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A NEW INTERMEDIATE MASS PROTOSTAR IN THE CEPHEUS A HW2 REGION

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ABSTRACT

We present the discovery of the first molecular hot core associated with an intermediate mass protostar in the Cep A HW2 region. The hot condensation was detected from single dish and interferometric observations of several high excitation rotational lines (from 100 to 880 K above the ground state) of SO_2 in the ground vibrational state and of HC_3N in the vibrationally excited states $v_7=1$ and $v_7=2$. The kinetic temperature derived from both molecules is ~ 160 K. The high–angular resolution observations ($1.25'' \times 0.99''$) of the SO_2 $J = 28_{7,21} \rightarrow 29_{6,24}$ line (488 K above the ground state) show that the hot gas is concentrated in a compact condensation with a size of $\sim 0.6''$ (~ 430 AU), located $0.4''$ (300 AU) east from the radio–jet HW2. The total SO_2 column density in the hot condensation is $\sim 10^{18}$ cm^{-2}, with a H_2 column density ranging from $\sim 10^{23}$ to 6×10^{24} cm^{-2}. The H_2 density and the SO_2 fractional abundance must be larger than 10^7 cm^{-3} and 2×10^{-7} respectively. The most likely alternatives for the nature of the hot and very dense condensation are discussed. From the large column densities of hot gas, the detection of the HC_3N vibrationally excited lines and the large SO_2 abundance, we favor the interpretation of a hot core heated by an intermediate mass protostar of 10^3 L$_\odot$. This indicates that the Cep A HW2 region contains a cluster of very young stars.

Subject headings: ISM: individual (Cepheus A) — ISM: molecules — stars: formation

1. INTRODUCTION

While the general scenario of low mass star formation is reasonably well understood, the formation of massive stars is still poorly known (see e.g. McKee & Tan 2003). Hot cores represent one of the earliest phases in massive star formation accretion (Garay & Lizano 1999). They are compact condensations (≤ 0.1 pc) with high densities ($\geq 10^6$ cm^{-3}), high kinetic temperatures (≥ 100 K) and a very rich chemistry. The abundances of sulfur–bearing molecules like SO_2, are expected to be enhanced in hot cores by several orders of magnitude with respect to the quiescent gas (Charnley 1997). So far, these hot cores have been mainly detected in objects whose luminosities are larger than 10^4 L$_\odot$ (Garay & Lizano 1999).

Cepheus A (CepA), with a total IR luminosity of 2×10^4 L$_\odot$, is a very active region of massive star formation. It contains sixteen ultracompact H II regions, molecular outflows and water vapor masers (e.g. Hughes & Wouterloot 1984; Rodríguez, Moran, & Ho 1980; Torrelles et al. 1996; Garay et al. 1996). The main powering source in the region is believed to be the thermal radio–jet, known as HW2, which is the brightest of the radio continuum sources in the region (Rodríguez et al. 1994; Garay et al. 1996). The surroundings of HW2 show a rather complex structure.

The morphology of the HW2 radio–jet suggests the presence of a disk of neutral gas whose size is unknown. Torrelles et al. (1996) reported evidence for water masers in a rotating and collapsing disk around the radio–jet. However, the warm molecular gas (about 50 K) around HW2 shows a ring like structure with complex kinematics which does not seem to be consistent with a simple rotating disk (Torrelles et al. 1999).

In addition to the expected neutral disk, within a few hundred AU of the radio–jet, there is clear evidence for very recent star formation. Two radio continuum sources detected by Curiel et al. (2002), one of them claimed to be the source of the expanding bubble found in H_2O masers (Torrelles et al. 2001), are very likely protostars. Furthermore, the multiple outflow activity (Hayashi, Hasegawa, & Kaifu 1988; Narayanan & Walker 1996) seems to be powered by three different young stellar objects in the surroundings of HW2 (Codella et al. 2003). Two of these sources have not been yet identified.

In this letter, we report the detection of a hot (160 K), very dense ($\geq 10^7$ cm^{-3}) compact ($0.6''$; 430 AU) condensation located $0.4''$ (300 AU) east from the radio–jet HW2. From the properties of the hot condensation and the large H_2 column densities of hot gas, we conclude that this condensation is likely a hot core associated with an intermediate mass star with a luminosity of 10^3 L$_\odot$ which could be the driving source of one of the molecular outflows observed in the CepA region.

