied to the line data sets. The spectral line data were Hanning smoothed during imaging to produce a final spectral resolution of ~ 1.4 km s⁻¹ (except for the archival SMA dataset with 5.9 km s⁻¹ spectral resolution). To create the highest possible sensitivity continuum image, all of the final continuum datasets were combined in the ν-ν plane and imaged.

2.1. CepA Submillimeter Continuum

Fig. 1a shows the combined naturally weighted 875 μm SMA continuum image with a beam of 1″3 × 1″1 and integrated flux density of 7.7 Jy; the rms noise is 13 mJy beam⁻¹. The peak of the single dish submm source (see e.g. Mueller et al. 2002) has been resolved for the first time into a number of distinct components. Archival 2002 Very Large Array⁵ (VLA) 3.6cm continuum contours are also shown on for comparison. While there is rough agreement between the peak 875 μm continuum emission and the well-known ionized thermal jet HW2 (e.g. Rodríguez et al. 1994; Garay et al. 1996),

³ The National Radio Astronomy Observatory operates the Very Large Array and is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.
there is excess emission to the NW of HW2 suggestive of additional unresolved structure.

In order to better compare the morphology of the cm and submm emission, we have also created a superuniform weighted image using baselines $> 40$ kλ, resulting in a beam size of $0.8 \times 1.7''$. To further delineate the morphology of the emission in the vicinity of HW2, in Fig. 1b we present the superuniform weighted image restored with a $0.6''$ beam (equivalent to 1.8 times the longest baseline sampled) which emphasizes the locations of the clean components. Fig. 1b reveals the presence of at least two distinct submm sources in the vicinity of HW2, HW2-SMA and SMA1, in addition to an extension NW of HW2-SMA which we denote SMA2 (see §3). A weak extension south of HW2-SMA (denoted SMA3) is also visible, which may be a submm counterpart to the low mass protostar VLA-R5 (Curiel et al. 2002). The combined morphology of HW2-SMA, SMA2, and SMA3 is the structure reported by Patel et al. (2005) as a dust disk; their Fig. 1 with $\sim 0.75''$ resolution also shows that the centroid of submm emission is not centered on the axis of the HW2 jet. The HW2-SMA 875 $\mu$m continuum peak is within $0.7''$ of the proposed location of the powering source of the HW2 thermal jet based on high resolution ($0.05''$) 7 mm VLA data (Curiel et al. 2006) which is well within our absorption position uncertainty of $0.15''$. Two additional submm cores are detected to the south of HW2, one coincident with the cm-wavelength source HW3c (denoted HW3c-SMA) and another located at the NE tip of the cm-wavelength source HW3b (designated SMA4). No distinct compact 875 $\mu$m counterparts to HW8, HW9, HW3a, HW3b or HW3d are detected in the SMA data.

2.2. CepA Hot Core Line Emission

Within the 8 GHz of total bandwidth observed (Table 1) we detect more than 20 distinct species along with a number of their isotopologues. A few transitions with low excitation energies ($^{12}$CO (3–2), CS (7–6), $^{13}$CO (4–3)) show extended emission over the full primary beam ($\sim 36''$) corresponding to the previously studied outflows (see e.g. Codella et al. 2005). However, the emission from most species is restricted to compact regions ($\lesssim 2''$) that coincide with the submm continuum emission (Fig. 1b). At $1'' - 2''$ resolution (Table 1) the species exhibiting compact emission in the vicinity of HW2 are strongest at one of two distinct velocities: $-5.0 \pm 0.5$ or $-10.5 \pm 0.5$ km s$^{-1}$ (Fig. 1b,c,d; see also Codella et al. 2006). These two kinematic features are also spatially distinct. Without exception, molecules that are strongest at $\sim -10.5$ km s$^{-1}$ have peak positions $\sim 0.0''$ west of SMA2-SMA (we denote this position HW2-NE), and molecules that are strongest at $\sim -5$ km s$^{-1}$ peak at the position of SMA2. Although this dichotomy exists for all observed species, a few abundant high density tracers like CH$_3$CN and C$^{34}$S, show emission of nearly equal strength toward both positions (Fig. 1c,d).

