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CEPHEUS A HW2: A POWERFUL THERMAL RADIO JET

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ABSTRACT

At angular resolution of $\sim 1''$ the Cepheus A East radio source is known to consist of 16 compact components clustered within a 25″ radius region, most of which are aligned in stringlike structures. We present multifrequency VLA radio continuum observations of Cep A HW2, the elongated radio object believed to be associated with the most luminous ($\sim 10^4\ L_\odot$) source in the region. In the frequency range from 1.5 to 43 GHz, we find that its flux density increases with frequency as $\nu^{0.69}$, while the angular size of its major axis decreases with frequency as $\nu^{-0.57}$. The above frequency dependences are very close to the theoretical values of $\nu^{0.6}$ and $\nu^{-0.7}$ expected for a biconical thermal jet and make Cep A HW2 the best example known of this type of object. We suggest that Cep A HW2 is responsible for at least part of the complex outflow and excitation phenomena observed in the region. The estimated ionized mass-loss rate in this source, $\sim 8 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$, is about 100 times larger than the value expected for a star of the same luminosity in the main sequence.

Subject headings: H II regions — ISM: individual (Cepheus A) — ISM: jets and outflows — radio continuum: stars — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Cepheus A is the densest condensation within the molecular cloud complex Cepheus OB3 (Sargent 1977). It has been identified as an active zone of star formation on the basis that it contains H_2O masers (Blitz & Lada 1979; Lada et al. 1981), OH masers (Rodríguez et al. 1980b; Cohen, Rowland, & Blair 1984), Herbig-Haro objects (Gyulbudaghian, Glushkov, & Denisyuk 1978; Hartigan & Lada 1985; Lenzen 1988), infrared sources (Lenzen 1988), and a molecular outflow (Rodríguez, Ho, & Moran 1980a; Bally & Lane 1991). The region has been recently reviewed by Staude & Elsasser (1993).

Two main regions of ionized gas, separated by $\sim 1\farcm5$, have been detected in Cepheus A: Cep A East and Cep A West (Hughes & Wouterloot 1982; Rodríguez & Cantó 1983). High-resolution radio continuum observations show that Cep A East consists of several compact sources, most of them appearing in string-like structures. In their discovery observations, made with the Very Large Array (VLA), Hughes & Wouterloot (1984) identified a total of 14 compact components. Later observations showed that some of these sources exhibited changes in their flux density and also revealed the presence of two new, highly variable, compact radio sources (Hughes 1988, 1991). Most of the compact radio sources are located at the edges of dense molecular clumps and have been interpreted as gas externally excited by two stars located at the centers of the H_2O maser activity (Torrelles et al. 1985, 1986, 1993b). One of these stars is related to Cep A HW2, which is the only radio continuum source in the region which is found to be embedded in circumstellar (~ 2000 AU), high-density [$n(H_2) \sim 10^7\ \mathrm{cm}^{-3}$], hot ($T_K \geq 100$ K) material possibly related to a circumstellar disk (Torrelles et al. 1993a).

In spite of numerous studies made to date, a clear understanding of the nature of the radio emission from the Cep A East sources has not yet emerged. In this *Letter* we report new observations, made with the VLA, of the radio object Cep A HW2 designed to determine accurately the spectral index and angular size of its radio emission. A detailed study of the characteristics of other sources in the region will be presented elsewhere. Previous determinations of the spectral indices of these sources were made using data taken in different epochs (Hughes 1985). Since the radio sources are extended and potentially time variable, our observations were made quasi-simultaneously and with similar angular resolution to determine accurately the spectral indices.

2. OBSERVATIONS

The matching beam 20, 6, and 2 cm observations were made with the Very Large Array of the National Radio Astronomy Observatory[7] during 1991 July 15 and 1991 December 13/14. To obtain similar angular resolution at the different frequencies observed we split the array into two subarrays. The first session corresponds to matching beam observations at 20 and 6 cm, in the A configuration. The subarray used for the 20 cm observations consisted of the four outer antennas of each arm, while that for the 6 cm observations was formed by the five inner antennas of each arm. The second session corresponds to matching beam observations at 6 and 2 cm, in the B configuration, designed to obtain images with angular resolutions similar to those in the first session and to check for source variability at 6 cm. The subarray used for the 6 cm observations consisted of the four outer antennas of each arm, while that for the 2 cm observations was formed by the five

