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EVIDENCE FOR TIME EVOLUTION IN THE EXCITING SOURCE OF THE EXPANDING WATER MASER BUBBLE IN CEPHEUS A

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RESUMEN

Analizamos observaciones hechas con el Very Large Array a 6 cm hacia Cep A en las épocas 1982.4, 1986.4, y 1990.2. Confirmamos que el chorro térmico Cep A HW2 muestra clara variabilidad en el tiempo en su densidad de flujo y morfología. Aproximadamente $0\rlap{.}''6$ al sur de Cep A HW2 se encuentra la fuente de radiocontinuo R5, aparentemente el objeto excitador de la burbuja de máseres de agua en expansión detectada con el Very Long Baseline Array. Nuestros mapas de la región sugieren que la fuente R5 era considerablemente más débil en 1982.4 que en las dos épocas posteriores, presentando por primera vez evidencia de su variabilidad en el tiempo. Esta variabilidad es consistente con la esperada para una región H II en expansión. Especulamos que el "encendido" de R5 entre 1982.4 y 1986.4 podría estar relacionado con un aumento en la pérdida de masa del cercano chorro térmico Cep A HW2 ocurrido en la misma época.

ABSTRACT

We analyze VLA-A observations made at 6 cm towards the Cepheus A star-forming region at three epochs: 1982.4, 1986.4, and 1990.2. We confirm that the thermal jet Cep A HW2 shows clear time variability in flux density and morphology. The radio-continuum source R5 is located about $0\rlap{.}''6$ south of Cep A HW2 and seems to be the exciting source of the expanding bubble of H_2O masers detected with the VLBA. Our maps of the region suggest that the source R5 was considerably weaker in 1982.4 than in the other two later epochs, showing for the first time evidence of its time variability. This variability is consistent with that expected for an expanding H II region. We speculate that the "turn on" of the source R5 between 1982.4 and 1986.4 may be related with an enhancement in the mass loss of the nearby thermal jet Cep A HW2 during the same epoch.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: FORMATION — STARS: MASS LOSS — RADIO CONTINUUM: STARS**

1. INTRODUCTION

Radio continuum emission at centimeter wavelengths is frequently found in association with young stellar objects (YSOs) that power outflows. This emission is, in general, weak and compact and can be angularly resolved only through subarcsecond observations, which typically reveal that the sources are elongated in the direction of the large scale outflow. This radio continuum emission is believed to have a free-free nature and to trace the origin of the ionized outflow, very close ($\leq$ 100 AU) to the star.

The Cep A region is a condensation in the larger molecular cloud Cepheus OB3 (Sargent 1977). Two components of ionized gas, East and West, are located in the area (Hughes & Wouterloot 1982); the western component has an optical counterpart while the eastern one corresponds to a very embedded ($A_V \sim 100$ mag; Hughes 1991) star forming region. Cep A contains several indicators of active star formation such as compact H II regions (Hughes & Wouterloot 1984), a molecular outflow (CO: Rodríguez, Ho, & Moran 1980a; Bally & Lane

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1990; HCO^+: Gómez et al. 1999), molecular cores (NH_3: Torrelles et al. 1986, 1993; CS Moriarty-Schieven, Snell, & Hughes 1991), and H_2O and OH masers (e.g., Rodríguez et al. 1980b; Cohen, Rowland, & Blair 1984; Torrelles et al. 1996).

Hughes & Wouterloot (1984) identified 14 compact components associated with Cep A East and later observations have shown variations in the flux density of some components (e.g., HW3a: Hughes 1985, Hughes 1997; HW3b,c,d: Hughes, Cohen, & Garrington 1995; HW8: Hughes 1988, Garay et al. 1996; HW9: Hughes 1991, Hughes et al. 1995). This variability in some radio-sources is evidence of the evolution of the intense star formation activity in the region, even in intervals as short as ~ 100 days.

In particular, we are interested in the study of the time-variability of Cep A HW2 and its surroundings. Cep A HW2 is an elongated radio object believed to be associated with the most luminous source ($\sim 10^4 L_\odot$) in the region and has been identified as a powerful biconical thermal jet (Rodríguez et al. 1994).