2. OBSERVATIONS & RESULTS

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The observations of the high excitation SO_2 rotational lines and of the HC_3N vibrationally excited lines (hereafter HC_3N^*) in Tab. 1 were made with the IRAM[2] 30 m telescope at Pico Veleta (Spain). The lines were observed with the 1.3, 2 and 3 mm SIS receivers simultaneously. The half power beam width (HPBW) of the telescope ranged from $14''$ to $25''$. The receivers were tuned to single side band with image rejections larger than 10 dB. The system temperatures of the 1.3, 2 and 3 mm receivers were, respectively, $\sim$450, $\sim$310 and $\sim$170 K. As spectrometers, we used the VESPA autocorrelator, configured to provide velocity resolutions ranging from 0.037 to $3.3\,\mathrm{km\,s^{-1}}$. The line intensities were converted to main brightness temperatures using the beam efficiencies of 0.55, 0.69 and 0.77 for the 1.3, 2 and 3 mm lines respectively.

The $J = 28_{7,21} \rightarrow 29_{6,24}$ SO_2 line (489 K above the ground state) was also observed with high angular resolution using the IRAM Plateau de Bure Interferometer – PdBI– (France) in the A and B configurations. The 3 mm receiver was tuned to double side band. The HPBW of the synthesized beam was $1.25'' \times 0.99''$, PA=$-25°$. The correlator was configured to cover 145 MHz ($439\,\mathrm{km\,s^{-1}}$) with a spectral resolution of 625 KHz ($1.89\,\mathrm{km\,s^{-1}}$). CRL618 (1.73 Jy) and MWC349 (1.03 Jy) were used as flux density calibrators. The total observing time on–source was about 7 hours.

Fig. 1 shows the SO_2 and HC_3N^* line profiles observed with the 30 m telescope and the PdBI toward CepA HW2, and Tab. 1 gives the line parameters obtained by fitting Gaussian profiles. Our $J = 16_{2,14} \rightarrow 15_{3,13}$ and $J = 3_{1,3} \rightarrow 2_{0,2}$ SO_2 lines are in agreement with those of Codella et al. (2003). The $J = 3_{1,3} \rightarrow 2_{0,2}$ SO_2 line will be not used in our analysis since it is easily excited and mainly arises from the extended molecular outflow. Like most of the low excitation lines of many molecules (Martín–Pintado, Bachiller, & Fuente 1992; Bergin et al. 1997; Codella et al. 2003), all of the high excitation lines of SO_2 and HC_3N^* peak around – $10\,\mathrm{km\,s^{-1}}$. The SO_2 lines also show a slightly asymmetric profile with a weak redshifted wing. This asymmetry is probably associated with the high velocity shocks observed in SO_2 (Codella et al. 2003).

Fig. 2 shows the high angular resolution PdBI images of the continuum emission (thin solid contours and grey map) and of the $J = 28_{7,21} \rightarrow 29_{6,24}$ SO_2 line intensity at $-10\,\mathrm{km\,s^{-1}}$ (thick solid contours). The continuum emission is unresolved in our beam with a peak continuum intensity of 110 ± 15 mJy, in agreement with those previously measured by Mehringer, Zhou, & Dickel (1997) and Gómez et al. (1999), and consistent with the continuum emission arising from the HW2 radio–jet. For all radial velocities, the $J = 28_{7,21} \rightarrow 29_{6,24}$ SO_2 line emission is also spatially unresolved, indicating that the highly excited gas is very compact with a size of $\leq 0.6''$ (430 AU). The unresolved SO_2 condensation contains most of the flux (70%) measured with the 30 m telescope. As shown in Fig. 2, the SO_2 emission is located $0.4''$ east from the radio–jet. This is consistent with the warm NH_3 emission

observed in the (3,3) line by Torrelles et al. (1999).

