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VLA OBSERVATIONS OF Z CMA: THE ORIENTATION AND ORIGIN OF THE THERMAL JET

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RESUMEN

Presentamos observaciones sensitivas y de alta resolución angular ($\sim 0\farcs45$) hechas a 6 y 3.5 cm con el Conjunto Muy Grande de Radiotelescopios (Very Large Array) hacia el chorro térmico asociado con la estrella joven Z CMa. Hemos encontrado que el ángulo de posición del eje del chorro térmico es coincidente dentro del error con la orientación del chorro óptico y con la orientación del flujo bipolar observado en CO. Las estructuras débiles observadas en radio alrededor de Z CMa (principalmente al este de esta fuente) podrían ser el resultado de eyecciones periódicas. Se sabe que Z CMa tiene una compañera infrarroja $0\farcs1$ al noroeste. Hemos usado nuestros datos de alta resolución angular ($\sim 0\farcs2$) tomados en la configuración A y la posición astrométrica de *Hipparcos* para establecer que el chorro se origina en la compañera visible.

ABSTRACT

We present sensitive, high angular resolution ($\sim 0\farcs45$) Very Large Array observations made at 6 and 3.5 cm toward the thermal jet associated with the young star Z CMa. We found that the position angle of the axis of the thermal jet is coincident within error with the orientation of the optical jet and the orientation of the CO bipolar outflow. The faint radio features detected around this young star (mostly to its east) are probably the result of periodic material ejection from the central source. It is known that Z CMa has an infrared companion about $0\farcs1$ to its northwest. We have used our high angular resolution ($\sim 0\farcs2$) A configuration data and the astrometric position from *Hipparcos* to establish that the jet originates from the optical component of this binary.

Key Words: **ISM: JETS AND OUTFLOWS — RADIO CONTINUUM: STARS — STARS: FORMATION — STARS: INDIVIDUAL (Z CMA)**

1. INTRODUCTION

Young stars are characterized by the presence of strong collimated outflows that can be studied with a variety of techniques at different physical scales. At the scale below 100 AU, where the jet is believed to be accelerated and collimated, one of the most powerful techniques has been the high angular resolution imaging, at centimeter wavelengths, 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.

These observations are very valuable for identifying the true exciting source of the outflow in regions

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where there is large obscuration and several candidate young objects could be present. They also provide accurate positions, that in general are better than those provided at present by IRAS, near-IR, and mm techniques. Finally, they provide information on the subarcsecond scale regarding the orientation and time behavior of the jet. While observations of the molecular outflow trace the average activity of the outflow over the last thousands of years, the thermal jets reveal the ionized gas that has emanated from the star in the last few months or years (Rodríguez 1997; 1999).

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, although in a few sources (i.e., HH 80–81: Martí, Rodríguez, & Reipurth 1995, 1998; HH 1–2: Rodríguez et al. 2000; Cep A HW2: Rodríguez et al. 2001) it has been possible to follow in time the proper motion of brightness enhancements that travel within the jet. The velocities derived from these observations, are in the range of $\sim$ 400–1400 km s^{-1}.

Z CMa (= HD 53179) is a young system that shows clear evidence of vigorous accretion as well as of outflow activity. At a distance of 1150 pc (Herbst, Racine, & Warner 1978), the estimated bolometric luminosity of the source is $L_{bol} \simeq 3 \times 10^3\ L_\odot$ (Hartmann et al. 1989). It has usually been classified as a Herbig Ae/Be star, but the high resolution spectroscopy of Hartmann et al. (1989) shows that Z CMa has the double-peaked emission line profiles whose shapes and widths are characteristic of FU Ori objects. The currently accepted interpretation for the FU Ori objects is that they are T Tau stars undergoing episodes of very rapid disk accretion. Indeed, under this interpretation, Z CMa has one of the highest accretion rates, $M_{acc} \simeq 10^{-4}\ M_\odot$ yr^{-1}, observed in FU Ori systems (Hartmann & Kenyon 1996). Malbet et al. (1993) found in the near-infrared elongated emission at position angle (PA) of $161^\circ \pm 8^\circ$ that is interpreted as a disk-like structure. This disk-like feature was questioned by Tessier, Bouvier, & Lacombe (1994).

