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Submillimeter Array observations of 321 GHz water maser emission in Cepheus A

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Abstract. Using the Submillimeter Array (SMA) we have imaged for the first time the 321.226 GHz, $10_{29} - 9_{36}$ ortho-H_2O maser emission. This is also the first detection of this line in the Cepheus A high-mass star-forming region. The 22.235 GHz, $6_{16} - 5_{23}$ water masers were also observed with the Very Large Array 43 days following the SMA observations. Three of the nine detected submillimeter maser spots are associated with the centimeter masers spatially as well as kinematically, while there are 36 22 GHz maser spots without corresponding submillimeter masers. In the HW2 source, both the 321 GHz and 22 GHz masers occur within the region of $\sim$ 1" which includes the disk-jet system, but the position angles of the roughly linear structures traced by the masers indicate that the 321 GHz masers are along the jet while the 22 GHz masers are perpendicular to it. We interpret the submillimeter masers in Cepheus A to be tracing significantly hotter regions (600$\sim$2000 K) than the centimeter masers.

Keywords. ISM: jets and outflows, submillimeter, masers, stars: formation

1. Introduction

It is well known that water masers in star-forming regions are closely associated with highly energetic gas dynamics during an early stage of evolution of the protostar, as first pointed out by Strelńitskii and Sunyaev (1972). These masers arise in hot ($\geqslant$ 500 K) and dense (10^9 cm^{-3}) gas in shocked regions associated with bipolar outflows (Elitzur *et al.* 1989). VLBI observations of the 22 GHz masers have been very helpful in revealing the kinematics of the gas around young stellar objects (YSO) over length scales of one to several hundreds of AU (e.g., Torrelles *et al.* 2001a; 2001b; Uscanga *et al.* 2007; Patel *et al.* 2000). From the observations of just this single $6_{16} - 5_{23}$ transition, however, it is difficult to infer the physical conditions of the masing regions very close to the YSO. With observations of multiple masing transitions, we can use the line ratios to check theoretical models of the excitation of these lines and infer the physical conditions in the masing regions. All the known masing transitions in H_2O, except for the $6_{16} - 5_{23}$ transition lie in the millimeter and submillimeter range of wavelengths (Neufeld and Melnick 1991). With the availability of the Submillimeter Array (SMA; Ho *et al.* 2004), interferometric observations of these lines are now possible (see review by Humphreys 2007). Here we briefly present results from our study of the $10_{29} - 9_{36}$ water maser emission at 321.226 GHz (along with the 22 GHz water masers) from the high-mass star-forming region Cepheus A, as reported in more detail in Patel *et al.* (2007).

2. 321 GHz water maser emission

The $10_{29} - 9_{36}$ ortho-H_2O transition at the frequency of 321.226 GHz lies about 1200 K above the well studied $6_{16} - 5_{23}$ transition at 22.235 GHz (which itself is about 640 K above the ground level). Hence, the excitation of the 321 GHz line would require relatively much higher temperature and these masers are expected to arise in highly shocked regions. The first astronomical detection of the 321 GHz maser emission was made by Menten *et al.* (1990) using the Caltech Submillimeter Observatory 10.4 m telescope toward the star-forming regions W3(OH), W49N, W51 IRS 2, and W51 Main and the supergiant star VY CMa. About one month after the submillimeter observations, Menten *et al.* obtained 22 GHz observations using the Haystack 37 m telescope. Their comparison of the 321 GHz and 22 GHz spectra (see Figure 3 of Menten *et al.* 1990) show the 321 GHz emission to be significantly weaker and having very different line profiles compared to the 22 GHz spectra. The angular resolution in these single dish observations was inadequate to check if the 22 GHz and 321 GHz masers were arising from the same location.

3. Cepheus A high-mass star-forming region

Cepheus A is a well-known high-mass star-forming region located at a distance of ~725 pc in the Cepheus OB3 complex of molecular clouds (Sargent 1977). Several compact objects in this region have been identified from radio continuum observations at centimeter wavelengths with the VLA (hereafter described as HW sources: Hughes & Wouterlout 1984; Garay *et al.* 1996). The 22 GHz water masers have been observed towards several of these HW sources (Torrelles *et al.* 1996, 2001a, 2001b; Vlemmings *et al.* 2006; Gallimore *et al.* 2004). HW2 appears to be the most dominant among these sources and the 1.3 cm and 3.6 cm thermal jet associated with HW2 is shown to have proper motions of $\sim$500 km s^{-1} (Curiel *et al.* 2006). Perpendicular to this jet and nearly coincident with it, was found an elongated structure in 330 GHz continuum emission observed with the SMA. This structure was interpreted to be a circumstellar disk around HW2 (Patel *et al.* 2005). A different interpretation has been suggested by Brogan et al. (2007) who propose that the elongated structure is due to multiple sources within 1" of HW2. See also Comito *et al.* (2004), Martín-Pintado *et al.* (2005). VLBI observations of methanol masers in this region are reported by Sugiyama *et al.* (2007) and Torstensson & van Langevelde (2007).