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inner antennas of each arm. In this manner the 20, 6, and 2 cm observations have an angular resolution of ~1″ and are sensitive to angular structures of up to ~6″ in extent. All observations were made with an effective bandwidth of 100 MHz and two circular polarizations. The flux density scale was determined by observing 1328+307 (3C 286), and the phase calibrator was 0016+731. The data were edited and calibrated following the standard VLA procedures. Maps were made by Fourier transforming the (u, v) data with natural weighting and cleaned using the MX algorithm. We applied a small Gaussian convolution to make the beamwidth the same, 1″.2, at all three frequencies. We did not detect variations ($<5\%$) in the 6 cm integrated flux density of source HW2 between the epochs of 1991 July and December. We also made maps at 3.6 cm of data taken with the VLA in the A configuration during 1991 July 6 (obtained quasi-simultaneously to our 20, 6, and 2 cm observations) kindly provided to us by V. Hughes. These data, with an angular resolution of 0″.2, were taken using 0134+329 (3C 48) as absolute amplitude calibrator and 2229+695 as phase calibrator. The elongated morphology of Cep A HW2 is evident in the 3.6 cm map, shown in Figure 1. A similar elongation is observed in our 20, 6, and 2 cm maps as well as in the maps of Hughes (1991) and Hughes, Cohen, & Garrington (1994). Elliptical Gaussian fittings were made for Cep A HW2 at 20, 6, 3.6, and 2 cm using the AIPS task IMFIT. Table 1 lists the flux densities, deconvolved FWHM angular diameters, and position angles determined for Cep A HW2 at the different frequencies observed.

Additional observations to help constrain the spectral index of Cep A HW2 were made with the VLA using the new 7 mm receivers during 1994 January 23 and 30. At that epoch five antennas were equipped, providing an angular resolution of about 2″. We integrated for a total of 2.5 hr on source. We used 0134+329 (3C 48) as absolute amplitude calibrator (with an adopted flux density of 0.53 Jy at 43.3 GHz). The phase calibrator was the compact ($\leq 0''.4$) H II region NGC 7538 IRS 1 (Campbell 1984), with a bootstrapped flux density of 0.49 ± 0.01 Jy. Both amplitude and phase calibrators as well as the source were observed only in the elevation range of 53°–62°. This restriction is expected to cancel out the effects of opacity and elevation-dependent gain variations. Although the 7 mm data are not quasi-simultaneous with the rest of our observations, we included them in our discussion since they significantly extend the frequency range studied. A cleaned, natural weight map of the 43.3 GHz data is shown in Figure 2. Two sources were detected in the field: Cep A HW2 and HW3d, with flux densities of 35 ± 2 and 8 ± 2 mJy, respectively. Both appear as unresolved ($\leq 0''.5$) sources.

TABLE 1

INTEGRATED FLUX DENSITIES AND ANGULAR SIZES FOR CEPHEUS A HW2

Frequency (GHz)	Flux Density (mJy)	Angular Size
1.49	3.4 ± 0.1	2″.2 × 0″.3; P.A. 42°
4.86	7.5 ± 0.1	1″.1 × 0″.3; P.A. 43°
8.44	9.8 ± 0.1	0″.8 × 0″.1; P.A. 48°
14.9	15.8 ± 0.2	0″.6 × 0″.2; P.A. 41°
43.3	35 ± 2	≤0″.5

3. RESULTS AND CONCLUSIONS

Cep A HW2 has an elongated morphology that suggests a jet nature. New evidence that strongly favors this interpretation is that Cep A HW2 has flux densities and deconvolved FWHM major angular axis (Table 1) that fit very well power-law dependences of the form expected for a biconical, thermal jet. The theoretical radio continuum spectra of a confined

