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DETECTION OF A CANDIDATE FOR THE EXCITING SOURCE OF THE EXPANDING WATER MASER BUBBLE IN CEPHEUS A

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ABSTRACT

We report sensitive, high angular resolution VLA 3.6 cm and 7 mm continuum observations toward the star-forming region Cepheus A. Three embedded young stellar objects (YSOs) were found within a projected area of $\simeq$0".6 × 0".6 (400 × 400 AU^2). One of the sources is the already known radio continuum jet HW2 (detected at 3.6 cm and 7 mm), while the other two weak sources were not previously known. One of these two new sources is detected only at 7 mm and is located $\simeq$0".15 south from HW2. The other source, detected only at 3.6 cm, is located 0".6 south from HW2 and nearly coincides with the center of the enigmatic expanding bubble of water masers recently detected with the Very Long Baseline Array. We suggest that this radio continuum source is the embedded YSO powering the water maser structure, but its nature is still unknown at present. We also discuss possible scenarios that could explain the surprisingly precise spherical geometry of the water maser bubble.

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

1. INTRODUCTION

Cepheus A is a very active star formation region, containing the second source in the sky ever noted to exhibit the phenomenon of bipolar molecular outflow (Rodríguez, Moran, & Ho 1980). The powering source of this outflow is a thermal radio jet (Rodríguez et al. 1994), known as HW2, which is the brightest of the radio continuum sources detected in the region (Hughes & Wouterloot 1984). From observations made with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO)[8] in its A configuration, Torrelles et al. (1996) reported a group of 25 H_2O masers distributed in a flattened structure, associated with the Cep A/HW2 radio jet. More recent Very Long Baseline Array (VLBA) observations have revealed that some of the "individual" masers detected previously with the VLA unfold into unexpected and remarkable linear/arcuate "microstructures" (R1 through R5; Torrelles et al. 2001a, 2001b; hereafter T01a and T01b, respectively) with sizes of $\simeq$3–100 mas (2–70 AU at the distance of the source of 725 pc; Johnson 1957). Both the spatial distribution and the proper motions of these H_2O maser microstructures indicate that they delineate shock fronts. In particular, the H_2O maser spots in the R5 structure, located about 0".6 to the south of HW2, exhibit a most unusual arclike distribution that can be fitted by a circle with an accuracy of 0.1% (T01a). The circle has a radius of 62 AU, is expanding uniformly at a rate of 9 km s^{-1}, and by the time of the 1996 VLBA observations, had a dynamical age of about 33 yr. These characteristics are consistent with the observed H_2O maser structure being limb-brightened parts of a spherical expanding bubble driven by a very young stellar object (YSO) deeply embedded in the dense molecular core and located at the center of the circle (T01a). The spherical symmetry of the expanding H_2O maser structure is surprising and is not predicted by current theories on star formation, given that the ejection of material in YSOs is expected to be bipolar and highly collimated, driven by the accretion processes within a circumstellar disk.

In this Letter we report radio continuum observations of this region, carried out with the VLA. In addition, we requested archive subarcsecond VLA data to further study this region. We have found that close to the center of the expanding bubble of H_2O masers, there is a weak radio source that is probably associated with the embedded YSO driving the expanding bubble (§ 2). We also discuss the nature of this radio continuum source, as well as possible scenarios that could explain some of the observational characteristics of the enigmatic maser structure R5 (§ 3).

2. OBSERVATIONS AND RESULTS

The observations were carried out with the VLA at 3.6 cm during 2000 December 12 and at 7 mm during 1996 December 21 (see Table 1). These observations were made with an effective bandwidth of 100 MHz and two circular polarizations. The data were edited and calibrated following standard procedures with the Astronomical Image Processing System software of NRAO. We have also compared these results with previous observations, using 3.6 cm archive data taken in 1991 July 7 and the 1.3 cm data reported by Torrelles et al (1996) taken in 1995 July 5. Contour maps at 3.6 cm and 7 mm are

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TABLE 1
Summary of the Observations

λ (cm)	Date	Phase Calibrator	Flux Density (Jy)	Synthesized Beam HPFW (arcsec)	Synthesized Beam P.A. (deg)	rms (μJy beam^{-1})
3.6	2000 Dec 23	2202 + 422	2.76	0.24 × 0. 17	−29	30
0.7	1996 Dec 21	2229 + 695[a]	0.47	0.05 × 0. 04	−56	250
1.3	1995 Jul 5	2200 + 420[a]	3.60	0.08 × 0. 07	88	120
3.6	1991 Jul 7	2229 + 695[a]	0.57	0.24 × 0. 17	33	30

[a] The 1996, 1995, and 1991 data were obtained using B1950 coordinates

shown in Figures 1 and 2, respectively. All the data used in this Letter were taken with the A configuration of the VLA.