On the other hand, the presence of strong outflow activity is evident in the optical jet detected by Poetzel, Mundt, & Ray (1989), that extends over $\sim 10'$ with a well-defined PA of 60° reaching radial velocities of -620 km s^{-1}. This optical jet has been designated HH 160. Z CMa also has an associated CO outflow (Evans et al. 1994) that extends by about $1'$ with a PA of $\sim 60^\circ$, a position angle consistent with that seen in the optical jet. The observations of centimeter continuum emission (Bieging, Cohen, & Schwartz 1984; Cohen & Bieging 1986; Skinner, Brown, & Stewart 1993) are also indicative of outflow activity. Bieging et al. (1984) found that the source is elongated roughly in the east-west direction. They also reported the presence of a second, weaker component about $1\farcs6$ to the east of Z CMa. The presence of this second component was not confirmed by posterior observations, and it is unclear if this is due to time variability or to problems with the data. Finkenzeller & Mundt (1984) reported Z CMa as a binary system with $1\farcs5$ separation in the E-W direction, but later observations have failed to confirm this additional component. Skinner et al. (1993) marginally resolved the source at 3.5 cm and find a slight extension along a PA of $\sim 78^\circ$, roughly consistent with the position angle determined from the optical jet and the CO outflow.

Koresko et al. (1991) discovered that Z CMa has an infrared companion at an angular separation of $0\farcs1$ and PA of 300° from the optical star. This result was confirmed by Haas et al. (1993), Whitney et al. (1993), Barth, Weigelt, & Zinnecker (1994), Thiebaut et al. (1995), and Fischer, Stecklum, & Leinert (1998). There has been discussion in the literature concerning which of the stars is responsible for the outflow activity. Whitney et al. (1993) favor the infrared companion as the source of the outflow and of the recent optical variability. However, Lamzin et al. (1998) propose that the main source of stellar wind and optical variability in this binary system is the optical primary (the SE component).

In this paper we analyze VLA archive 6 cm observations of Z CMa and present new 3.5 cm data of the source. The new data, made with high angular resolution and sensitivity, finally allow us to image accurately the thermal jet and to discuss its properties and its relation with the larger outflow phenomena, as well as to establish from which of the components of the binary emanates.

2. OBSERVATIONS AND DATA REDUCTION

The new observations were made with the A (1994 April 16) and B (1993 April 30) configurations of the Very Large Array (VLA) of NRAO[3] in the radio continuum at 3.5 cm . To obtain maximum sensitivity, we concatenated these data and refer hereinafter to it as the 1993.8 epoch. We have also employed VLA archive data, but in the radio continuum at 6 cm . These data were observed with

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

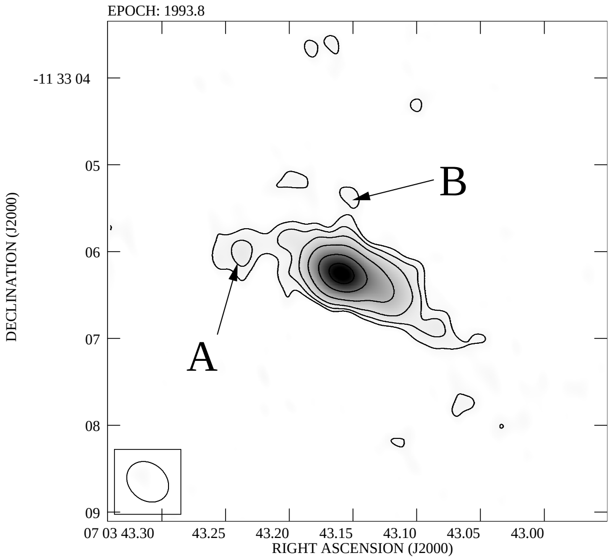

Fig. 1. Greyscale and contour image of the radio continuum of Z CMa at 3.5 cm (1993.8 epoch), obtained with the A+B configurations of the VLA. The greyscale varies from 0.03 to 1 mJy/beam, while the contour levels correspond to (1.0, 1.5, 2.5, 5.0, 10.0, 15.0)×0.06 mJy/beam. The angular resolution is $0''.52\times0''.42''$, PA=50°, and the rms noise is 18 μJy/beam.