Using 3mm Plateau de Bure (PdBI) data Martín-Pintado et al. (2005) also find that SO$_2$ emission peaks to the E/NE of HW2 at a velocity of $\sim -10.5$ km s$^{-1}$ and suggest that this emission is due to a distinct intermediate mass protostar; the SMA and PdBI SO$_2$ positions agree to within the absolute position uncertainty of $0.15''$. This result has recently been confirmed by the VLA detection of SO$_2$ emission and weak 7mm continuum emission at the position of HW2-NE (Jiménez-Serra et al. 2007). In an extensive PdBI spectral line study Comito et al. (in preparation) also find strong spatial, chemical, and kinematic differentiation in general agreement with the SMA results. The two velocity components at $\sim -5$ km s$^{-1}$ and $\sim -10.5$ km s$^{-1}$ have also been observed in single dish H$_2$CS, CH$_3$OH, and HDO data with resolutions ranging from $10''$ to $30''$ (Codella et al. 2006). The single dish emission from both velocity components is extended. Our SMA data are insensitive to spatial structures $> 15''$, but it seems likely that SMA2 is associated with the larger scale $\sim -5$ km s$^{-1}$ component.

For CH$_3$OH towards SMA2 (at $\sim -5$ km s$^{-1}$), and SO$_2$ and HC$_3$N toward HW2-NE (at $\sim -10.5$ km s$^{-1}$), we have measured enough transitions to construct rotation diagrams (Fig. 2; see Goldsmith & Langer 1999). Emission from the two velocity components are well-separated, even though they are not completely spatially resolved by our observations (Fig. 1c,d). The CH$_3$OH and SO$_2$ data have been corrected for optical depth effects by first estimating the opacity of...
one transition using a less abundant isotopologue and assuming Galactic abundance ratios of $^{12}$C/$^{13}$C=70 and $^{32}$S/$^{34}$S=23 (Milam et al. 2005; Chin et al. 1996, and references therein). Then, assuming LTE, the other transitions were corrected using the formalism described in Sutton et al. (2004). The CH$_3$OH optical depths are significant (up to 28.2); the SO$_2$ optical depth is more moderate (up to 2.4). A moderate optical depth in the lower lying HC$_3$N lines is also possible (see e.g. Wyrowski et al. 1999), correction for which would yield an HC$_3$N $T_{\text{rot}}$ more consistent with SO$_2$. Three of the lower energy A-type transitions of CH$_3$OH and the two lowest energy transitions of HC$_3$N are also detected toward HW3c-SMA and SMA4; rotation diagram analysis for these two submm cores yield $T_{\text{rot}}$=65 $\pm$ 25 K.

In addition to the kinematic and chemical dichotomy between SMA2 and HW2-NE, their $T_{\text{rot}}$ differ by more than 100 K. Both values of $T_{\text{rot}}$ (Fig. 2) are significantly larger than reported by Torrelles et al. (1999) based on $\sim$ 1" resolution VLA NH$_3$ data [$T_{\text{rot}}$=30-50 K], influenced by their reported non-detection of NH$_3$ (4,4) [$E_u/k$ = 202 K]. An NH$_3$ (4,4) integrated intensity image from our reduction of these archival data is shown in Figure 3; emission is clearly detected toward both HW2-NE and SMA2. A new analysis of the NH$_3$ data gives $T_{\text{rot}}$ within a factor of two of those reported here. Our $T_{\text{rot}}$ are also larger than those estimated by Patel et al. (2005) (25-75 K) though the sense of the temperature gradient is in agreement (i.e. warmer in the E than W). Although Patel et al. (2005) report that CH$_3$CN (18-17) is not detected above K=3, our reduction of their archival SMA data detects CH$_3$CN up through K=8 [$E_u/k$ = 607 K, K=6 is shown in Fig. 3], and we find similar $T_{\text{rot}}$ to those shown in Fig. 2. Using 30m data, Martin-Pintado et al. (2005) derived $T_{\text{rot}}$ ~ 150 K for 3mm SO$_2$ and HC$_3$N transitions toward HW2-NE, however, beam dilution may well play a role in this single dish result.

