Revista Mexicana de Astronomía y Astrofísica, **41**, 435–442 (2005)

PROPER MOTIONS IN CEPHEUS A

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Received 2005 February 2; accepted 2005 May 17

RESUMEN

Presentamos un análisis de observaciones de radiocontinuo hechas con el *Very Large Array* hacia la región de formación estelar masiva Cefeo A. El propósito principal de este análisis es buscar y estudiar movimientos propios en las fuentes de radio a lo largo de las dos décadas de tiempo cubiertas por las observaciones. Las cuatro componentes de la fuente W, ubicada en la parte occidental de Cefeo A, muestran claros movimientos hacia el oeste con velocidades en el intervalo de 120 a 280 km s^{-1}. Creemos que estas componentes están siendo excitadas por el chorro térmico Cep A HW3d, ubicado hacia el este de ellas. Más aún, proponemos que, después de ser deflectado en la posición de la fuente W, el chorro Cep A HW3d se mueve hacia el noroeste y produce la fuente óptica GGD 37. La fuente Cep A HW7 muestra un complejo patrón de movimientos propios para los que se discuten varias posibles explicaciones.

ABSTRACT

We present an analysis of radio continuum observations made with the *Very Large Array* toward the region of massive star formation Cepheus A. The main purpose of this analysis is to search and study proper motions in the radio sources over the two decades of time covered by the observations. The four components of source W, located in Cep A West, clearly show westward proper motions in the range of 120 to 280 km s^{-1}. We believe that these components are being excited by the thermal jet Cep A HW3d, located to their east. Furthermore, we propose that after being deflected at the position of source W, the Cep A HW3d jet moves towards the NW and produces the optical source GGD 37. The source Cep A HW7 shows a complex pattern of proper motions for which we discuss several possible explanations.

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

1. INTRODUCTION

The Cep A region is a condensation in the larger molecular cloud Cepheus OB3 (Sargent 1977). Two main components of ionized gas, East and West, are located in the area (Hughes & Wouterloot 1982; Rodríguez & Cantó 1983); 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.

In Figure 1 we show a 6 cm image of intermediate angular resolution of the region, where the main components of the East and West regions are evident. In this figure we indicate the seven main components of Cep A East, with the numbering given by Hughes & Wouterloot (1984). We also indicate in the Cep A West region the W component (Hughes 1989), as well as the radio counterpart to the visible nebula GGD 37 (Gyulbudaghian, Glushkov, & Denisyuk 1978).

Over the years, the nature of several of these radio continuum sources has been clarified (e.g., Garay et al. 1996). Perhaps the best studied source is component 2 in Cep A East, also known as Cep A HW2,

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that is well established to be a thermal jet with its major axis aligned along a position angle of $\sim 45°$ (Rodríguez et al. 1994; Rodríguez et al. 2001). A high angular resolution 6 cm image of the central region of Cep A East is shown in Figure 2. Given the position and alignment shown in Fig. 2, Cep A HW2 probably excites the components 1, 4, 5, and 6 of Cep A East (Garay et al. 1996). This hypothesis is strengthened by the fact that these components are located at the edge of ammonia condensations (Torrelles et al. 1985; 1986; 1993), suggesting that they result from the interaction of the Cep A HW2 jet with dense molecular material. The thermal jet Cep A HW2 is also associated with enigmatic water maser emission (Torrelles et al. 2001).

The exciting source or sources of component 7 in Cep A East and of components W and the GGD 37 object in Cep A West (see Fig. 1) remain undetermined. Garay et al. (1996) propose that the component W and the associated GGD 37 object constitute an isolated region of activity, powered by an energy source distinct from those powering the Cep A East region. On the other hand, it is also possible to speculate that these structures, roughly distributed in the east-west direction, could be excited by source Cep A HW3d (see Fig. 2), given the position and orientation of the latter. Both Cep A HW 2 and HW3d show the positive centimeter spectral index (Garay et al. 1996) that characterizes thermal jets (Anglada 1996; Rodríguez 1997).

In this paper we present a proper motion study of the Cep A region, made with Very Large Array (VLA) data accumulated over the last two decades. Our main purpose is to help identify, using proper motions, the exciting sources of the multiple radio continuum components in the region.