A two-epoch study (1990.2 and 1991.5) of VLA-A continuum observations at 6 cm was recently presented by Rodríguez et al. (2001). The minimum rms technique of image subtraction (Martí, Rodríguez, & Reipurth 1998) provides a contour map of negative and positive residuals that can be interpreted as motions of the features in the jet. The Cep A HW2 residual map clearly shows the motion of a "pair" of brightness enhancements along the HW2 jet. The authors also estimate the position of the unseen exciting star of the jet to be $\alpha(\mathrm{B1950}) = 22^{\mathrm{h}}\ 54^{\mathrm{m}}\ 19\overset{\mathrm{s}}{.}042 \pm 0\overset{\mathrm{s}}{.}008$, $\delta(\mathrm{B1950}) = 61^\circ\ 45'\ 47\overset{''}{.}36 \pm 0\overset{''}{.}06$, and the moment of enhanced ejection probably to be at epoch 1989.4 ± 0.2.

Moreover, the study of H_2O masers in the region has added new and interesting elements to our global picture of Cep A. Water masers are mainly associated with the HW2 source. The mean velocity of the 25 maser spots detected by Torrelles et al. (1996), about -11 km s^{-1}, is consistent with that of the ambient molecular cloud (Torrelles et al. 1993), while their spatial distribution suggests that they are tracing a circumstellar molecular disk of $0\overset{''}{.}08$ diameter (~ 600 AU at a distance of 725 pc), perpendicular to the Cep A HW2 jet.

VLBA observations (Torrelles et al. 2001a,b) have revealed, in particular, five "microstructures" of maser spots, R1 to R5, with sizes of 3–100 mas (2–70 AU). The most unusual structure of maser spots is R5, which can be fitted by a circle of 62 AU of radius, and is expanding uniformly at 9 km s^{-1}, which implies a dynamical age of ~ 33 yr. Torrelles et al. (2001a) suggest that this bubble is driven by a YSO at the center of the circle. Recently, Curiel et al. (2002) report VLA-A (December 2000) observations at 3.6 cm that detect the source VLA-R5, located at $0\overset{''}{.}6$ south of HW2 and nearly coincident with the center of the water bubble in R5. The VLA-RS position is $\alpha(\mathrm{B1950}) = 22^{\mathrm{h}}\ 54^{\mathrm{m}}\ 19\overset{\mathrm{s}}{.}036$, $\delta(\mathrm{B1950}) = 61^\circ\ 45'\ 46\overset{''}{.}83$. They suggest that this source may correspond to an embedded YSO powering the spherical water maser structure. The R5 radio continuum source was previously detected by Hoare & Garrington (1995; their component 2(iii)), who noted that its nature was unclear, but that it could be another patch of HH-like emission associated with the thermal jet Cep A HW2. In addition, the R4-A ring of masers observed in 1996 and 2000 (Torrelles et al. 2001a; Gallimore, Cool, & Thornley 2002) might be tracing proper motions of material in an expanding disk surrounding a forming A or B star. Nevertheless, this ring is only $0\overset{''}{.}2$ south of HW2 and is not resolved in our 6 cm maps (see § 3).

In this paper we present a study of the time-variability of the thermal jet Cep A HW2 and its surroundings. We analyze observations made at 6 cm, in three epochs separated by about 4 years from each other. Our analysis of the data suggests that the source VLA-R5 may have turned on between 1982.4 and 1986.4 and that this may have been related to an ejection event in the Cep A HW2 jet.

In § 2 we describe the observations, in § 3 we comment on the comparison of clean and maximum entropy restoration maps, while in § 4 a general discussion and our main conclusions are given.