3. PROPERTIES OF THE COMPACT MOLECULAR CONDENSATION

Tab. 2 summarizes the properties of the compact molecular condensation. Fig. 3 shows the population diagrams (see e.g. Goldsmith & Langer 1999) derived for SO_2 and HC_3N^*. The level populations of both molecules can be fitted by straight lines with similar excitation temperatures of 150–160 K, indicating the presence of a hot condensation (hereafter HC). We have constrained the size of the HC by using the upper limit to the size measured from the interferometric maps of $0.6''$, and the lower limit of $0.3''$ derived from the measured main beam brightness temperature of the $J = 28_{7,21} \rightarrow 29_{6,24}$ SO_2 line and the excitation temperature of 160 K. In the following discussion, we will consider a size of $0.6''$ (430 AU) for the HC. The derived excitation temperature from the HC_3N^* transitions is unlikely affected by optical depth effects since the observed lines are weaker than those expected from a source of $0.6''$ and optically thick emission with an excitation temperature of 160 K.

Combining the column density derived from the PdBI data of the $J = 28_{7,21} \rightarrow 29_{6,24}$ SO_2 line (see Table 1) with the estimated source size of $0.6''$ and the excitation temperature of 160 K, we derive a total SO_2 column density for the HC of $\sim 10^{18}\,\mathrm{cm^{-2}}$. Although the H_2 column density of the HC is unknown, it can be constrained between 10^{23} and $6 \times 10^{24}\,\mathrm{cm^{-2}}$. The upper limit of $6 \times 10^{24}\,\mathrm{cm^{-2}}$ is derived from our 3 mm continuum intensity of 30 mJy measured at the location of the HC, and by assuming that it arises from dust at a temperature of 160 K. The lower limit is obtained by assuming the extreme case that 50% of the cosmic sulfur abundance is in SO_2. Assuming spherical symmetry, the H_2 densities in the HC range between 10^7 and $6 \times 10^8\,\mathrm{cm^{-3}}$. Hereafter (see Tab. 2), we will consider the intermediate case for a H_2 column density of $10^{24}\,\mathrm{cm^{-2}}$ (i.e. a SO_2 abundance of 10^{-6}). In this case, the H_2 density and the mass of the HC will be $\sim 10^8\,\mathrm{cm^{-3}}$ and $4 \times 10^{-2} M_\odot$ respectively. The kinetic temperature, (T_{kin}), of the HC is unknown, but it must be equal or larger than the derived excitation temperature of 160 K. For the high density ($> 10^7\,\mathrm{cm^{-3}}$) derived for the HC, the SO_2 transitions are thermalized and the excitation temperature should be a direct measurement of the kinetic temperature. Furthermore the dust and gas must be also closely coupled and the dust temperature should be equal to the gas kinetic temperature. Since the HC is optically thick in the mid–IR, we estimate a bolometric luminosity of $\sim 10^3\,L_\odot$ by assuming that it emits like a black body at 160 K.

In summary, we have detected a warm (160 K), very dense ($> 10^7\,\mathrm{cm^{-3}}$) and compact condensation (size $\sim$400 AU) located 300 AU east from the radio–jet HW2. The HC has a total mass of $4 \times 10^{-2}\,M_\odot$, a luminosity of $\sim 10^3\,L_\odot$ and a very large abundance ($\geq 2 \times 10^{-7}$) of SO_2.

4. THE NATURE OF THE HOT CONDENSATION. A HOT CORE

In view of the complexity of the region in the vicinity of HW2, we discuss the two most likely possibilities for the nature of the HC. The first one consists of a hot and dense spot in the expected circumstellar disk around the radio–jet. In the disk scenario, the large H_2 column density ($10^{24}\,\mathrm{cm^{-2}}$) of hot gas (160 K) in the HC could be

externally heated by the IR radiation from HW2 or by the shocks produced by the stellar wind of HW2. For the projected distance between HW2 and the HC, external heating by radiation would require the IR luminosity of HW2 to be few 10^5 L$_\odot$ (Fig. 7 of Kaufman, Hollenbach, & Tielens 1998), which is at least one order of magnitude larger than that measured in the whole region of 2×10^4 L$_\odot$. Shock heating would require collisional excitation of the $v_7 = 1$ and 2 vibrationally levels of HC$_3$N and the conversion of 10% of the total bolometric luminosity in the region into mechanical luminosity. Collisional excitation of the vibrational levels of HC$_3$N is possible since the H$_2$ densities estimated for the HC are close to the critical densities of 2×10^8 cm^{-3} (Goldsmith et al. 1982). Shocks should then provide a mechanical luminosity of 10^3L$_\odot$ in a region of only 400 AU. This is very unlikely since the total mechanical luminosity in the large scale outflow powered by HW2 is only 30 L$_\odot$ (Narayanan & Walker 1996), nearly two orders of magnitude smaller than the mechanical luminosity required to heat the HC.