2. OBSERVATIONS

The 2002 February 4 observations were made with the VLA of the NRAO[7] at 6 cm in the A configuration. All other observations listed in Table 1 were taken from the VLA archives. The data taken with equinox B1950 were precessed to equinox J2000. To obtain accurate absolute astrometry, the positions of the phase calibrators were corrected for the latest refined positions given in the list of VLA calibrators. All data were reduced using the standard VLA procedures and were self-calibrated in phase and amplitude.

For the purpose of proper motion search, the most sensitive data sets are those of 1982 May 11, 1986 May 30, 1990 March 13, and 2002 February 4, all taken at 6 cm in the A configuration with an angular resolution of $\simeq 0\farcs4$. All images were made with the ROBUST parameter (Briggs 1995) of the task IMAGR set to 0 (to optimize the compromise between angular resolution and sensitivity) and reconstructed with a circular beam of $0\farcs38$.

[7]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

3. RESULTS

Our comparison of the images failed to show clear evidence for systematic proper motions in the components 1, 4, 5, and 6 of Cep A East, presumably excited by the Cep A HW2 jet. This lack of clear motion could imply that the jet is impinging on very dense material that does not move significantly. However, we did find clear proper motions in the components of source W of Cep A West and of source 7 in Cep A East. We describe these proper motions in the following sections.

3.1. *The W Region*

This region shows clear proper motions in all its components: W1, W2, W3, and W4 (see Figure 3). In Table 2 we summarize the characteristics of these proper motions. At an adopted distance of 725 pc (Johnson 1957), the proper motions translate into velocities on the plane of the sky in the range of ~ 120 to ~ 280 km s^{-1}, with a clear gradient in these velocities from west to east (that is, W4 has larger proper motions than W3, and so forth). The components W1 to W4 form a chain along a position angle of $\sim 300°$ (see Fig. 3). However, the proper motions of all condensations are, within $\pm 15°$, consistent with a westward motion (position angle of $\sim 270°$). This is the first report of radio proper motions in source W. From optical observations, Lenzen (1988) reported proper motions for source W as a single component with $v \simeq 120$ km s^{-1} and due west. By comparison with Table 2, we believe that these optical measurements were probably dominated by component W1.

Two main conclusions can be derived from these proper motions. First, these proper motion with PA $\simeq 270°$ align well with the position of Cep A HW3d. At high angular resolution the source Cep A HW3 (see Figs. 1 and 2) breaks up into subcomponents a, b, c, and d. We then coincide with Lenzen (1988) in suggesting that source W is being excited by the Cep A HW3d jet. Second, Garay et al. (1996) proposed that component W2 could be the site of an independent energy source. However, the proper motions observed in all four components indicate that they are rapidly moving clumps of excited gas and not stationary exciting sources.