2. OBSERVATIONS

Cep A East has been observed at different radio-wavelengths and configurations for about two decades with the Very Large Array (VLA) of the NRAO.[4]

The continuum observations of Cep A that we present here were made during 1982 May 11, 1986 May 30 and 1990 March 13, using the A configuration and were requested from the VLA archive. The observations were made in both circular polarizations with an effective bandwidth of 100 MHz, except for 1982.4, when the observations were made with an effective bandwidth of 50 MHz. On-source integration times in each epoch were of 290, 164,

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TABLE 1

OBSERVED EPOCHS AT 6 cm

Epoch	Phase Calibrator	Bootstrapped Flux Density (Jy)	rms noise (μJy)	Synthesized Beam Size (arcsec)	Synthesized Beam PA (deg)	Cep A HW2[a] Flux Density (mJy)
1982.4	2146+608	1.210 ± 0.018	29	0.41×0.36	-88	4.3 ± 0.4
1986.4	2229+695	1.382 ± 0.004	28	0.45×0.37	-84	7.7 ± 0.4
1990.2	2229+695	0.877 ± 0.005	28	0.43×0.34	$+31$	10.7 ± 0.5

[a]From a box of $3''\!.6 \times 3''\!.6$.

and 75 minutes, respectively. The absolute amplitude calibrators used were 3C48 (1982.4) and 3C286 (1986.4 and 1990.2), with adopted flux densities of 5.48 and 7.47 Jy, respectively.

The source data were self-calibrated in phase using the software package AIPS. The phase calibrators used at each epoch and their bootstrapped flux densities, as well as the rms noise at the center of the fields and the dimensions of the synthesized beam of the clean maps (made with the ROBUST parameter of the task IMAGR set equal to zero), are given in Table 1. Only for the last epoch did we reach an rms noise consistent with that expected theoretically. The other two epochs have rms noises about $\sqrt{2}$ larger than expected. We also include, in the last column, the values of the integrated flux densities for HW2, which show its brightness enhancement with time over this period.

Since the position of the phase calibrator 2146+608 was refined during the period of the observations analyzed, the 1982.4 position of this calibrator was corrected by $\Delta\alpha = -0^{s}\!.0745$, $\Delta\delta = 0''\!.313$. To estimate the error in the alignment of maps we measured the position of three background sources outside the central region in the three epochs. The variations in these positions, which already include the 1982.4 phase calibrator correction, are small and consistent with the variations obtained using the Martí et al. (1998) method ($\lesssim 0''\!.1$; see below). Therefore, we consider that our absolute positional accuracy error is $\lesssim 0''\!.1$.

3. ANALYSIS

In order to compare features in the HW2 region, we made images of Cep A HW2 for all three epochs using the parameter ROBUST set to 0 in the IMAGR task of AIPS and reconstructing with a circular beam of HPBW = $0''\!.3$, the angular resolution of the interferometer. Figure 1 shows three clean maps of the Cep A HW2 region corresponding to the epochs, 1982.4, 1986.4, and 1990.2, respectively.

The 1982.4 and 1986.4 maps were aligned with respect to the 1990.2 map according to the Martí et al. (1998) minimal rms noise procedure. To do this, we followed a cycle of three steps: (1) using the task OGEOM in AIPS, the individual maps of the first two epochs were systematically shifted by $0''\!.1$ to eight positions (toward the directions W, NW, N, NE, E, SE, S, and SW, respectively); (2) a grid of differences between the 1990.2 map and these maps with shifted positions (1982.4 and 1986.4 epochs) was computed with the task COMB; and (3) we chose the minimum of the residuals with an rms criterion, using the task IMSTAT, to redefine the central pixel to perform a new three step cycle with a smaller shift. We repeated this cycle with shifts of $0''\!.05$, $0''\!.025$ and $0''\!.01$ around the new minimal rms center each time.

Finally, the alignment corrections were of $\Delta\alpha = 0^{s}\!.0033$, $\Delta\delta = 0''\!.050$, for the 1982.4 map and $\Delta\alpha = -0^{s}\!.0027$, $\Delta\delta = -0''\!.025$ for the 1986.4 epoch. The maximum alignment correction was then less than $0''\!.1$.