The second possibility is that we are observing a hot core internally heated. This option will explain the presence of the vibrationally excited emission which in hot cores is usually produced by IR radiation (see e.g. de Vicente et al. 2000). The luminosity and the mass of the hot core in HW2 will be more than one order of magnitude smaller than those reported for hot cores associated with massive stars. Then, the HC will be the first hot core associated with an intermediate mass star. The luminosity of the hot core would require a main sequence B5 star. Large SO$_2$ abundance ($\sim 10^{-7}$) seems to be a general property of hot cores associated with massive protostars (Keane et al. 2001). Our lower limit to the SO$_2$ abundance of 2×10^{-7} suggests that intermediate mass hot cores have similar sulfur chemistry than those associated with massive protostars. The derived HC$_3$N abundance in the HC of $\sim 10^{-8}$, is also in agreement with the abundances measured in hot cores associated with massive stars (de Vicente et al. 2000). It has been proposed that the large abundance of sulfur–bearing molecules can be driven by fast gas phase reactions after the evaporation from grain mantles of key molecules like H$_2$S (Charnley 1997), OCS (van der Tak et al. 2003; Martín et al. 2005) and SO (Jimenez–Serra et al. 2005) or atomic sulfur (Wakelam et al. 2004). From the available data on other sulfur–bearing molecules, SO$_2$ seems to be the most abundant species in the HC. We can set upper limits to the abundance of other sulfur–

bearing molecules and of atomic sulfur by assuming that all their emissions observed with beams of 10–30$''$, are optically thin and arise from the hot core. From the H$_2$S, SO and [S I] 25.2μm observations of Codella et al. (2003), Martín–Pintado et al. (1992) and Wright et al. (1996) respectively, we derive column densities for the three species of 1–2×10^{17}cm^{-2}. Their corresponding abundances are $\leq 10^{-8}$, at least one order of magnitude smaller than the SO$_2$ abundance. Viti et al. (2004) have performed model calculations to follow the sulfur chemistry evolution from the collapse phase to the hot core stage using new experimental data on desorption temperatures for mixed ices. The model predicts that an intermediate mass star of 5 M$_\odot$ in the hot core phase will evaporate H$_2$S from the grain mantles, and after few 10^5 years, will produce SO$_2$ in gas phase with abundances similar to that observed in the intermediate mass hot core in HW2.

The discovery reported in this letter of an intermediate mass protostar, and the recent detection of two embedded young stellar objects (Curiel et al. 2002) within 500 AU of HW2, support the scenario of the formation of a cluster of stars. The new protostar in the HW2 region is an excellent candidate for powering one of the three molecular outflows observed in the region (Codella et al. 2003). If the relationship found between the mechanical luminosity of the molecular outflows and the luminosity of their exciting sources (Shepherd & Churchwell 1996) holds for the outflows in the CepA region, the new protostar will be luminous enough to power the east outflow (Hayashi et al. 1988). However, high angular resolution observations of these outflows are needed to confirm if the new protostar is the driving source of one of the multiple outflows found in this region.

In summary, we have detected a hot and dense condensation in the vicinity of the radio–jet HW2 in the CepA region. From the properties of the hot condensation, we suggest that it is a hot core heated by an intermediate mass protostar. This protostar could be the driving source of one of the observed multiple molecular outflows. The detection of a new protostar in the vicinity of HW2 supports the idea of the formation of a cluster of massive and intermediate stars in the CepA region.