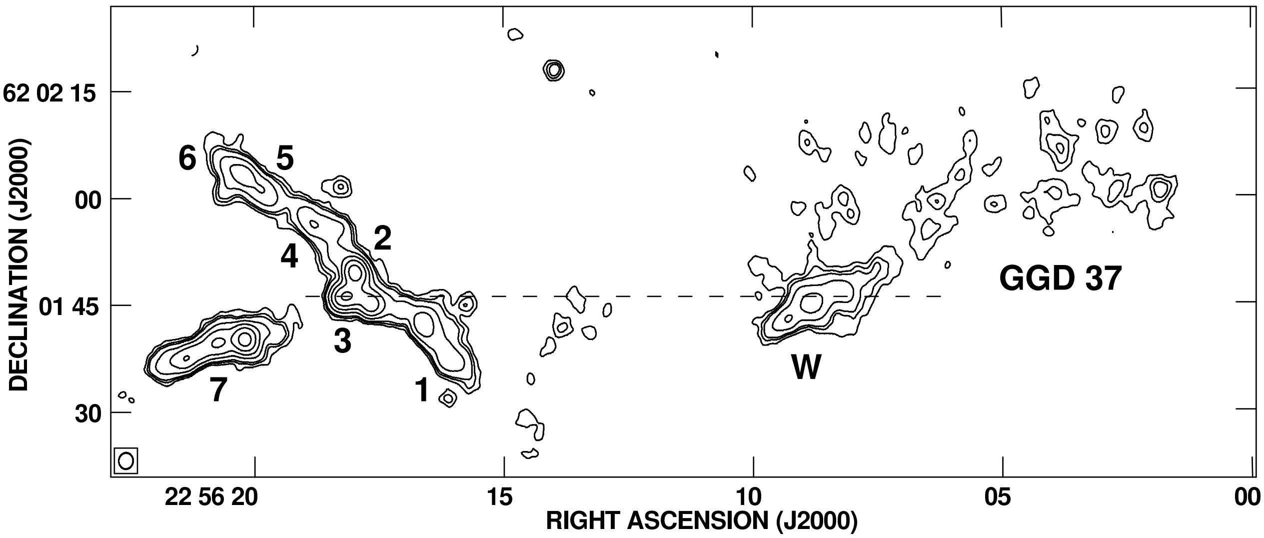

Fig. 1. Contour image of the 6 cm continuum emission from the Cep A region, made from data taken in 1991 May 4 (D configuration) and in 1991 July 6 (A configuration), and concatenated in a single file. The contours are −4, 4, 8, 16,32, 64, 128, 256, and 512 times 36 μJy, the rms noise of the image. The main components of the region are labeled following Hughes & Wouterloot (1984), Hughes (1989), and Gyulbudaghian et al. (1978). The dashed line goes through the peak of source 3 in the east-west direction and suggests the possible direction of the collimated flow from source 3 to the W region. In this paper we propose that at the W region the jet is deflected toward the NW direction, producing the GGD 37 object. The half power contour of the beam ($2''\!.3 \times 2''\!.0$; $PA = -5°$), is shown in the bottom left corner.

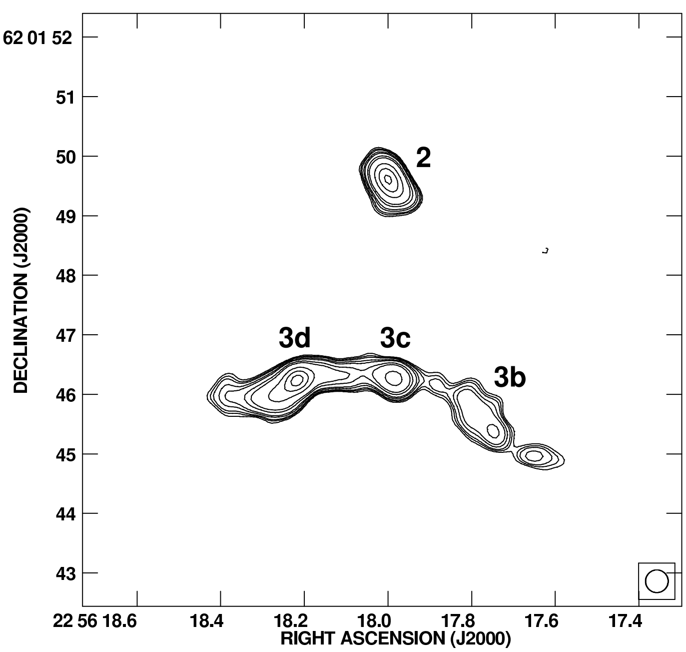

Fig. 2. Contour image of the 6 cm continuum emission from the core of the Cep A East region, made from data taken in 1982 May 11 with the VLa in the A configuration. The contours are -4, 4, 5, 6, 8, 10, 15, 20, 40, 60, and 80 times 26 μJy, the rms noise of the image. The components in the image are labeled following Hughes & Wouterloot (1984). The half power contour of the restoring beam ($0''\!.38 \times 0''\!.38$), is shown in the bottom right corner.

