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VLA OBSERVATIONS OF BRIGHTNESS ENHANCEMENTS MOVING ALONG THE AXIS OF THE CEP A HW2 THERMAL JET

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RESUMEN

Analizamos observaciones sensitivas y de alta resolución angular (0.″3) hechas a 6-cm con el Conjunto Muy Grande de Radiotelescopios (Very Large Array) hacia el chorro térmico Cep A HW2 en dos épocas separadas por 1.3 años. La substracción de los mapas hechos en las dos épocas muestra claramente la presencia de incrementos en el brillo que viajan con el chorro a una velocidad de 950±150 km s^{-1}. Usamos también estos resultados para estimar una posición más precisa de la estrella excitadora del chorro.

ABSTRACT

We analyze sensitive, high angular resolution (0.″3) Very Large Array observations made at 6-cm of the thermal jet Cep A HW2 in two epochs separated by 1.3 years. The subtraction of the maps made at the two epochs clearly shows the presence of brightness enhancements that travel in the jet at a velocity of 950±150 km s^{-1}. We also use these results to estimate an accurate position for the exciting star of this jet.

Key Words: **ISM: INDIVIDUAL (CEP A HW2) – ISM: JETS AND OUTFLOWS – RADIO CONTINUUM: STARS – STARS: FORMATION**

1. INTRODUCTION

The outflow phenomenon that characterizes young stars can be studied with a variety of techniques at different physical scales. At the scale below 100 AU, where the jet accelerates and collimates, one of the most powerful techniques has been the imaging with high angular resolution of the free-free emission that traces the ionized outflow close to its origin. Because of its thermal (free-free) nature, these jets are referred to as thermal jets. The most serious drawback of this technique is that, since we are observing a continuum emission process, it does not directly provide kinematic information regarding the velocity of the gas. In a few sources (i.e., HH 80-81: Martí, Rodríguez, & Reipurth 1995; HH 1-2: Rodríguez et al. 2000) it has been possible to follow in time

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the proper motion of brightness enhancements that travel within the jet. The velocities derived from these observations, ∼600–1400 km s^{-1} for the exciting source of HH 80-81, and ∼400 km s^{-1} for the exciting source of HH 1-2, agree well with the values expected for jets from high-mass and low-mass young stars, respectively.

The brightest thermal jet known is Cep A HW2, in the very active Cep A region of star formation. Hughes & Wouterloot (1984) identified a total of 14 compact components in the region, one of them being HW2. On the basis of its flux density and angular size dependences with frequency, Rodríguez et al. (1994) proposed that Cep A HW2 is a powerful thermal jet. Gómez et al. (1999) report an HCO^+ outflow that is clearly powered by Cep A HW2. In this paper we analyze 6-cm observations of the Cep A region available at the Very Large Array archive that reveal, as in HH 80-81 and HH 1-2, the presence of moving brightness enhancements in Cep A HW2 and allow for the first time to obtain an estimate of the jet velocity as well as to gain knowledge on other parameters of this source.

2. OBSERVATIONS AND RESULTS

The observations were made with the Very Large Array (VLA) of NRAO[2] in the continuum mode at 6-cm during 1990 March 13 and 1991 July 06. At those epochs, hereinafter referred to as 1990.2 and 1991.5, the VLA was in the A configuration, providing an angular resolution of ∼0″.3. The absolute amplitude calibrators were 1328+307 for the 1990.2 observations and 0134+329 for the 1991.5 observations. The phase calibrator was 2229+695, with an assumed position of $\alpha(1950)$ = 22 29 11.655; $\delta(1950)$ = 69 31 02.649. The bootstrapped flux densities for 2229+695 were 0.872±0.001 and 0.717±0.001 Jy for the 1990.2 and 1991.5 epochs, respectively. The data were calibrated, edited, and imaged using the software AIPS of NRAO.

The individual data sets were self-calibrated using a time average of 1 minute and we made images of Cep A HW2 for both 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). The total flux densities of the source for the two epochs are 9.2±0.2 (epoch 1990.2) and 7.3±0.2 mJy (epoch 1991.5), indicating moderate time variability.