The 3.6 cm continuum contour maps obtained in the epoch 2000.9 and with the archive data (epoch 1991.5) show, in addition to the HW2 radio continuum thermal jet, a weak (0.2 mJy beam^{-1}) and compact radio continuum source (hereafter referred to as VLA-R5; Fig. 1), located ~0″.57 to the south of HW2. This weak source was not detected at 7 mm (epoch 1996.9). On the other hand, the 7 mm map also shows the radio continuum jet HW2 as well as a compact source located ~0″.15 to the south of HW2 (Fig. 2), hereafter referred to as VLA-mm. This source is not seen in our observations at 3.6 cm, probably because of blending with the radio continuum emission from the HW2 jet. Neither of the two new continuum sources was detected in the

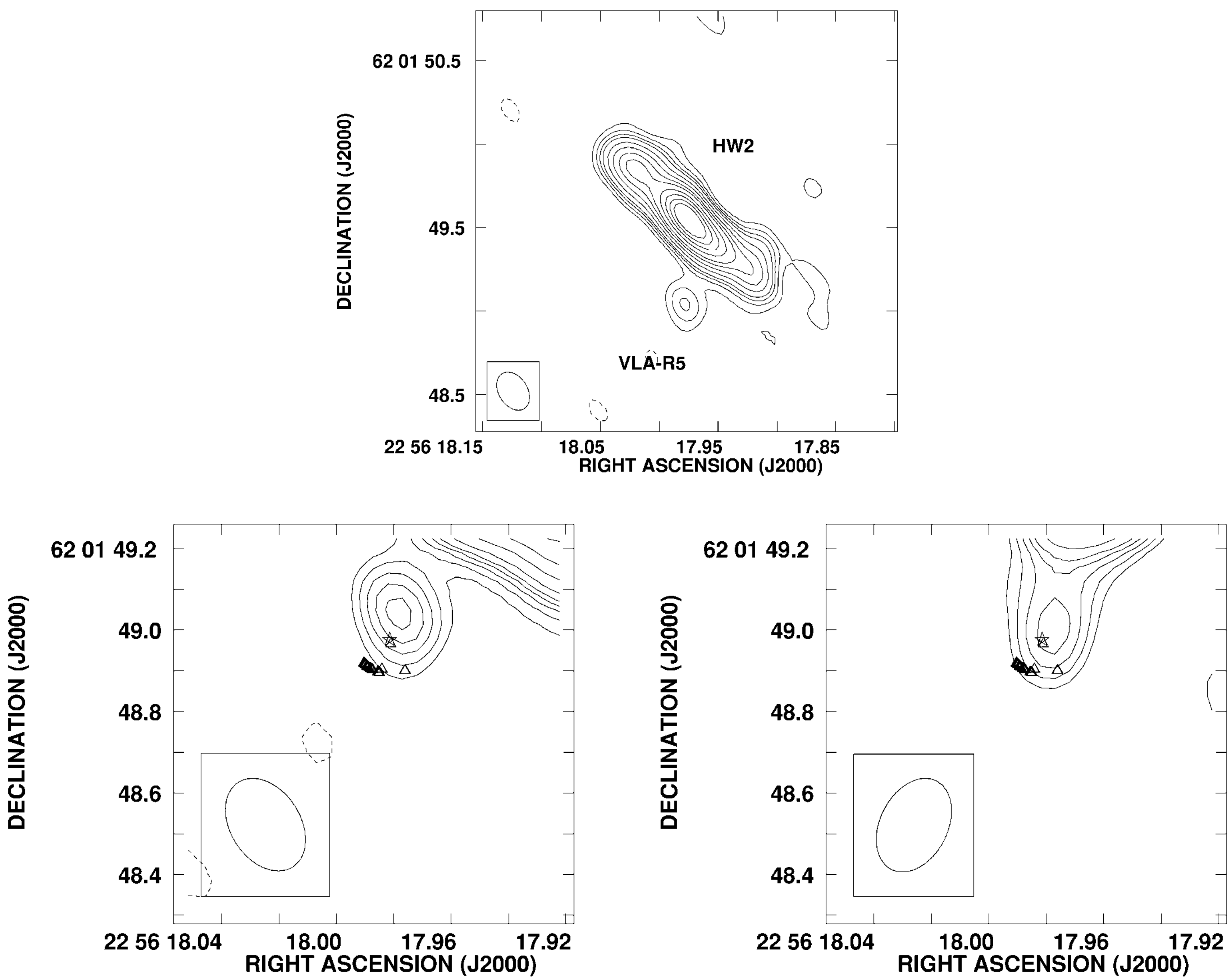

Fig. 1.—*Top*: Contour map of 3.6 cm continuum emission (epoch 1991.52) in the Cep A/HW2 region. Contours are −5, −3, 3, 5, 7, 9, 13, 18, 24, 30, 40, 50, and 60 times 30 μJy beam^{-1}, the rms