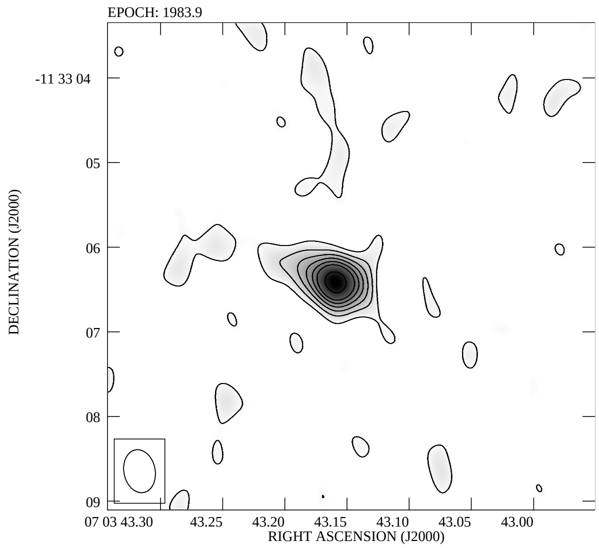

Fig. 2. Radio continuum of Z CMa at 6 cm (1983.9 epoch). The greyscale is in the range [0.06,0.69] mJy/beam and the represented contours are (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0)×0.15 mJy/beam. The angular resolution is $0''.52\times0''.4$, PA=1.4°. The rms noise is 54 μJy/beam.

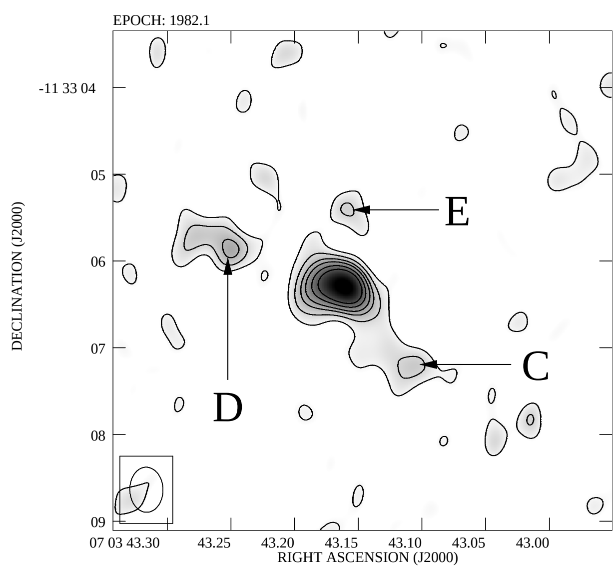

Fig. 3. Z CMa image corresponding to the radio continuum at 6 cm (1982.1 epoch). The 1982.1 greyscale lies in the range [0.1, 0.8] mJy/beam and contours correspond to (0.5, 0.85, 1.2, 1.5, 1.9, 2.3)×0.25 mJy/beam. The angular resolution is $0''.51\times0''.4$, PA=11°. The rms noise is 80 μJy/beam.

the A configuration of the VLA, during 1982 February 8 and 13, and 1983 November 20 and 23 (hereafter the 1982.1 and 1983.9 epochs, respectively).

The amplitude calibrators were 3C286 (for the 1982.1 and 1983.9 epochs) and 1328+307 (for the 1993.8 epoch). As phase calibrator we employed 0727–115 in all epochs, obtaining 6 cm flux densities of 2.224±0.003 and 2.24±0.01 Jy for the 1982.1 and 1983.9 epochs, respectively. For the 3.5 cm observations, we obtained bootstrapped flux densities for 0727–115 of 4.965±0.004 Jy (for the 1994 April 16 observations) and 7.118±0.006 Jy (for the 1993 April 30 observations).