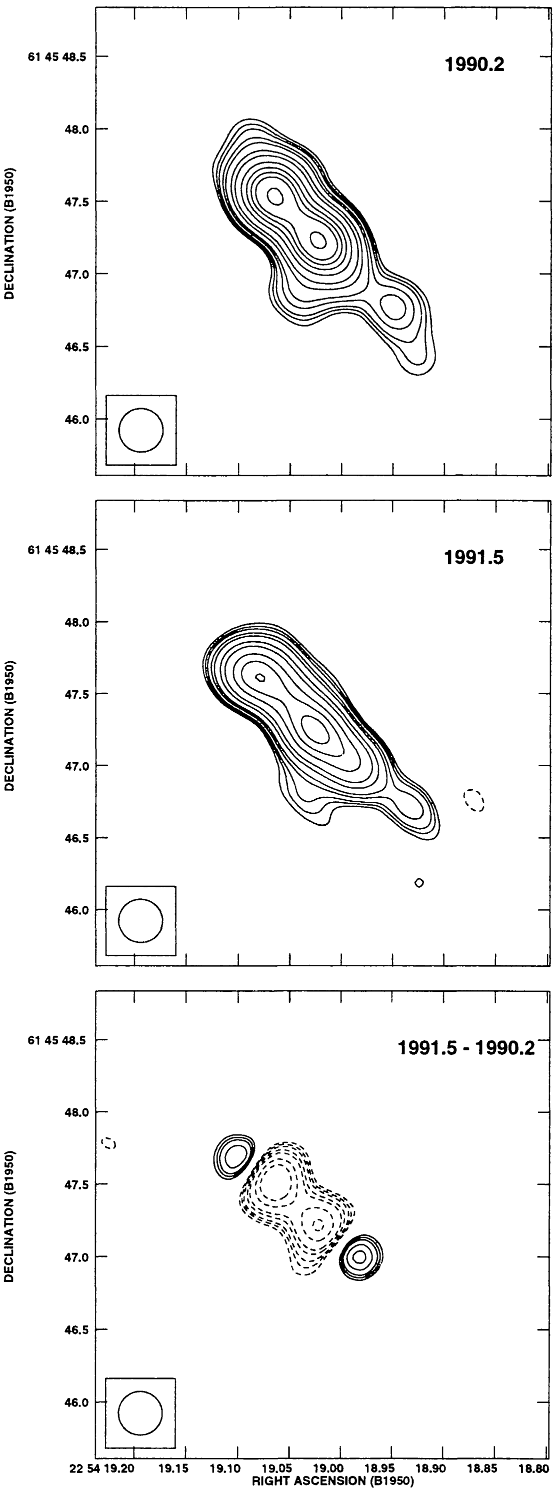

Fig. 1. Continuum contour maps of Cep A HW2 for 1990.2 (top), 1991.5 (middle) and 1991.5−1990.2 (bottom). The contours are −30, −20, −15, −10, −8, −6, −5, −4, 4, 5, 6, 8, 10, 15, 20, 30, 40, 50, 60, and 80 times 32 μJy $beam^{-1}$ for the 1990.2 and 1991.5 maps and 45 μJy $beam^{-1}$ for the 1991.5−1990.2 difference map.

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[2] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

At first sight, the maps look similar (see Fig. 1). In addition to the main bright body of the jet, both show a protuberance to the south that we believe is associated with an independent, weaker source discussed by Curiel et al. (2001). Both maps also show a faint protuberance to the SW that seems to have suffered a small displacement between epochs. However, a more reliable comparison comes from the subtraction of the images and an analysis of the difference map. To align the maps as accurately as possible, we followed the "least-squares" procedure described by Martí, Rodríguez, & Reipurth (1998) and Rodríguez et al. (2000). For this, the 6-cm 1990.2 was kept fixed as the reference epoch and the 6-cm 1991.5 image was systematically shifted by different amounts and a grid of difference maps (1991.5–1990.2) was computed. The shifts that were found to provide the minimum rms noise in the difference images were $\Delta\alpha = -0\farcs020$ and $\Delta\delta = +0\farcs025$. The alignment correction required is therefore, of the order of a few tens of milliarcsec. The resulting difference image is shown also in Fig. 1. As a verification of the reliability of the difference map, we show in Figure 2 a similar sequence of maps for a larger region where several of the other compact sources are seen. The difference map shows significant signal only in sources HW2 (discussed here), in HW8 (previously known to be time variable; see Hughes 1988 and Garay et al. 1996) and in a relatively faint source located between HW3c and HW3d, that was reported first by Hughes et al. (1995).