noise of the map. *Bottom*: Contour maps of VLA-R5 at 3.6 cm for epochs 1991.52 (*left*) and 2000.98 (*right*). Contours are −5, −4, −3, 3, 4, 5, 6, and 7 times 30 μJy beam^{-1}, the rms noise of the maps. The half-power contour of the synthesized beam is shown in the bottom left corner. Triangles indicate the H_2O maser spots in the R5 structure (epoch 1996 February 11) observed by T01a and T01b. The star indicates the expected center of the spherical bubble according to the circle least-squares fit.

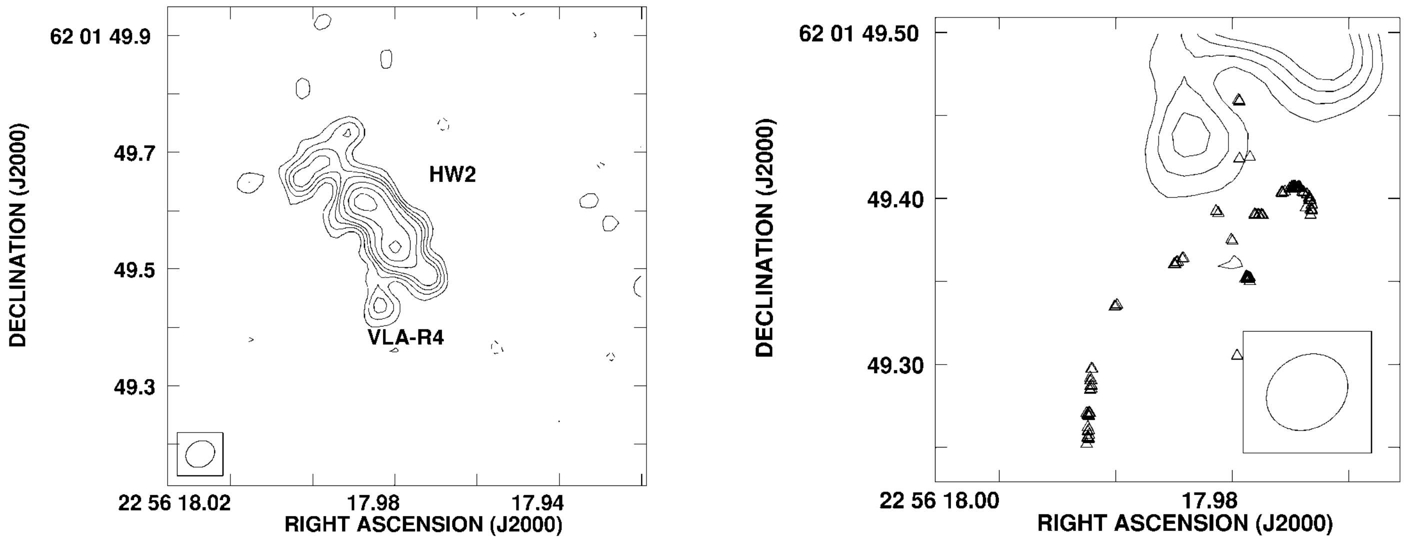

FIG. 2.—Contour maps of the 7 mm continuum emission in the Cep A/HW2 region (*left*) and the VLA-mm source (*right*). Contours are −5, −3, 3, 5, 7, 9, 13, 18, and 24 times 250 μJy beam^{-1}, the rms noise of the map. The half-power contour of the synthesized beam is shown in the bottom left or right corners. Triangles indicate the H_2O maser spots in the R4 structure (epoch 1996 February 11) observed by T01a and T01b.