REFERENCES

Bergin, E. A., Ungerechts, H., Goldsmith, P. F., Snell, R. L., Irvine, W. M., Schloerb, F. P. 1997, ApJ, 482, 267

Charnley, S. B. 1997, ApJ, 481, 396

Codella, C., Bachiller, R., Benedettini, M., & Caselli, P. 2003, MNRAS, 341, 707

Curiel, S. et al. 2002, ApJ, 564, L35

de Vicente, P., Martín–Pintado, J., Neri, R., & Colom, P. 2000, A&A, 361, 1058

Garay, G., Ramírez, S., Rodríguez, L. F., Curiel, S., & Torrelles, J. M. 1996, ApJ, 459, 193

Garay, G. & Lizano, S. 1999, PASP, 111, 1049

Goldsmith, P. F., Snell, R. L., Deguchi, S., Krotkov, R., & Linke, R. A. 1982, ApJ, 260, 147

Goldsmith, P. F. & Langer, W. D. 1999, ApJ, 517, 209

Gómez, J. F., Sargent, A. I., Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., Cantó, J., & Garay, G. 1999, ApJ, 514, 287

Hayashi, S. S., Hasegawa, T., & Kaifu, N. 1988, ApJ, 332, 354

Hughes, V. A. & Wouterloot, J. G. A. 1984, ApJ, 276, 204

Jimenez–Serra, I., Martín–Pintado, J. Rodríguez–Franco, A., & Martín, S. 2005, submitted

Kaufman, M. J., Hollenbach, D. J., & Tielens, A. G. G. M. 1998, ApJ, 497, 276

Keane, J. V., Tielens, A. G. G. M., Boogert, A. C. A., Schutte, W. A., & Whittet, D. C. B. 2001, A&A, 376, 254

Martín, S., Martín–Pintado, J., Mauersberger, R., Henkel, C., & García–Burillo, S. 2005, ApJ, 620, 210

Martín–Pintado, J., Bachiller, R., & Fuente, A. 1992, A&A, 254, 315
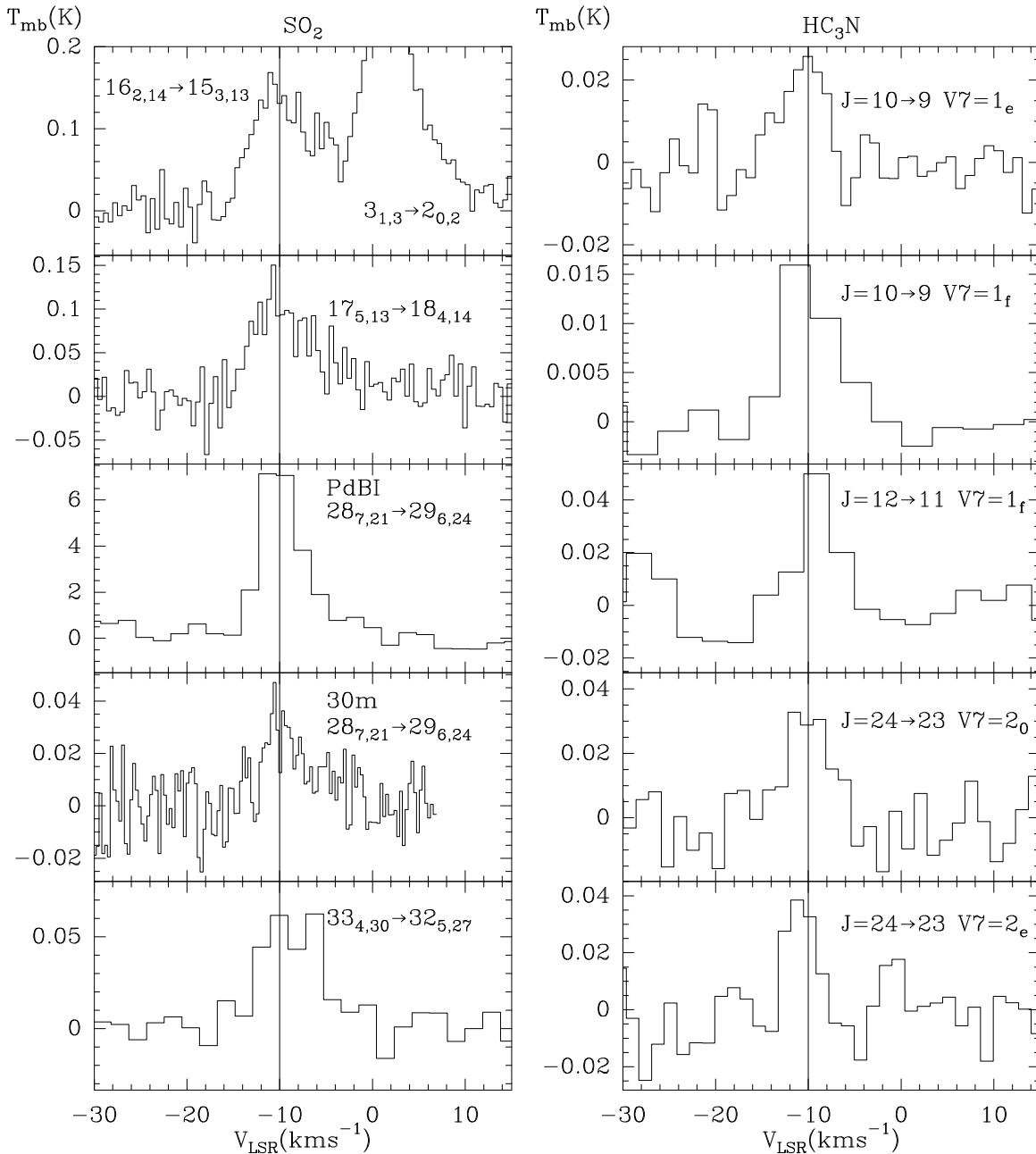
McKee, C. F. & Tan, J. C. 2003, ApJ, 585, 850