4. SMA and VLA observations

We observed the Cepheus A region with the SMA on 2004 August 30 using seven antennas in the extended configuration with a maximum baseline length of 220 m. The phase center was $\alpha(2000) = 22^h56^m17.971^s, \delta(2000) = +62°01'49.''279$. We used a tuning of 321.226 GHz to center the water maser lines in the lower sideband (LSB). With uniform weighting, the synthesized beam was $0.''8 \times 0.''7$ with a position angle (P. A.) of -80°. The rms noise in the images was $\sim$160 mJy/beam.

We also observed the 22.235 GHz water masers in Cepheus A with the VLA in the A configuration on 2004 October 12. The rms noise level in our VLA observations is about 3.3×10^{-3} Jy beam^{-1} in channels free of maser emission and $\sim 4.5 \times 10^{-1}$ Jy beam^{-1} in the channel with the strongest maser spot. The line and continuum data at 1.3 cm were obtained simultaneously and the astrometric registration between the maser and continuum emission is better than $0.''01$.

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5. Results and discussion

The submillimeter maser emission was detected only from HW2 and HW3c in the Cepheus A region. The 1.3 cm continuum emission is shown as contours in Figure 1 for these two sources. The 22 GHz masers are shown as crosses and the positions of the 321 GHz masers are shown with error bars representing their 1σ uncertainties. The 321 GHz masers appear to lie along the thermal jet with velocities in agreement with the larger scale bipolar outflow (Gomez *et al.* 1999; Rodriguez *et al.* 1980). The 22 GHz masers on the other hand, appear to be along the perpendicular direction, presumably associated with the elongated structure seen in submillimeter continuum emission.

In HW2, only 2 out of the 7 submillimeter masers are found to be coincident with the 22 GHz masers (occurring within few tens of milliarcseconds and <3 km s^{-1}). In HW3c, the single submillimeter maser spot is found to be agreeing in position and velocity with the 22 GHz maser. There are several 22 GHz masers unaccompanied by the 321 GHz maser emission. The spectra of 321 GHz and 22 GHz masers (see Figure 2 of Patel *et al.* 2007) show that in HW2, the 321 GHz masers seem to prefer higher velocities w.r.t. the systemic velocity of HW2.

Shortly after the discovery of the 321 GHz masers, Neufeld & Melnick (1990), showed that the observed 22 and 321 GHz masers can be explained by collisional excitation within the same volume of gas. These authors presented models of the emissivity ratio R of 22 GHz/321 GHz maser luminosity as a function of ξ and T, where ξ is the "maser emission measure" defined by Elitzur *et al.* 1989 and is proportional to the square of the gas density. Yates *et al.* (1997) carried out similar calculations covering a wider range of physical conditions than in Neufeld & Melnick (1990). According to these models, the 321 GHz maser is strongly inverted under more restricted conditions than the 22 GHz line (see Fig. 3 of Neufeld & Melnick 1990 and Fig. 4a of Yates *et al.* 1997). Hence, there can be 22 GHz emission but the 321 GHz masers must always have associated 22 GHz masers.

In the three regions where the 321 and 22 GHz masers appear coincident, the observed emissivity ratio R (22/321 GHz) implies the kinetic temperature to be in the range of 500–2000K, depending on the value of ξ. According to Neufeld & Melnick (1990), the typical value of log ξ would be in the range of –1.25 to –0.25 for the shocked gas in star-forming regions and their Figure 3 would then imply a temperature of $\sim$ 600K to 2000K for a wide range of ξ.

With respect to the remaining six 321 GHz masers which do not appear to be associated with 22 GHz masers, we cannot apply any of the existing theoretical models to these $R \rightarrow 0$ cases that imply that the 22 GHz masers are quenched but the 321 GHz emission remains strong. According to Figure 3 of NM90, which has the lowest contour corresponding to $R = 1.5$, the regions with $R \rightarrow 0$ may imply temperatures greater than 2000K.