1.3 cm data (epoch 1995.5). In this Letter we discuss the characteristics of the two new sources reported here; the structure of the thermal radio jet HW2 will be discussed in detail elsewhere.

We have also plotted in the radio continuum maps the water maser positions of the R4 and R5 structures observed with the VLBA by T01b (see Figs. 1 and 2). The alignment between the water maser structures observed with the VLBA and the 3.6 cm and 7 mm continuum maps was carried out in two steps. First, the water masers were aligned with the 1.3 cm continuum map following the method described by T01b. Second, the 3.6 cm and 7 mm maps were aligned with the 1.3 cm map using a compact source (HW3c) located about 3″.4 to the south of HW2, which appears in all the maps and does not show evident proper motions with respect to other sources in the field. We estimate that the error in the alignment of the maps is less than 0″.05. This overlay (see Fig. 1) shows that the weak 3.6 cm continuum source VLA-R5 coincides quite well with the predicted position for the driving source of the expanding bubble of water masers (T01a). On the other hand, the compact source VLA-mm detected at 7 mm to the south of HW2 is located nearby, but is displaced ∼0″.1 to the northeast of the R4-A micro bow-shaped water maser structure (Fig. 2). VLA-mm does not seem to be the powering source of this maser structure, given that the proper motions of the water masers suggest that its powering source must be located to the southeast, along the symmetry axis, and probably close to this micro bow-shaped structure. However, the small group of water maser spots that nearly coincide with VLA-mm might be associated with this source.

These results indicate that there are at least three (probably four, if we account for the undetected exciting source of the micro bow-shock R4) embedded YSOs within a projected area of only $\simeq$0″.6 × 0″.6 (about 400 × 400 AU^2 at the distance of the source), suggesting that the previously known radio continuum source HW2 may actually be a small cluster of YSOs in formation.

3. DISCUSSION

Although VLA-mm was detected at only 7 mm, a lower limit for its spectral index can be estimated using the upper limit obtained at 1.3 cm (see Table 2). We obtain that the spectral index between 1.3 and 0.7 cm is $\alpha \gtrsim 2.0$ ($S_\nu \propto \nu^\alpha$), which is consistent with a compact, optically thick H II region or dust emission from a protostellar disk and/or a dusty envelope. Since this source appears unresolved in the 7 mm map, the size of the H II region or the protostellar disk (and/or envelope) is only $\lesssim$30 AU, which implies that either the H II region is extremely compact or the protostellar disk is smaller

TABLE 2

FLUX DENSITIES AND UPPER LIMITS

Source	λ (cm)	Epoch	α(J2000.0)[a]	δ(J2000.0)[a]	Flux Density[b] (mJy)
VLA-mm	0.7	1996 Dec 21	22 56 17.9845	62 01 49.447	2.06 ± 0.25
	1.3	1995 Jul 5	...	...	$\lesssim$0.6
VLA-R5	3.6	2000 Dec 23	22 56 17.977	62 01 49.04	0.20 ± 0.03
	3.6	1991 Jul 7	22 56 17.976	62 01 49.05	0.23 ± 0.03
	0.7	1996 Dec 21	...	...	$\lesssim$1.25
	1.3	1995 Jul 5	...	...	$\lesssim$0.60

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] The positional errors are about 0″.05 at 3.6 cm and 0″.02 at 7 mm, while the relative error between the maps at different wavelengths and the water masers and the continuum emission is better than 0″.05.

[b] Flux densities with 1 σ uncertainties and 5 σ upper limits.

than the typical size of 100 AU and similar in size to those found in some YSOs, such as L1551 IRS 5 and HH 211 (Rodríguez et al. 1998; Avila, Rodríguez, & Curiel 2001). Subarcsecond resolution observations at wavelengths shorter than 7 mm will be needed to further study the nature of the source.