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FIG. 1.— Sample of profiles of the SO$_2$ and HC$_3$N vibrationally excited rotational transitions observed toward CepA HW2.

Mehringer, D. M., Zhou, S., & Dickel, H. R. 1997, ApJ, 475, L57

Narayanan, G., & Walker, C. K. 1996, ApJ, 466, 844

Rodríguez, L. F., Moran, J. M., & Ho, P. T. P. 1980, ApJ, 240, L149

Rodríguez, L. F., Garay, G., Curiel, S., Ramírez, S., Torrelles, J. M., Gómez, Y., & Velázquez, A. 1994, ApJ, 430, L65

Shepherd, D. S., & Churchwell, E. 1996, ApJ, 472, 225

Torrelles, J. M., Gómez, J. F., Rodríguez, L. F., Curiel, S., Ho, P. T. P., & Garay, G. 1996, ApJ, 457, L107

Torrelles, J. M., Gómez, J. F., Garay, G., Rodríguez, L. F., Miranda, L. F., Curiel, S., & Ho, P. T. P. 1999, MNRAS, 307, 58

Torrelles, J. M., et al. 2001, Nature, 411, 277

van der Tak, F. F. S., Boonman, A. M. S., Braakman, R., & van Dishoeck, E. F. 2003,A&A, 412, 133

Viti, S., Collings, M. P., Dever, J. W., McCoustra, M. R. S., & Williams, D. A. 2004, MNRAS, 354, 1141

Wakelam, V., Caselli, P., Ceccarelli, C., Herbst, E., & Castets, A. 2004, A&A, 422, 159