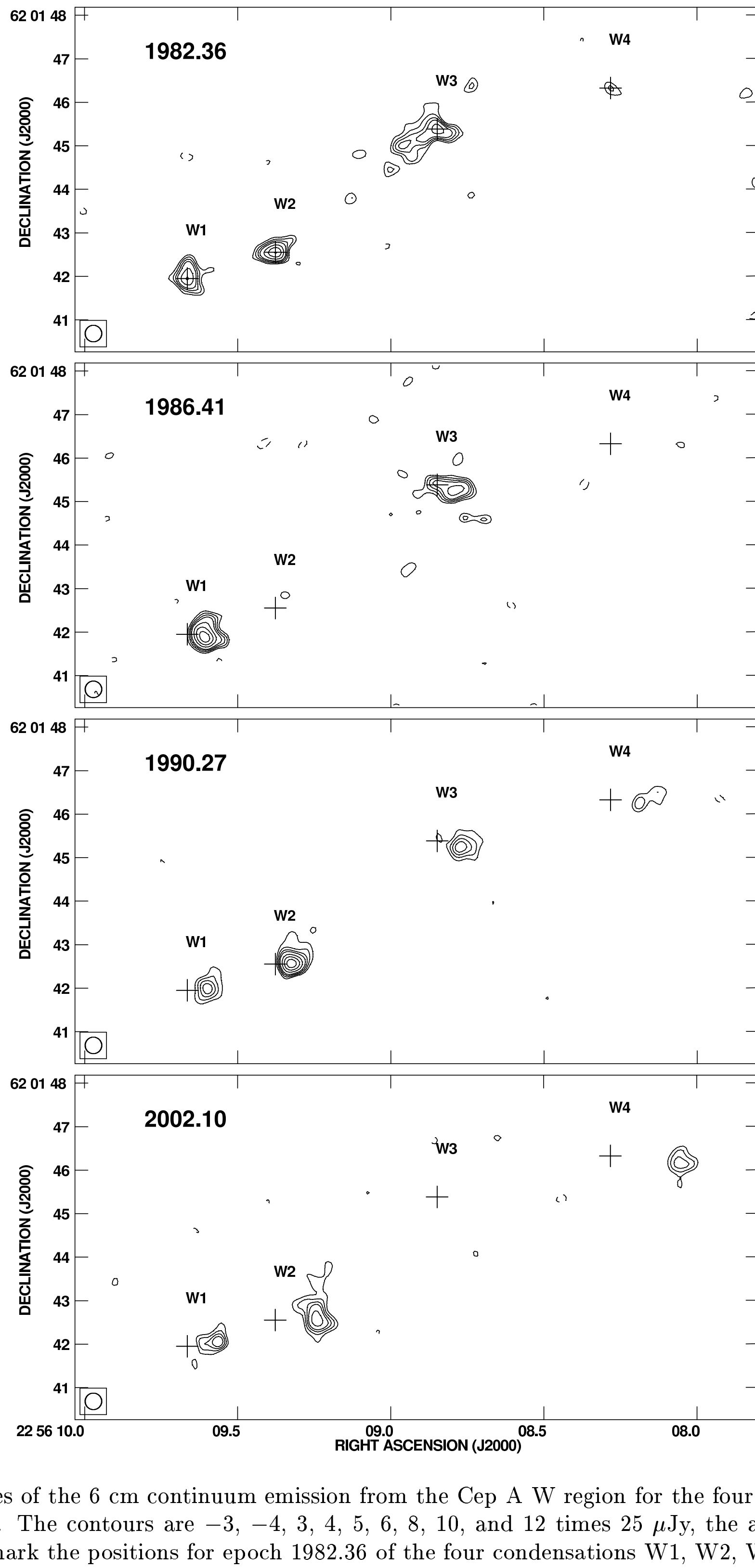

Fig. 3. Contour images of the 6 cm continuum emission from the Cep A W region for the four epochs indicated in the top left of each panel. The contours are −3, −4, 3, 4, 5, 6, 8, 10, and 12 times 25 μJy, the average rms noise of the images. The crosses mark the positions for epoch 1982.36 of the four condensations W1, W2, W3, and W4, as given in Table 2. Note the westward proper motion of the condensations.