3. INTERPRETATION OF THE DIFFERENCE MAP

The difference map shown in Fig. 1 has two inner minima outflanked by two outer maxima, all aligned along the axis of the jet. Features of related nature have been found in the difference maps of the thermal jets that excite HH 80-81 (Martí et al. 1998) and HH 1-2 (Rodríguez et al. 2000). However, it is in the case of Cep A HW2 that the negative-positive "pairs" that should characterize the motion of a brightness enhancement in a difference map, are first clearly seen. As discussed by Martí et al. (1998), the flux density of the enhancement is expected to decrease rapidly with distance from the star and in a noisy map it is difficult to detect the outer, weaker "positive" feature (see Fig. 3 of Rodríguez et al. 2000).

In Table 1 we show the positions and peak flux densities of the four features seen in the difference map. In this table we also list the fraction (in absolute value) of the peak flux density in the difference

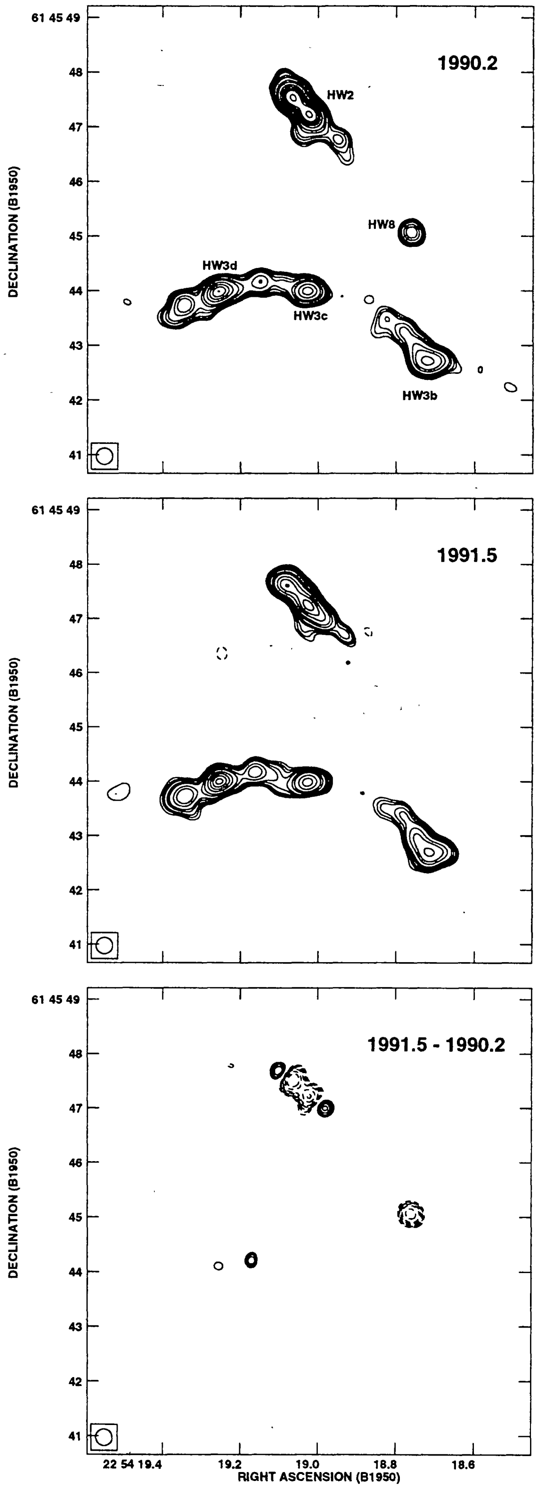

Fig. 2. Continuum contour maps of the central region of Cep A for 1990.2 (top), 1991.5 (middle) and 1991.5–1990.2 (bottom). The contours are as in Figure 1. Significant residuals in the difference map (bottom) are obtained only for the sources HW2 (discussed here), HW8, and a source located between HW3c and HW3d.