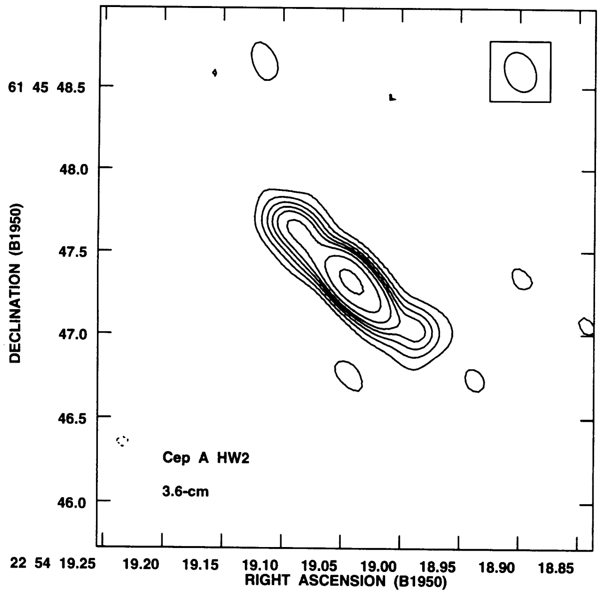

FIG. 1.—Cleaned, uniform-weight VLA radio continuum map of Cep A HW2 at 3.6 cm. Contours are −3, 3, 6, 9, 12, 15, 20, 30, and 50 times 50 μJy beam^{-1}, the rms noise of the map. The half-power contour of the beam (0″.25 × 0″.18, with a position angle of 25°) is shown in the top right-hand corner.

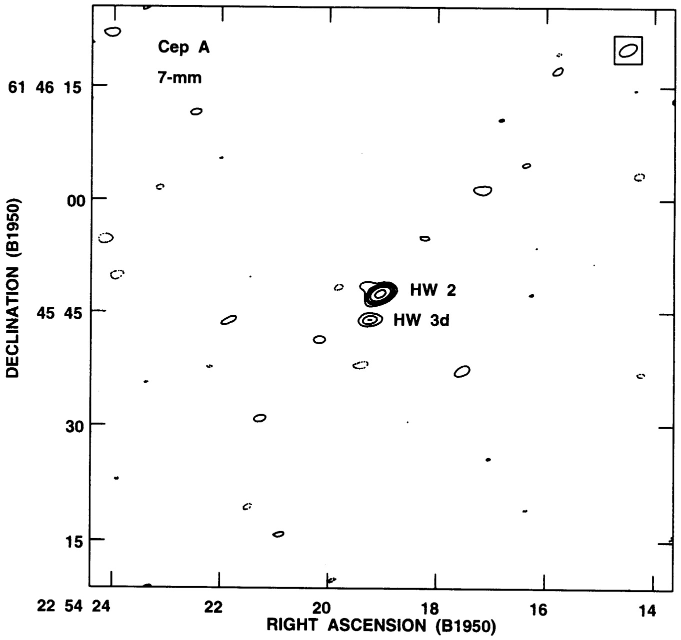

FIG. 2.—Cleaned, natural-weight VLA radio continuum map of the Cep A region at 7 mm. Contours are −3, 3, 6, 9, 15, and 30 times 0.9 mJy beam^{-1}, the rms noise of the map. The sources detected, Cep A HW2 and HW3d, appear unresolved ($\leq 0''.5$) and are indicated in the figure. The half-power contour of the beam (2″.5 × 1″.3, with a position angle of −64°) is shown in the top right-hand corner.

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thermal jet has been calculated by Reynolds (1986). For a collimated wind of constant temperature, velocity, and ionization fraction, the flux density and angular dimension of the source depend on frequency as $S_\nu \propto \nu^{1.3-0.7/\epsilon}$ and $\theta_\nu \propto \nu^{-0.7/\epsilon}$, respectively, where ϵ is the power-law index that describes the dependence of the jet half-width, w, (perpendicular to the jet axis) with the distance to the jet origin ($w \propto r^\epsilon$). A jet with constant opening angle (a conical jet) has $\epsilon = 1$.