The HW2 radio jet is present in all three of our maps. It is clear that there have been changes in the size and flux density of HW2 with time (cf. Table 1, last column). The chronological change in size implies that in this period there was an ejection of material in HW2, similar to that shown by Rodríguez et al. (2001). The cross in these maps indicates the position of VLA-R5 (Curiel et al. 2002), while the star shows the position of the exciting star of HW2 (Rodríguez et al. 2001). In the second and third maps, this cross appears to be associated with 6 cm emission, but in 1982.4 there is no evidence of emission above ~ 0.1 mJy at this position. We roughly estimate the 6 cm flux density of R5 to be 0.3 mJy for the 1986.4 and 1990.2 epochs, while less than 0.1 mJy for the 1982.4 epoch. The flux density estimates for 1986.4 and 1990.2, combined with the flux density of 0.7 ± 0.1 mJy obtained by Hoare & Garrington (1995) at 18 cm and that of 0.20 ± 0.03 mJy

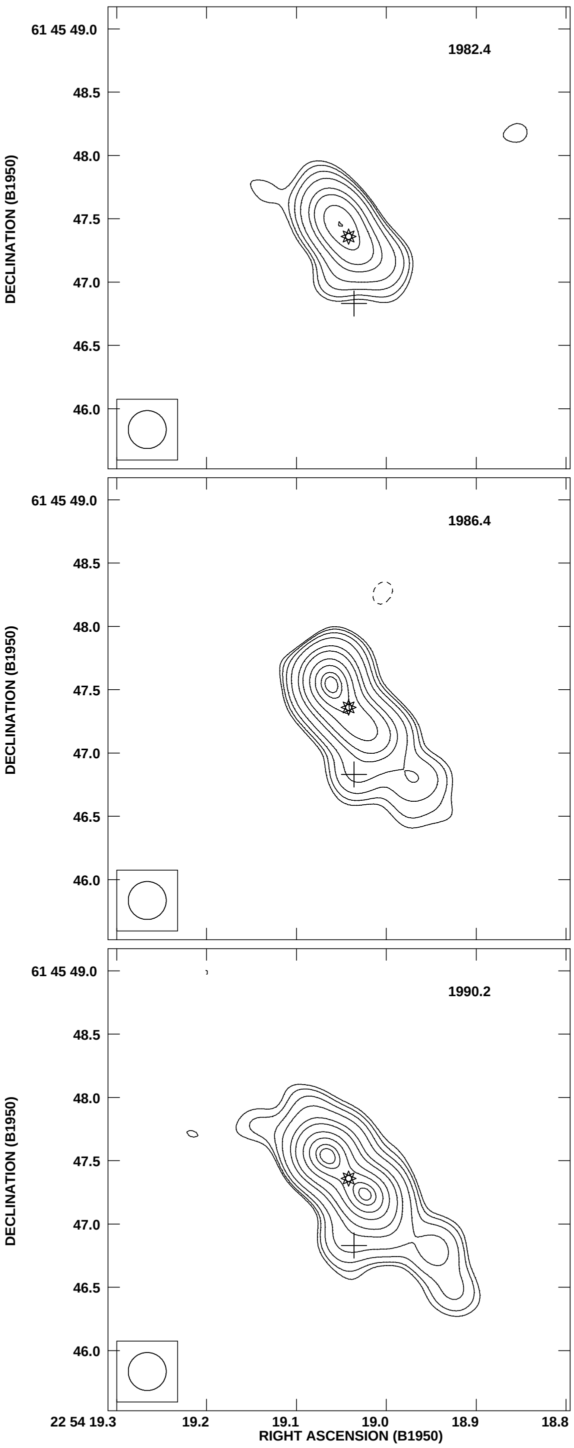

Fig. 1. Continuum contour maps of the Cep A HW2 region for 1982.4 (top), 1986.4 (middle), and 1990.2 (bottom). The contours are −3, 3, 4, 6, 10, 20, 30, 50, 70, 90, and 100 times 28 μJy, the average rms noise of the images. The position of VLA-R5 (cross) and the exciting source of HW2 (star) are indicated.