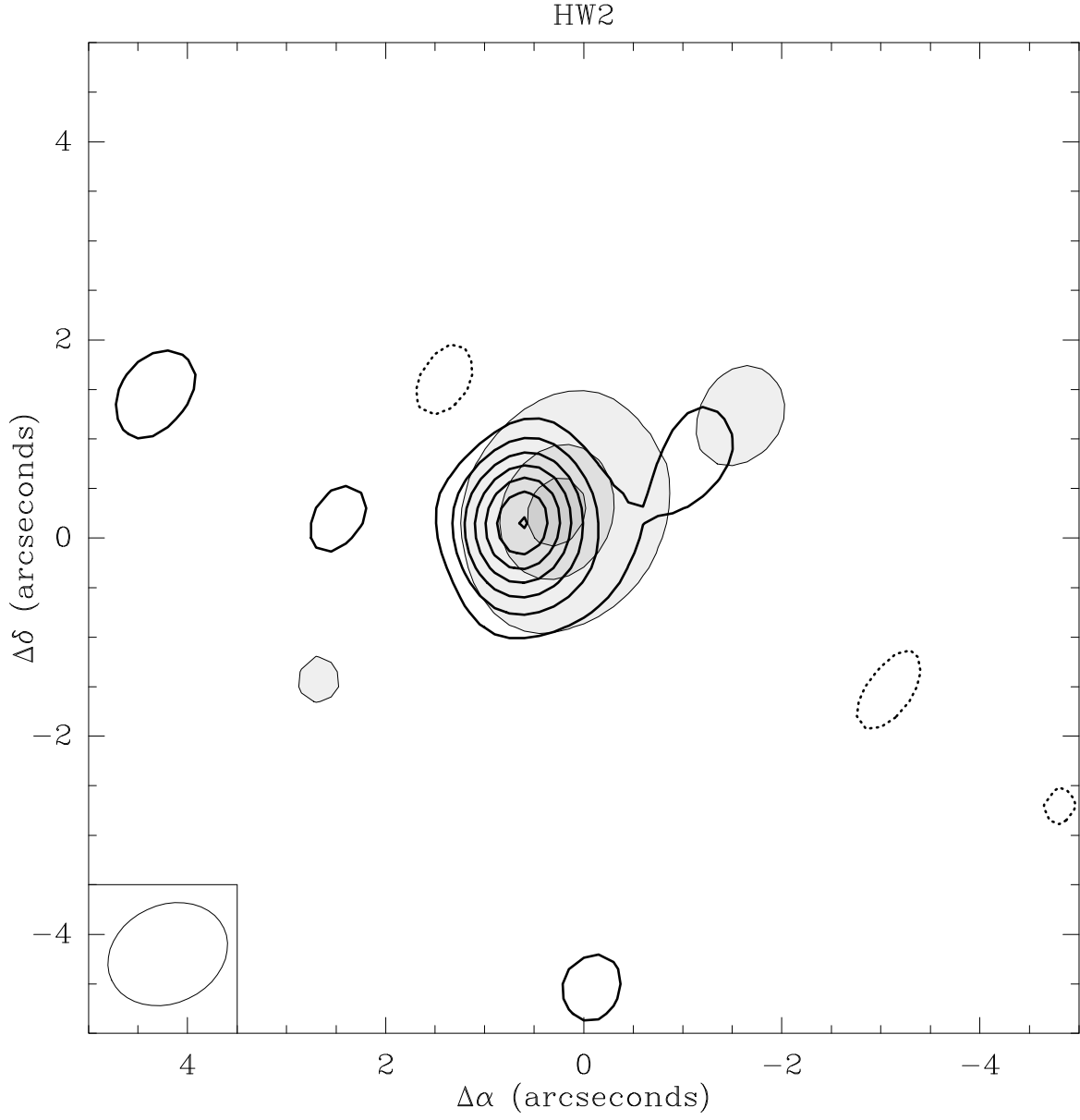Wright, C. M., Drapatz, S., Timmermann, R., van der Werf, P. P., Katterloher, R., & de Graauw, T. 1996, A&A, 315, L301

HW2

FIG. 2.— Images of the $J = 28_{7,21} \rightarrow 29_{6,24}$ SO$_2$ line intensity at $-10\,\mathrm{km\,s^{-1}}$ (thick solid contours) superimposed on the radio continuum emission at 3 mm (thin solid contours and grey map). The lowest level and the step for the continuum map are 0.01 Jy/beam and 0.04 Jy/beam respectively. The contour levels for the SO$_2$ map are -0.01, 0.01, 0.02, 0.03, 0.04, 0.05, 0.06 and 0.07 Jy/beam km s^{-1}. Beam size is shown in the lower left corner.
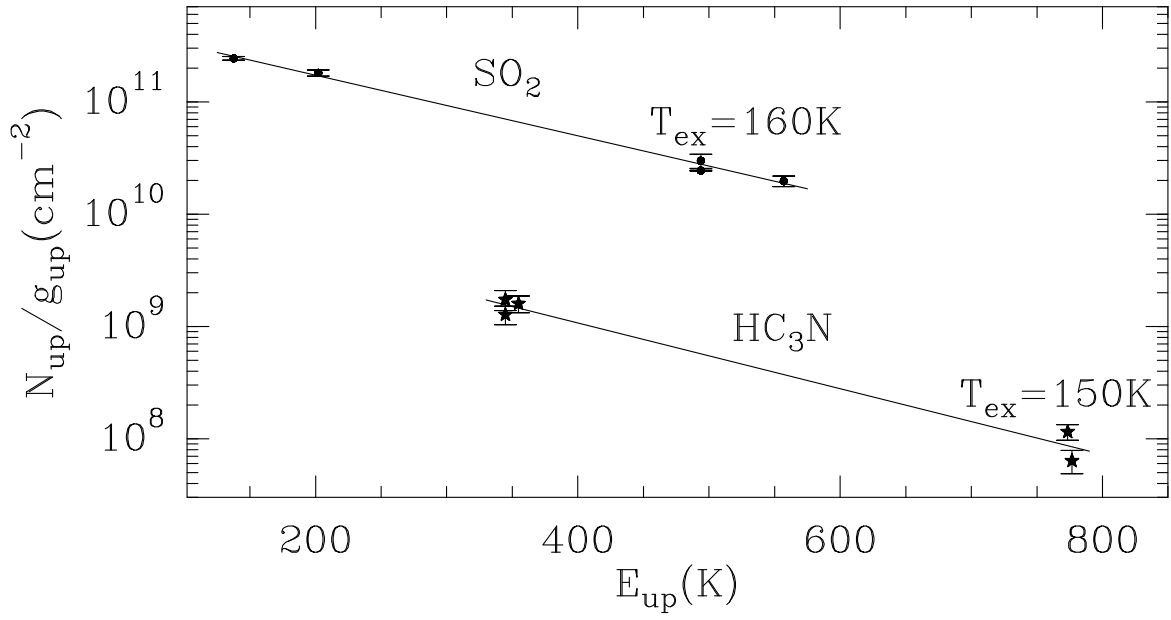
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F<small>IG</small>. 3.— Population diagrams for all the SO₂ and HC₃N* rotational transitions observed toward CepA HW2. The column densities are averaged values in a beam of 24″ for SO₂ and 27″ for HC₃N*.