3. DISCUSSION

The observed distribution of submm continuum emission in the immediate vicinity of HW2 ($\pm0.5''$) allows for two possible interpretations: a single elongated structure or two (or more) marginally-resolved individual sources. Although the kinematic dichotomy between the positions labeled HW2-NE and SMA2 (Fig. 1b) could be interpreted as a velocity gradient across a continuous structure (e.g. Patel et al. 2005), the dramatic chemical and thermal differentiation demonstrated by our multi-species analysis is difficult to explain with this picture. Chemical and thermal gradients might be expected in the radial and vertical directions within a protostellar disk, but such dramatic azimuthal asymmetries are more difficult to conceive in a single source scenario. We also note that beyond a velocity gradient, the kinematic evidence for a Keplerian rotating disk is quite weak. For example, the weakness of the emission at the central HW2 position in position-velocity (P-V) diagrams such as those in Patel et al. (2005, and in our own data, but not shown) are inconsistent with theoretical expectations unless a central hole is invoked (e.g. Richer & Padman 1991). Even with this modification, it remains difficult to explain the unequal position offsets of the two velocity peaks from the HW2 stellar position (see NH$_3$ in Fig.3 and the K=3 P-V diagram of Patel et al. 2005). In contrast, the presence of multiple sources at different velocities naturally explains the observed behavior. We therefore favor the multiple source hypothesis (see also Martín-Pintado et al. 2005), with at least three sources in the vicinity of HW2 (HW2-SMA, HW2-NE, and SMA2). The remaining discussion proceeds with this interpretation.

Table 2 summarizes the properties of the submm cores identified in Fig. 1b (excluding SMA3). The gas masses were estimated using

$$M_{\text{gas}} = \frac{R S_{\nu} D^2 \tau_{\text{dust}}}{B[\nu, T_d] \kappa(\nu) \left(1 - \exp(-\tau_{\text{dust}})\right)},$$

and assuming a gas-to-dust ratio $R = 100$, $D = 725$ pc, and a dust opacity $\kappa_{875\mu m} = 1.84$ cm$^2$ g$^{-1}$ extrapolated from Ossenkopf & Henning (1994) for thin ice mantles and density $10^6$ cm$^{-3}$. Values for the peak flux density $S_{\nu}$ (none of the cores appear to be resolved), the continuum brightness temperature ($T_b$), and the range of assumed dust temperatures ($T_d$) are also listed in Table 2. The $M_{\text{gas}}$ have been corrected for the continuum opacity calculated from $\tau_{\text{dust}} = -\ln[1-(T_b/T_d)]$.

The derived masses are very sensitive to the assumed temperatures (Table 2). For SMA2, HW3c, and SMA4, we have used the range of dust temperatures from rotation diagram analysis (§2.2). Temperatures for HW2-SMA and SMA1 are difficult to estimate due to the proximity of strong emission from HW2-NE and SMA2. No species peak at the position of HW2-SMA suggesting it is not very warm (i.e. compared to SMA2 or HW2-NE), though its association with the strong bipolar jet suggests it is unlikely to be very cold either. Thus we have assumed a moderate temperature range of 40 to 100 K for HW2-SMA. Since SMA1 is lacking both a

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**TABLE 2**

| Name | R.A., Dec.$^a$ | $S_{\nu}$ | $T_b$ | $T_d$ | $M_{\text{gas}}$ ($M_\odot$) |
|------|----------------|----------|------|------|------------------|
| SMA1 | 17.873, 50.56  | 0.28     | 5.0  | 20-100 | 1.0-0.1          |
| SMA2 | 17.927, 49.74  | 0.80     | 14.4 | 115-135| 0.32-0.27        |
| HW2-SMA| 17.999, 49.43 | 1.17     | 21.0 | 40-100 | 2.0-0.6          |
| HW3c-SMA| 17.949, 46.07 | 0.25     | 4.5  | 40-90  | 0.3-0.1          |
| SMA4 | 17.820, 45.33  | 0.16     | 2.9  | 40-90  | 0.2-0.1           |

$^a$J2000 coordinates added to 22h56m, 62°01’. The relative and absolute position uncertainties are better than 0"002 and 0"015, respectively.

$^b$Using superuniform weighted image with restoring beam 0"84 x 0"70.
from HW3c-SMA (see Fig. 1b). HW3b is consistent with being a one-sided jet emanating from SMA4 or possibly the counterjet to HW3d (also see Garay et al. 1996).

We detect at least five submm sources (HW2-SMA, SMA1, SMA2, HW3c-SMA, and SMA4) within a projected radius of 4′′ (2900 AU). If the five low mass sources HW3a, HW8, HW9, VLA-R5, and VLA-R4 (Hughes 1988; Curiel et al. 2002) are included and equal clustering in the perpendicular dimension is assumed, then the implied protostellar density is $5.7 \times 10^3 \text{pc}^{-3}$. This approaches the minimum theoretical value ($10^6 \text{pc}^{-3}$) needed to test the induced binary merger hypothesis proposed as a formation mechanism for the most massive stars (Bonnell & Bate 2005).

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