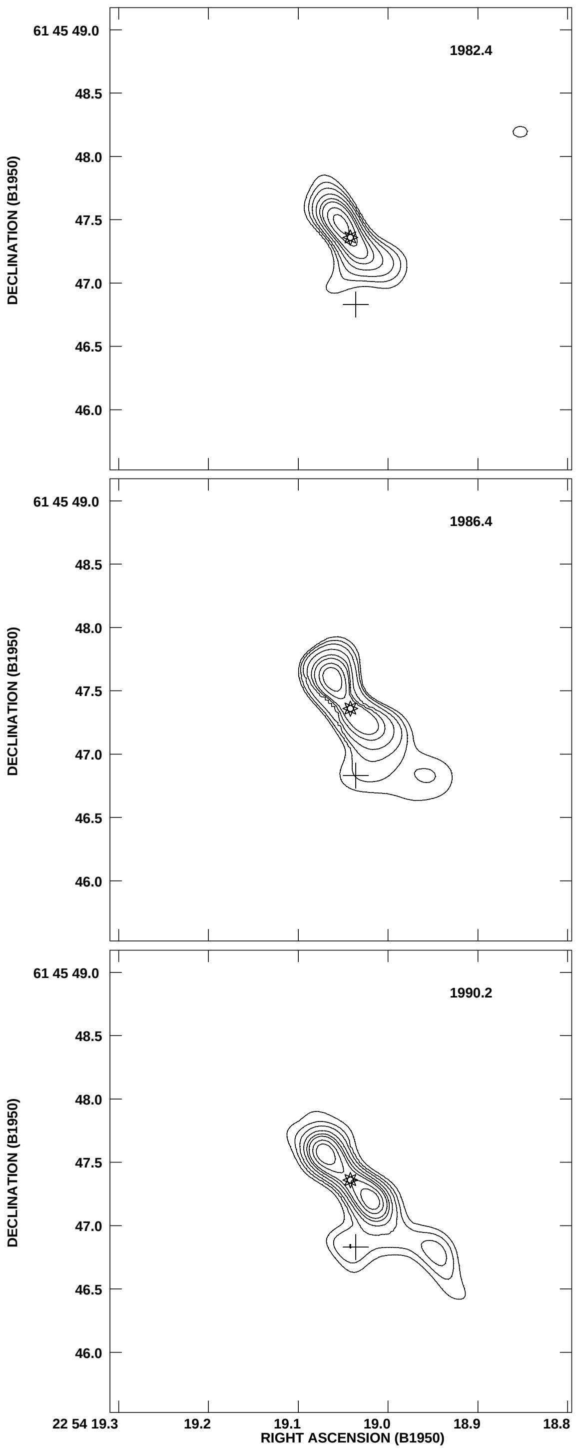

Fig. 2. Maximum entropy restoration maps corresponding to the maps shown in Fig. 1, symbols (cross and star) are the same as in Fig. 1. The contours are 0.8, 1.8, 4, 10, 20, 30, 50, 70, and 100% of the peak value of each map. Note the improvement in angular resolution obtained with the MEM.

obtained by Curiel et al. (2002) at 3.6 cm, suggest a non-thermal spectrum. However, given the time variability reported here, a simultaneous measurement is required to study the spectral index of this source.

To confirm that the source has been changing with time, we obtained restored maps using the Maximum Entropy Method (MEM; Narayan & Nityananda 1986). The MEM image restoration technique performs a non-linear deconvolution of the dirty beam from the dirty image, selecting the solution with the greatest entropy. In practice, the resulting image has, in its regions with highest signal-to-noise ratio, a modest improvement in angular resolution (less than 2) with respect to the angular resolution obtained from clean algorithms (Cornwell & Evans 1985; Narayan & Nityananda 1986). In this case, the restoration was done using the task VTESS in the AIPS data reduction package.

The restored maps for the Cep A HW2 region are shown in Figure 2. Again, we observe in the restored maps the variations in size and that there is detectable emission related to VLA-R5 in the 1986.4 and 1990.2 epochs. In the case of 1982.4 we see a marginal protuberance near VLA-R5, but its position is significantly displaced to the north.

4. DISCUSSION AND CONCLUSIONS

Our main result is that the radio continuum source R5, which has been detected systematically in centimeter images made after 1986, was not present or was significantly fainter in the 1982.4 image reanalyzed here. A straightforward explanation for this time variability is that we are observing the birth of an expanding H II region. Assuming a constant expansion velocity of 9 km s^{-1} for the water bubble around R5, Torrelles et al. (2001a) derive a kinematic age of 33 years and thus that the expansion started near epoch 1963.