The 22 GHz masers are well known to be time-variable. Previous VLBA observations of Cepheus A (Torrelles *et al.* 2001a, 2001b) and IRAS 21391+5802 (Patel *et al.* 2000), show that several masing spots disappear over time-scales of 1 month. These masers however, tend to be relatively weaker. The theoretical models as in NM90 predict strong emission at 22 GHz corresponding to the 321 GHz masers. If these corresponding 22 GHz masers existed during the epoch of the submillimeter observations, they are unlikely to have been completely extinguished about a month later in the centimeter wavelength observations. See also Lekth *et al.* (1982) and Brand *et al.* (2007).

The 22 GHz masers that are not associated with the 321 GHz masers are likely to be arising in relatively cooler regions among the various HW sources in Cepheus A,

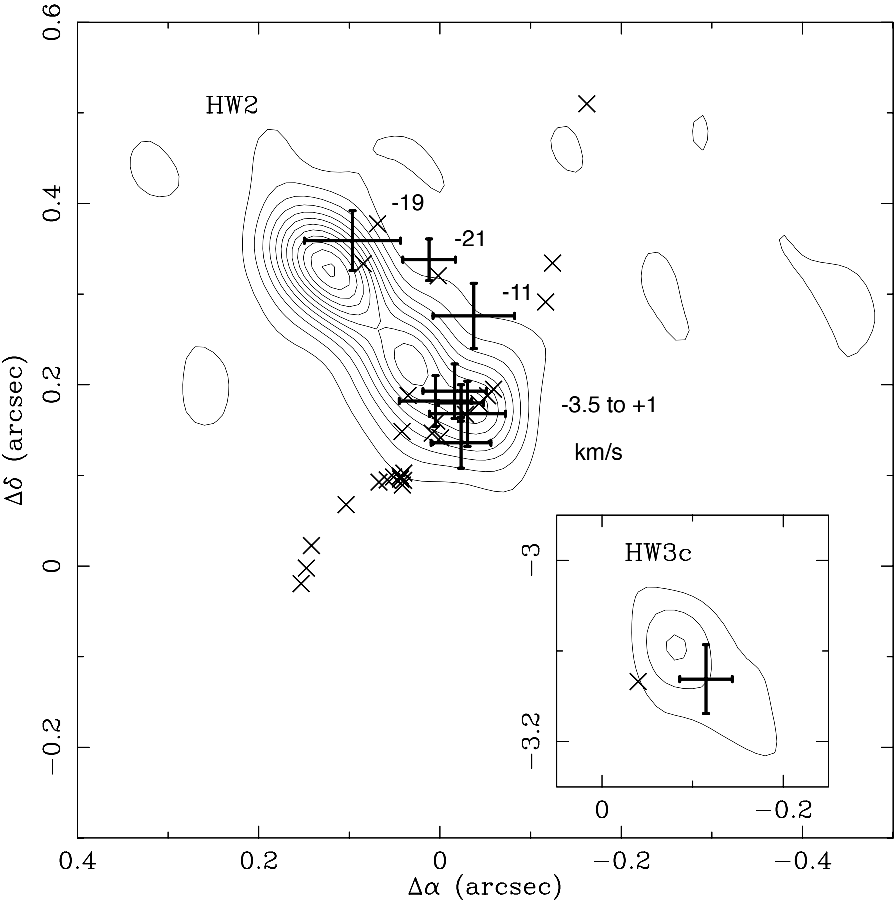

Figure 1. VLA map of 1.3 cm continuum emission from HW2 and HW3c (*inset*). The positions of submillimeter water masers observed with the SMA are shown with error bars representing the formal uncertainties. The position offsets were obtained by fitting two-dimensional elliptical Gaussians to integrated intensity maps over channels in which the maser emission appeared. The numbers denote the LSR velocities of the 321 GHz water masers. (The systemic velocity of the HW2 source is ~ -10 km s^{-1}.) The position offsets are with respect to the absolute coordinates: $\alpha(2000) = 22^h 56^m 17.971^s, \delta(2000) = +62°01'49.''279$. The crosses show the positions of the 22 GHz water masers observed with the VLA (43 days after the SMA observations). The errors in the positions of the 22 GHz water masers are smaller than the size of the symbols shown. The VLA beam is $0.''09 \times 0.''07$ (P.A. 14°). The SMA beam is $0.''8 \times 0.''7$ with a P.A. of -80°. Figure from Patel *et al.* 2007

compared to HW2 and HW3c. The fact that the submillimeter wavelength masers in HW2 are found along the major axis of the jet, lead us to propose that they are arising in hotter gas regions due to the impact of the jet.