TABLE 1

OBSERVATIONS OF CEPHEUS A

Epoch	Phase Center[a] α(J2000)	Phase Center[a] δ(J2000)	Phase Calibrator	Bootstrapped Flux Density (Jy)	Configuration	Wavelength (cm)
1982 May 11	22 56 17.97	+62 01 49.3	2148+611	1.210±0.018	A	6
1986 May 30	22 56 17.97	+62 01 49.3	2230+697	1.382±0.004	A	6
1990 Mar 13	22 56 17.97	+62 01 49.3	2230+697	0.877±0.005	A	6
1991 May 04	22 56 18.45	+62 01 47.3	2230+697	0.664±0.001	D	6
1991 Jul 06	22 56 18.44	+62 01 48.3	2230+697	0.675±0.003	A	6
1998 Jul 03	22 56 17.97	+62 01 49.3	2230+697	0.350±0.002	B	3.6
2002 Feb 04	22 56 17.97	+62 01 49.3	2322+509	1.179±0.005	A	6

[a]Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.

TABLE 2

OBSERVED PARAMETERS OF THE COMPONENTS OF SOURCE W

Component	Position[a] α(J2000)	Position[a] δ(J2000)	Proper Motion μ(mas yr^{-1})	Proper Motion v(km s^{-1})[b]	Proper Motion Position Angle
W1	22 56 09.665	+62 01 41.95	35±3	120±10	281°±5°
W2	22 56 09.377	+62 01 42.55	48±2	170±7	271°±3°
W3	22 56 08.848	+62 01 45.38	61±12	210±40	256°±9°
W4	22 56 08.282	+62 01 46.32	81±3	280±11	264°±2°

[a]For epoch 1982.36 and equinox J2000. Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds.

[b]Velocity in the plane of the sky for an adopted distance of 725 pc.

We speculate that the W components are produced by the interaction of the Cep A HW3d jet with dense molecular gas located to the SW of source W. Torrelles et al. (1985;1986;1993) have studied exhaustively the Cep A region in ammonia, but centered on the Cep A East region, with Cep A West falling outside of their primary beam. Observations of ammonia and other tracers of dense gas centered on Cep A West are needed to test whether this component is present.

The exciting source of the optical object GGD 37, to the NW of source W, remains undetermined (see Hiriart, Salas, & Cruz-González 2004 for a recent discussion). Although the Cep A HW3d jet seems at first sight like a poor candidate (since its E-W axis does not align with the NW proper motion of GGD 37), we think that this jet is deflected towards the NW in its interaction with the dense gas that is expected to exist to the SW of source W and that, after this deflection, it excites GGD 37. There is some evidence from maps of the high velocity CO outflow that the red CO lobe changes direction near the position of the source W (see Figure 8 of Ho, Moran, & Rodríguez 1982).

A case of a "deflected" jet that has been studied in detail is that of HH 270/110 (e.g., Reipurth, Raga, & Heathcote 1996; Rodríguez et al. 1998). A feature in common between HH 270/110 and W/GGD 37 is that the condensations in the flow show proper motions whose direction significantly differs from the alignment of the chain of condensations on the plane of the sky (see Fig. 4 of Reipurth et al. 1996 and Fig. 3 of this paper). This difference may be one of the signatures of deflecting jets, since in a normal jet the direction of proper motions and the alignment of the chain of condensations are usually very similar.

The proposal that both the source W and GGD 37 are powered by Cep A HW3d is also supported by the 3D, gasdynamic simulations of jet/cloud collisions of Raga et al. (2002). Deflection angles of order 30°, as observed for GGD 37 with respect to source W, are easily obtained. There is also good morphological agreement between model and observations, as one can verify by comparing Fig. 8 of Raga et al. (2002) with the image of the region shown in Fig. 2 of Hartigan, Morse, & Bally (2000).

The large time variability shown by all four W components is also worth of discussion. In particular, we note that component W2 disappears at epoch 1986.41 (but is clearly present at the three other epochs), while source W3 disappears at epoch 2002.10 (but is clearly present at the three other epochs). This behavior may indicate a traveling "gap" in the jet or wind that excites the system. Since sources W2 and W3 are separated by $\simeq 4''$ and the time interval between 2002.10 and 1986.41 is of 15.69 years, we estimate that the "gap" (and thus the wind) move at a velocity of $\sim$ 900 km s^{-1}, comparable to the velocity determined for the Cep A HW2 jet by Rodríguez et al. (2001).