Line	V_{LSR}[a] $(\mathrm{km\,s^{-1}})$	Δv[a] $(\mathrm{km\,s^{-1}})$	T_{mb}[a] (K)	N_{up} $(\times 10^{11}\,\mathrm{cm^{-2}})$
SO$_2$				
$16_{2,14} \to 15_{3,13}$	-9.7 (1)	7.9 (4)	0.144 (3)	80.4
$17_{5,13} \to 18_{4,14}$	-9.6 (3)	7.8 (6)	0.100 (3)	70.3
$28_{7,21} \to 29_{6,24}$	-10.0 (1)	5.2 (3)	8.8 (1)	3628[b]
$28_{7,21} \to 29_{6,24}$	-9.4 (5)	6 (1)	0.030 (4)	15.4
$33_{4,30} \to 32_{5,27}$	-8.8 (4)	7.8 (9)	0.060 (4)	30.0
HC$_3$N				
$10 \to 9\ v_7 = 1e$	-10.5 (5)	4.8 (9)	0.026 (6)	0.36
$10 \to 9\ v_7 = 1f$	-10.3 (5)	5 (2)	0.017 (4)	0.27
$12 \to 11\ v_7 = 1f$	-8.9 (5)	4.3 (8)	0.050 (3)	0.57
$24 \to 23\ v_7 = 2_0$	-10.2 (5)	7 (1)	0.04 (1)	0.33
$24 \to 23\ v_7 = 2_e$	-10.8 (4)	3.4 (8)	0.04 (1)	0.18

[a]The 1σ errors from the gaussfits are shown in parenthesis.
[b]SO$_2$ column density derived for a beam of $1.25'' \times 0.99''$.

Source	Location[a] ($''$)	Size ($''$)	T_{kin} (K)	n_{H_2} $(\mathrm{cm^{-3}})$	Column densities[b] SO$_2$	HC$_3$N	H$_2$[c]	Luminosity (L$_\odot$)	Mass (M$_\odot$)
HC	$0.32(0.03) \times 0.15(0.03)$	0.3–0.6	160(10)	1.5×10^8	1×10^{18}	3×10^{16}	1×10^{24}	1×10^3	4×10^{-2}

[a]Offset from the continuum peak at $\alpha(2000) = 22^{\mathrm{h}}56^{\mathrm{m}}17.97^{\mathrm{s}}(0.01)$, $\delta(2000) = 62^{\mathrm{o}}1'49.70''(0.08)$ derived from gaussian fits.
[b]For a source size of $0.6''$ (430 UA) and a distance to the source of 725 pc. Column densities are in units of $\mathrm{cm^{-2}}$.
[c]See text for details.