6. Conclusions and future work

(1) The 321 GHz maser emission was detected in HW2 and HW3c in the Cepheus A high-mass star-forming region using the SMA. (2) 3 out of 9 submillimeter masers are found to be associated with the 22 GHz masers. (3) Submillimeter masers appear to

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trace the outflow jet in HW2, presumably arising in hot gas of temperature about 1000–2000 K. (4) Multi-transition observations of water masers can be used to constrain theoretical models of their excitation, and when these models are improved, such observations can be useful to probe the physical conditions of the masing regions. We plan to observe other high-mass star-forming regions such as W75N, W3(OH), W3 IRS5 and NGC 6334N with the SMA and VLA, nearly simultaneously. We also look forward to the availability of the 400 GHz band receivers on the SMA to allow observations of water maser transitions in this band (Melnick *et al.* 1993).

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References

Brand, J., Felli, M., Cesaroni, R. *et al.* 2007, *this volume*
Brogan, C., Chandler, C., Hunter, T., *et al.* 2007 *to appear in ApJL, astro-ph/0703626*
Comito C., Schilke, P., Jiménez-Serra, I. & Martín-Pintado, J. 2005, *IAU 231 Symposium Astrochemistry throughout the Universe, eds: Lis, D. C., Blake, G. A. & Herbst, E., Cambridge University Press*
Curiel, S., *et al.* 2006, *ApJ*, 638, 878
Elitzur, M., Hollenbach, D. J., & McKee, C. F. 1989, *ApJ*, 246, 983
Gallimore, J. F., Cool, R. J., Thornley, M. D., & McMullin, J. 2003, *ApJ*, 586, 306
Garay, G., Ramírez, S., Rodríguez, L. F., Curiel, S., & Torrelles, J. M., 1996, *ApJ*, 459, 193
Gómez, J. F., Sargent, A. I., Torrelles, J. M., *et al.* 1999, *ApJ*, 514, 287
Ho, P. T. P., Moran, J. M. & Lo, K. Y., 2006, ApJ, 616, L1
Hughes, V. A. & Wouterloot, J. G. A. 1984, *ApJ*, 276, 204
Humphreys, E. 2007 *this volume*
Lekht, E., Pashchenko, M., Rudnitskii, G., & Sorochenko, R. 1982, *Soviet Astron.*, 26, 168
Martín-Pintado, J., Jiménez-Serra, I., Rodríguez-Franco, A., Martín, S., & Thum, C. 2005, ApJ, 628, L61
Menten, K. M., Melnick, G. J., & Phillips, T. G. 1990, *ApJ*, 350, L41
Melnick, G., J., Menten, K. M., Phillips, T. G. & Hunter, T., 1993, ApJ, 416, L37
Neufeld, D. A., & Melnick, G. J. 1990, *ApJ*, 352, L9
——— 1991, *ApJ*, 368, 215
Patel, N. A., Greenhill, L. J., Herrnstein, J., *et al.* 2000, *ApJ*, 538, 268
Patel, N. A, Curiel, S., Sridharan, T. K., *et al.* 2005, *Nature*, 437, 109
Patel, N. A, Curiel, S., Zhang, Q., *et al.* 2007, *ApJ*, 658, 55
Rodriguez, L., Moran, J. M., & Ho, P. T. P. 1980, *ApJ*, 240, 149.
Sargent, A. I. 1977, *ApJ*, 218, 736
Strelńitskii, V. S. & Sunyaev, R. A. 1972, *Soviet Astron.*, 16, 579.
Sugiayama, K., FujiSawa, K., Honma, M., *et al.* 2007, *this volume*
Torrelles, J. M., Gómez, J. F., Rodríguez, L. F., Curiel, S., Ho, P. T. P., & Garay, G., 1996, ApJ, 457, L107
Torrelles, J. M., *et al.* 2001a, ApJ, 560, 853
——— 2001b, Nature, 411, 277
Torstensson, K. & van Langevelde, H. 2007, *this volume*
Uscanga, L., Canto, J. & Raga, A. C. 2007, *this volume*
Vlemmings, W. H. T., Diamond, P. J., van Langevelde, H. J., & Torrelles, J. M. 2006, *A&A*, 448, 597.
Yates, J. A., Field, D., & Gray, M. D., 1997, *MNRAS*, 285, 303.