However, an expanding H II region decelerates with time. Indeed, from the theory of expanding H II regions (Spitzer 1978; Shu 1992), the expansion velocity of the H II region is given by

$$v_s = \frac{2a_2}{\sqrt{4(R/R_0)^{3/2} - 1}},$$

where a_2 is the sound speed inside the H II region, R is the present radius of the H II region, and R_0 is the initial radius of the H II region (at the end of the initial ionization of the gas).

Adopting $a_2 = 13$ km s^{-1} and since the region had $R = 62$ AU and $v_s = 9$ km s^{-1} at epoch 1996, the time of the observations of Torrelles et al. (2001a), we derive an initial radius for the H II region of R_0 = 35 AU. The radius of the H II region during the expansion phase is given by

$$R = R_0 \left[1 + \frac{7}{4}\frac{a_2}{R_0}(t - t_0)\right]^{4/7},$$

where t_0 is the duration of the initial formation phase, of order

$$t_0 \simeq \frac{1}{n_0 \alpha_{\rm R}},$$

and where $\alpha_{\rm R}$ is the effective recombination coefficient of hydrogen, taken to be 2.6×10^{-13} cm^3 s^{-1}, and n_0 is the density of the unperturbed ambient medium, which Curiel et al. (2002) estimate to be 1.2×10^5 cm^{-3}. We obtain $t_0 \simeq 1.0$ years. We then finally obtain that, since $R = 62$ AU (Torrelles et al. 2001a), the age of the H II region in 1996 was about 13.5 years. This kinematic age gives a birth epoch around 1983, which is consistent with our results.

However, witnessing the birth of an H II region (that is, the birth of an OB star) seems like a very unlikely event and other possibilities should be explored.

It is also intriguing that, in addition to R5, the R4 region has also exhibited an expanding structure of H_2O masers with a kinematic age of the order of a decade (Gallimore et al. 2002). Is this another recently formed OB star? The almost simultaneous appearance of two OB stars so close together in the sky is improbable. It therefore appears profitable to consider mechanisms that could produce the observed phenomena (expanding H_2O maser structures and the turn-on of continuum sources) in a repetitive way.

From Figs. 1 and 2 it is evident that the turn-on of R5 happens near in time to what appears to be a major ejection event from the nearby thermal jet Cep A HW2. We speculate that the two events could be related. For example, both R4 and R5 could be either dense molecular clumps or circumstellar disks surrounding low-mass stars whose outer parts become ionized by the influence of the increased jet activity in their vicinity. The ionization of the surroundings of R4 and R5 could be due to ionizing radiation produced by recombinations in the jet or by shock phenomena. If the gas is clumpy enough, the expanding ionized gas can carry with it neutral molecular material that could produce the observed water maser emission. It is well known in the case of planetary nebulae (e.g., Rodríguez, Goss, & Williams 2002) that expanding ionized and molecular gas can coexist spatially in clumpy regions.

Another intriguing possibility is related to the fact that the 1982.4 image also shows a protuberance to the south of the source. Within the limitations of our data, one could argue that this protuberance marks the position of an ionized structure that moved between 1982.4 and 1986.4, remaining stationary between 1986.4 and 1990.2, as if an obstacle were present at this new position. The interaction of this hypothetical structure, which may be moving in the NE to SW direction, with a stationary molecular clump at the position of VLA-R5, could be related to the absence of water masers in the northern part of VLA-R5 (Torrelles et al. 2001a; 2001b).

These speculations can only be tested with detailed, high angular resolution monitoring of the radio continuum and H_2O maser emission in the region.

In conclusion, our analysis of the 6 cm data taken between 1982 and 1990 suggests that the radio continuum emission associated with R5 was not present or was much weaker in the first epoch of observation. The turn-on of the source may be related to the birth of an OB star or to a poorly understood interaction between the Cep A HW2 jet and a passive structure associated with R5. The expanding structure of water masers in the nearby source R4 could have a similar origin.

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