The velocity indirectly inferred for the wind ($\sim$ 900 km s^{-1}) is much larger than the velocities measured for the condensations W1–4 (in the range of $\sim$ 120 to 280 km s^{-1}). We speculate that the W1–4 condensations have been recently entrained in the wind and are still being accelerated by it. The gradient of velocities for the W1–4 condensations discussed above suggests that the condensations incorporate to the outflow close to the position of W1 and start been accelerated there, reaching larger velocities as they move to the west.

3.2. *The Cep A HW7 Source*

This stringlike source appears projected at the south edge of the ammonia condensation Cep A-3 (Torrelles et al. 1993). This location with respect to the dense gas traced by the ammonia molecule (Ho & Townes 1983) suggests that this source results from the interacion of a collimated outflow with dense gas.

The proper motions observed in this source are less straightforward to interpret than those in source W. While in source W all componentes clearly move to the west, in Cep A HW7 the individual components seem to move in different directions. Since in the 6 cm data taken in the A configuration there is a time gap from 1990 to 2002, we decided to use an additional data set, taken at 3.6 cm in the B configuration during 1998 July 3. For a proper comparison with these lower angular resolution 3.6 cm data, we tapered the 6 cm VLA-A observations to produce images of comparable angular resolution ($0\rlap{.}''70$).

A sequence of images for the five epochs is shown in Figure 4. The sources are numbered following Hughes & Wouterloot (1984). About $2''$ to the SW of component 7a there is a fainter component that we have called 7'. From the analysis of these images, we reach the following conclusions.

(*i*) Component 7d shows a clear proper motion towards the SE. For epoch 1998.50, the condensation breaks up into three subcomponents and by the last epoch of our observations, 2002.10, the three subcomponents have become very faint. The proper motion of component 7d is of 74±2 mas yr^{-1}, with a position angle of 134° ± 2°. At the adopted distance of 725 pc, this proper motion implies a velocity on the plane of the sky of 260±10 km s^{-1}. Hughes (1993) had previously suggested that proper motions of order 300 km s^{-1} were present near the east end of the source Cep A HW7.

(*ii*) For the epochs 1998.50 and 2002.10 a new condensation has appeared between components 7b and 7c.

(*iii*) Component 7c seems stationary, while component 7b exhibits a small proper motion towards the east.

(*iv*) Finally, components 7a and 7a' show proper motions towards the southeast and southwest, respectively, of the order of 200 km s^{-1}.

Taken at face value, the proper motions suggest that the exciting source of source Cep A HW7 is located a few arcsec north of the mean position of components 7a and 7a', roughly at $\alpha(2000) = 22^h\ 56^m\ 20\rlap{.}^s05$; $\delta(2000) = +62°\ 01'\ 42\rlap{.}''2$. However, there is no known source at this position. Hughes (1993) proposed that the components 7b, 7c, and 7d could be excited by source Cep A HW9, a time variable source (that was turned off at the epoch of the observations shown in our Figs. 1 and 2), located on the axis defined by the components 7b, 7c, and 7d, to the NW of these sources. However, the southward proper motions of components 7a and 7a' suggest that the situation is more complex, and that if there is a single exciting source it must be located at the position given above, or that two or more sources could be exciting source 7. Alternatively, the complex proper motion pattern of Cep A HW7 could be the result of the interaction of a single jet (perhaps Cep A HW3d) with the dense gas known to exist there.