Our observations show that Cep A HW2 is elongated at a P.A. of 44° ± 4°. We find, from a least-squares fit to the data, that the deconvolved FWHM major axis decreases with frequency as $\theta_{\rm maj} = (2.7 \pm 0.1)\nu^{(-0.57\pm0.02)}$, where $\theta_{\rm maj}$ is in arcsec and ν is in GHz. The minor axes are, on the other hand, much smaller than the beam, typically about $0\farcs2$. We also find that the total flux density, in the 1.5–43.3 GHz range, is well fitted by a power law of the form $S_\nu = (2.5 \pm 0.3)\nu^{(0.69\pm0.06)}$, where S_ν is in mJy and ν is in GHz. These results suggest that the radio emission from object 2 arises in a biconical, highly collimated ionized wind. The data and fits are shown in Figure 3. From the observations at 8.3 GHz and assuming that the opening angle is approximately given by $\theta_{\rm opening}(\text{radians}) = 2 \tan^{-1}(\theta_{\rm minor}/\theta_{\rm major})$, we estimate $\theta_{\rm opening} \simeq 15°$. The observed dependences of the angular size and flux density with frequency can be well explained by a model of an ionized gas flow with $\epsilon \simeq 1.2 \pm 0.2$. Within observational error, Cep A HW2 can be interpreted as a purely biconical ($\epsilon = 1$) jet. The exciting sources of the HH 1–2 (Rodríguez et al. 1990) and HH 80–81 (Martí, Rodríguez, & Reipurth 1993) complexes are also known to exhibit power-law flux density and angular size dependences with frequency, but these appear to depart significantly from the purely biconical case. In this sense Cep A HW2 may prove to be a simpler case to study the phenomena of jet collimation in young stars. To our knowledge, the only other source that fits so closely the expected theoretical power law for a conical wind in the flux density versus frequency dependence is the peculiar emission-line star MWC 349, with $S_\nu \propto \nu^{0.65\pm0.02}$ (Dreher & Welch 1983). This source, however, has modest collimation, with an opening angle of ~120° (White & Becker 1985).

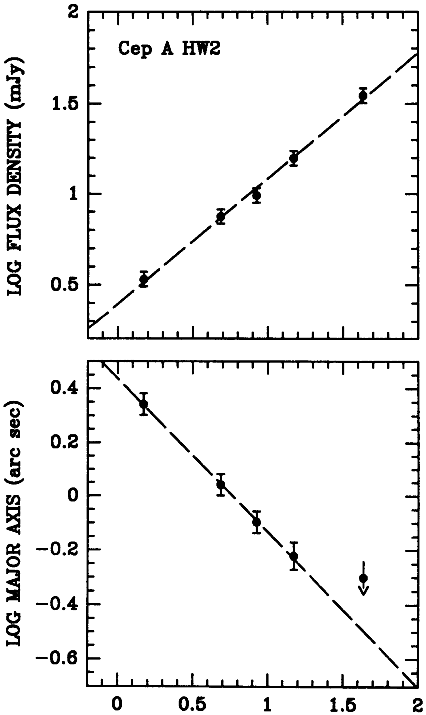

FIG. 3.—Flux density (*top*) and deconvolved major angular axis (*bottom*) as a function of frequency for Cep A HW2. The dashed lines are the power-law fits described in the text. At 43.3 GHz, the data point for the major angular axis is an upper limit.

From the observed flux density and opening angle a relationship between the ionized mass-loss rate, $\dot{M}_w$, and velocity, v_w, of the biconical stellar wind can be derived. Assuming an electron temperature of 10^4 K, a distance of 725 pc, and that the jet axis is nearly perpendicular to the line of sight, we obtain (using eq. [19] of Reynolds 1986 with $\epsilon = 1$) $\dot{M}_{w,-6}\, v_{w,3}^{-1} = 1.1$, where $\dot{M}_{w,-6}$ is the mass-loss rate in units of $10^{-6}\ M_\odot\ {\rm yr}^{-1}$ and $v_{w,3}$ is the velocity in units of 10^3 km s^{-1}. Young stars of solar luminosity are known to have wind velocities in the order of a few hundred km s^{-1}. However, an object of intermediate luminosity (see below) such as Cep A HW2 is probably more similar in wind velocity to IRAS 18162−2048, for which a velocity of ~700 km s^{-1} is estimated (Heathcote & Reipurth 1994; Martí et al. 1993). Assuming then that the wind velocity is 700 km s^{-1}, we derive a mass-loss rate of $8 \times 10^{-7}\ M_\odot\ {\rm yr}^{-1}$. The bolometric luminosity of the region is about $2.5 \times 10^4\ L_\odot$ (Evans et al. 1981). If, following Hughes et al. (1994), we assume that one-half of that luminosity can be attributed to Cep A HW2, we conclude that the exciting star will be a B0.5 once in the ZAMS, where a mass loss rate of only $\sim 10^{-8}$ is expected (Abbott, Bieging, & Churchwell 1981). Then, at present Cep A HW2 exhibits a mass-loss rate about 100 times larger than an object of similar luminosity in the ZAMS. Since it is suspected that winds from young stars can be largely neutral (Lizano et al. 1988), our determination of the ionized mass-loss rate should be considered a lower limit to the total mass-loss rate. It should be noted, however, that a much lower velocity for the jet will lower the derived ionized mass loss rate.