TABLE 1

PARAMETERS OF THE 6-cm FEATURES IN THE DIFFERENCE MAP

Feature	$\alpha(1950)^{a}$ (h m s)	$\delta(1950)^{a}$ (° ′ ″)	Peak Flux Density (mJy beam^{-1})	Fraction of Peak Flux
1	22 54 18.980	61 45 47.00	+0.49±0.04	0.54±0.05
2	22 54 19.021	61 45 47.22	−0.95±0.04	0.35±0.02
3	22 54 19.063	61 45 47.51	−1.31±0.04	0.49±0.02
4	22 54 19.103	61 45 47.70	+0.45±0.04	0.46±0.05

[a]Relative positional error is ~0.″03.

map with respect to that in the emission maps. The fraction of the outer (positive) features was measured with respect to the 1991.5 map, while the fraction of the inner (negative) features was measured with respect to the 1990.2 map.

Several conclusions can be drawn from the data shown in Fig. 1 and Table 1.

1) The average position of the four features is $\alpha(1950) = 22^h54^m19.^s042 \pm 0.^s008; \delta(1950) = 61°45'47.''36 \pm 0.''06$. Assuming that the components were ejected simultaneously and that they move with equal velocity, we can take this average position as the best estimate available for the location of the exciting star.

2) The ratio of the peak flux density of the enhancements with respect to the peak flux density of the total emission is quite large, of order 50%, comparable to the contrast seen en HH 1-2. In the case of HH 80-81 this ratio was smaller, of order 20%. These brightness enhancements have been previously interpreted as electron density enhancements (Martí et al. 1998). The electron density enhancement, Δn_e is approximately related to the flux density enhancement, ΔS_ν, by $\Delta n_e/n_e = (1/2)\Delta S_\nu/S_\nu$ (Martí et al. 1998), and we thus propose that the brightness enhancements are being caused by increases of order 25% in the electron density of the flow.

3) Extrapolating back in time, we estimate that the ejection of the enhancements took place at the epoch 1989.4±0.2.

4) As discussed by Martí et al. (1998), if the brightness enhancements are caused by electron density enhancements, for a freely expanding cone model one expects the flux density of the enhancements to decrease with time as $\Delta S_\nu \propto t^{-2}$. Our data are roughly consistent with $\Delta S_\nu \propto t^{-1}$, suggesting confinement in the jet.

5) An estimate can be given for the proper motions of the enhancements assuming that they have moved an angular distance equal to that marked by the separation between "pairs" of negative and positive features. The average displacement is $0.''35 \pm 0.''06$, that over 1.3 years and assuming a distance of 725 pc (Johnson 1957) gives a proper motion in the plane of the sky of 950±150 km s^{-1}. Since the inclination angle of the Cep A HW2 jet is not known, the derived velocity is a lower limit to the true velocity.

6) Given that Cep A HW2 shows evidence of time variability in total flux density and morphology, multifrequency studies such as those reported by Rodríguez et al. (1994) and Garay et al. (1997) can be taken as meaningful only if made simultaneously in time. Furthermore, as a result of opacity effects, in the case of thermal jets one is observing different regions at different frequencies and even simultaneous studies have to take into account possible variability. Additional multifrequency studies are needed to understand this source, in particular to test if the "textbook" behavior derived from the observations of Rodríguez et al. (1994) is present most of the time or if it is actually unusual.

Given the large flux density of this thermal jet, a monitoring program over several years could follow its detailed evolution and produce data relevant for our understanding of time variability in thermal jets.

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