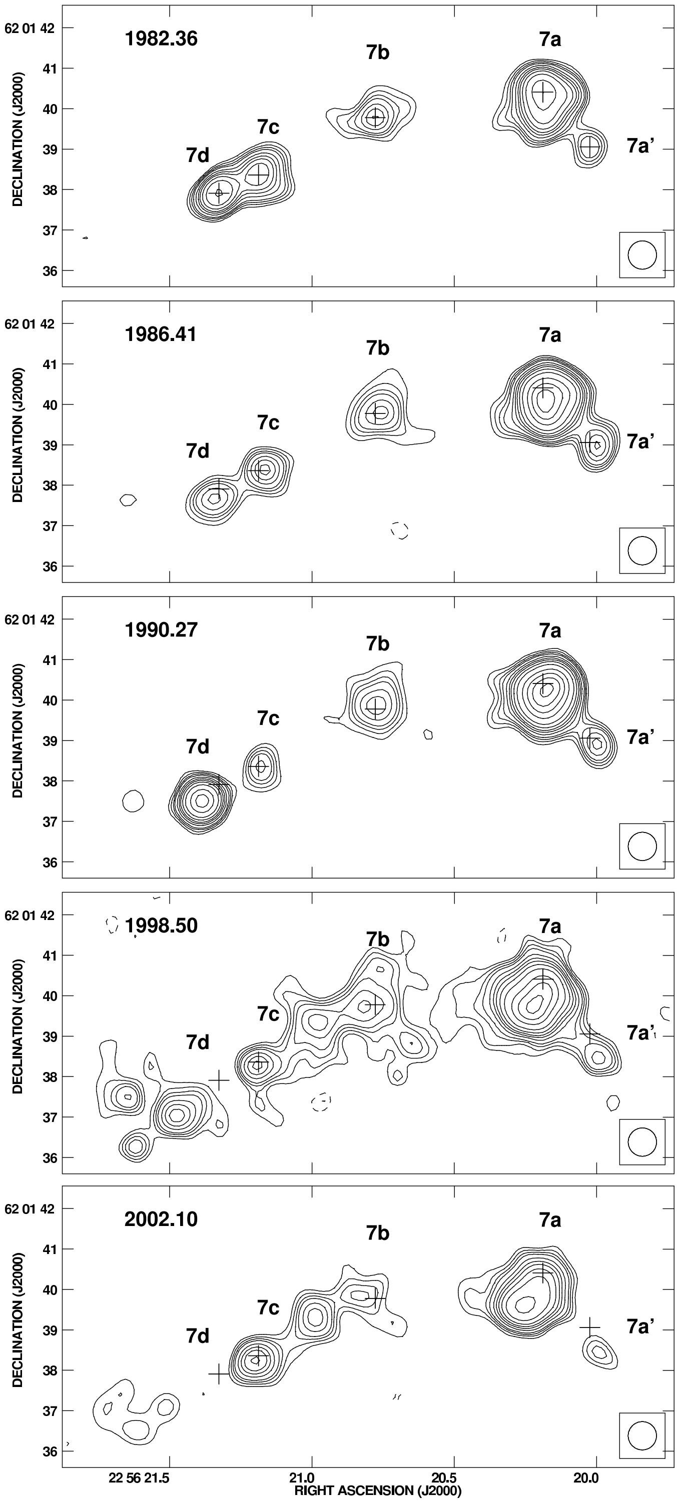

Fig. 4. Contour images of the continuum emission from the Cep A HW7 region for the five epochs indicated in the top left of each panel. The contours are −3, −4, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 50, and 60 times 40 μJy, the average rms noise of the images. The crosses mark the positions for epoch 1982.36 of the five components identified in the images (Hughes & Wouterloot 1984). Note the SE proper motion and eventual break up of component 7d.

4. CONCLUSIONS

We present multiepoch VLA observations made at 6 and 3.6 cm of the Cep A region over two decades, with the purpose of detecting and studying proper motions of the multiple radio components found here. Our main conclusions are summarized below.

1) We detected clear proper motions in source W (in Cep A West) and in source 7 (in Cep A East).

2) The four components of source W show westward proper motions in the range of 120 to 280 km s^{-1}. We speculate that they are being excited by the thermal jet Cep A HW3d. Furthermore, we propose that after being deflected at the position of source W, the Cep A HW3d jet starts to move in the NW direction and produces the optical object GGD 37.

3) We used the strong variability present in the components of source W to propose that there are traveling "gaps" in the jet or wind that move at velocities of the order of 900 km s^{-1}.

4) The proper motions observed in Cep A HW7 are complex and suggest that they are being produced by a source to its northwest, as yet undetected, or that the excitation could be due to multiple sources or to the interaction of a jet with dense molecular gas.

We thank I. Cruz-González for calling our attention to the search for the exciting source of GGD 37. LFR acknowledges the support of DGAPA, UNAM, and of CONACyT (México). JMT acknowledges partial support by grant AYA 2002-00376 (Spain). GG acknowledges support from the Centro de Astrofísica FONDAP No. 15010003. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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