An upper limit for the spectral index of VLA-R5 can also be estimated by using the measured flux density at 3.6 cm and the upper limit at 1.3 cm. In this case, we obtain $\alpha \lesssim 0.9$, which may be consistent with emission from a stellar wind or an H II region. This spectral index must be interpreted with some care given the low signal-to-noise ratio of the source and the fact that the observations were not taken simultaneously. A reliable estimate of the spectral index of VLA-R5 (and VLA-mm) requires both simultaneous observation with common calibrators (to reduce the systematic errors associated with potential source variability), and similar (u, v) coverage at different wavelengths (especially important for the detection of sources located close to extended emission as in HW2). Unfortunately, these two conditions are not fulfilled by our data, given that the observations at different wavelengths span about 10 yr (between 1991 and 2000) and rely on different calibrators (see Table 1).

Based on the present observations of this region, it is difficult to explain the origin of the continuum emission in VLA-R5, as well as the relationship between the expanding molecular bubble observed in water masers and the weak continuum source at 3.6 cm. T01a have proposed that the observed characteristics of the water maser structure can be explained by a scenario in which an initially smoothly expanding molecular shell (traveling through a medium already evacuated by a previous ejected shell) is overtaken by a subsequent ejection of material by a YSO. This could explain the extremely coherent structure observed in the water maser distribution, as well as the large spread in velocity seen in the line wings in some of the spots localized within the arc structure (T01a; T01b). The proposed model predicts that the expansion velocity would remain nearly constant until the expanding shell interacts with the external molecular medium and that the continuum emission will be compact ($<0''.20$) and with a spectral index probably consistent with that of a thermal wind (i.e., $\alpha \gtrsim 0.2$). On the other hand, the model implicitly assumes that the YSO periodically drives a spherical ejection of material, which is not explained by the current star formation theories. The ejection of material by a YSO is expected to be in two opposite directions and highly collimated. In addition, it is not clear how this YSO could have associated with it thermal radio continuum emission and have at the same time episodic ejection of molecular shells.

An alternative scenario to explain the nature of the expanding bubble of water masers would be to assume that the detected VLA-R5 source is a young expanding H II region. In fact, the measured expansion velocity of the spherical shell observed in water masers of about 9 km s^{-1} is consistent with this idea. In order to investigate this possibility, we assume that VLA-R5 represents a compact H II region with a temperature of 10^4 K, a flux density of 0.2 mJy at 3.6 cm, and a size in 1996 of $0''.17$ (or a radius of 62 AU at the distance of the source), which is expanding with a velocity of 9 km s^{-1}. In this scenario, the observed water maser emission would be produced in the shocked layer of ambient molecular material around the expanding H II region. Under these assumptions, we find that the H II region is optically thin [τ(3.6 cm) $\simeq 0.025$] with an emission measure EM $\simeq 6.9 \times 10^6$ cm^{-6} pc and an average density in the ionized gas of n_e(H II) $\simeq 1.1 \times 10^5$ cm^{-3}. The required rate of ionizing photons is $\simeq 1 \times 10^{43}$ s^{-1}, which is consistent with a B3-B4 zero-age main-sequence star. From the theory of expanding H II regions (e.g., Spitzer 1978; Shu 1992) we can further estimate the H_2 density of the unperturbed ambient medium, $n(H_2) \simeq 1.2 \times 10^5$ cm^{-3}, and the density inside the shocked layer (assuming an isothermal shock with a sound speed of $\simeq$0.63 km s^{-1}), $n(H_2) \simeq 2.5 \times 10^7$ cm^{-3}. The resulting gas densities inside and outside the H II region are similar to those expected in dense cores around YSOs, but lower than that estimated for this region from NH_3 observations, $n(H_2) \simeq 2 \times 10^7 (X_{NH_3}/10^{-8})^{-1}$ cm^{-3}, by Torrelles et al. (1999). Based on this simple model, some predictions about the evolution of this radio continuum source can be made. First, the expected size of the H II region would be about the same as the expanding water maser shell, i.e., about $0''.20$ at the present time (or ∼140 AU in 2001, at the distance of the source), which could be confirmed by subarcsecond, sensitive VLA-PT (VLA plus Pie Town extension) continuum observations. Second, the expanding shell should be decelerating with time, and thus new VLBA observations should show a lower expansion velocity (e.g., about 8 km s^{-1} at the present time). And third, the spectral index of the radio continuum source should be $\alpha = -0.1$ at centimeter wavelengths, which could also be measured by sensitive VLA-PT observations. Of course, in this scenario we would be witnessing the birth of an H II region, an unlikely situation given the improbability of observing such a short-lived event. In addition, the symmetry of the spherical molecular shell could be affected by internal instabilities and by ambient inhomogeneities during the expansion of the H II region.

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