The momentum rate injected by the jet into the surrounding medium is $\sim 6 \times 10^{-4}\ M_\odot\ {\rm yr}^{-1}$ km s^{-1}. This momentum rate is similar to the lower limit for the momentum rate of the molecular outflow derived by Rodríguez et al. (1982). Then, it appears possible that the jet could be driving the outflow in the frame of the unified stellar jet/molecular outflow model of Raga et al. (1993).

The relation of the Cep A HW2 thermal jet with the high-density [$n({\rm H_2}) \sim 10^7$ cm^{-3}], hot ($T_K \geq 100$ K), and compact (~2000 AU) condensation in which it appears to be embedded (Torrelles et al. 1993a) is poorly understood. Higher angular resolution observations are required to establish if the condensation is taking part in the outflow motions or if it helps collimate the jet. The OH and $\rm H_2O$ masers associated with Cep A HW2 exhibit radial (Cohen et al. 1984) and proper motion (Cohen & Migenes 1991) velocities of order 10 km s^{-1} and may trace very dense gas that is interacting with the jet although at present the nature of the interaction is unclear. In particular, the orientation of the jet does not coincide with the orientation proposed for the maser outflow (Cohen et al. 1984).

As discussed by Rodríguez et al. (1990), a biconical jet should appear as a double source when observed with sufficient angular resolution. This possibility is supported by observations at 15 GHz with angular resolution of $\sim 0\farcs1$, carried out with the VLA by Hughes (1988), which reveal the presence of two ultracompact components each of $\sim 0\farcs1$ in size, separated by ~0″.2. The ultracompact sources are aligned in a direction at a P.A. of ~40°, similar to the direction of the major axis of the more extended emission seen in our maps. Torrelles et al. (1993a) suggested that the two ultracompact sources may represent the ionized inner parts of a circumstellar disk around a massive young star. However, on the basis of the flux density and major axis dependences with frequency of this radio source, we suggest that the compact double structure seen at high resolution corresponds to the inner parts of the biconical jet of ionized gas. For a biconical jet that is resolved along its major axis and unresolved along its minor axis one expects to see a double source with peaks separated by $2(\tau_0/1.90)^{1/3\epsilon}\nu^{-0.7/\epsilon}$ arcsec, where τ_0 is the optical depth at 1 GHz and at 1″ from the jet center for a line of sight perpendicular to the major axis and ν is in GHz (Rodríguez et al. 1990). From the observed separation at 15 GHz of 0″.2 and adopting $\epsilon = 1$, we obtain $\tau_0 = 0.6$. Since the angular resolution of the VLA in its largest configuration (A) scales as ν^{-1}, while the angular separation of the peaks scales as $\nu^{-0.7}$, we expect to resolve the source into two components with the VLA-A only at frequencies above ~15 GHz.

We believe that Cep A HW2 may be exciting other sources in the region, in particular the components 1, 4, 5, and 6 which are aligned to the SW and NE of Cep A HW2 approximately along the jet axis. However, it also appears difficult to attribute all the activity of this region to Cep A HW2 since there are radio continuum components off the jet axis (components 3 and 7) and the molecular outflow is quadrupolar (Bally & Lane 1991). Nevertheless, the identification of Cep A HW2 with a powerful thermal radio jet presented here indicates that at least part of the complex phenomena observed in the region can be attributed to one star. Given the relatively large flux density of Cep A HW2, it may be the best source known to study the phenomenon of outflow collimation in young stars.

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