The data were calibrated, edited, and imaged using the software AIPS of NRAO, obtaining quite similar synthesized beams of $0''.52\times0''.42$ (PA=50°), $0''.52\times0''.40$ (PA=1.4°) and $0''.51\times0''.40$ (PA=11°), for 1993.8, 1983.9 and 1982.1 epochs, respectively. The resulting rms noises were 18, 54, and 80 μJy/beam for these three epochs. The maps were precessed from equinox 1950.0 to equinox 2000.0 using the AIPS task REGRD.

3. RESULTS

Figures 1, 2, and 3 correspond to maps made from the 1993.8, 1983.9 and 1982.1 epochs, respectively. We have generated images of Z CMa using the AIPS task IMAGR, with the parameter ROBUST set to 0. After that, we employ the AIPS task HGEOM in order to re-scale the images corre-

TABLE 1

PARAMETERS OF THE Z CMA THERMAL JET

Epoch	λ (cm)	$\theta_{maj}('')$	$\theta_{min}('')$	PA(°)	S_ν(mJy)
1982.1	6.0	0.71±0.07	0.38±0.11	71±11	1.73±0.17
1983.9	6.0	0.58±0.06	$0.24^{+0.09}_{-0.17}$	75±9	1.30±0.10
1993.8	3.5	0.68±0.04	0.26±0.04	65±4	1.74±0.06

sponding to the 1983.9 and 1982.1 epochs with the geometry of the 1993.8 image.

The 3.5 cm continuum map shown in Fig. 1, obtained from our new data, has the best signal-noise ratio and shows that the object has an elongated jet-like shape in direction North-East to South-West. The morphology of this feature is asymmetric, resulting more extended to the South-West. To the East of the source, there is a faint emission feature, called A in Fig. 1, which is partially connected to the jet, approximately located at J2000: $7^h\ 3^m\ 43\overset{s}{.}24$, $-11°\ 33'\ 6''$. To the North of the central core of Z CMa, a weak feature is observed (labeled as B in Fig. 1), which is probably related with Z CMa (see below). The B feature is approximately centered at J2000: $7^h\ 3^m\ 43\overset{s}{.}15$, $-11°\ 33'\ 6''$. In a circle of radius $1\overset{''}{.}2$, centered on Z CMa, there are no other interesting features or structures.

In Fig. 2 we show the 1983.9 epoch continuum of Z CMa at 6 cm. The observed emission is extended in the North-East direction. There are other faint emission structures around Z CMa but their association with the thermal emission of this source is not clear. However, one of these structures has a position which is close to the position of the A feature observed in Fig. 1.

The 1982.1 epoch, 6 cm map shown in Fig. 3 has a bright central core, with an extension in the NE-SW direction, and a secondary weaker peak (labeled as letter C in Fig. 3), located at J2000: $7^h\ 3^m\ 43\overset{s}{.}11$, $-11°\ 33'\ 7\overset{''}{.}2$. To the East and the North of the bright core, there are two weak features located at J2000: $7^h\ 3^m\ 43\overset{s}{.}25$, $-11°\ 33'\ 5\overset{''}{.}9$ and J2000: $7^h\ 3^m\ 43\overset{s}{.}16$, $-11°\ 33'\ 5\overset{''}{.}44$, labeled as D and E, respectively (see Fig. 3).

It is remarkable that the positions of the features D and E, in the 1982.1 epoch map (Fig. 3), result similar to the positions of features A and B, observed in the 1993.8 epoch map (Fig. 1). Nevertheless, these features exhibit changes in morphology and flux density, and appear to be marginally closer to the central core in the 1993.8 epoch than in 1982.1 epoch. Bieging et al. (1983) (see also Cohen & Bieging 1986) reported the existence of the Eastern feature D, and interpreted it as a variable secondary component of Z CMa. Our new data corroborate the existence of this faint eastern component, although its nature is still unclear. From optical observations, Finkenzeller & Mundt (1984), also proposed the presence of a 12 mag source about $1\overset{''}{.}5$ to the east of Z CMa.

In order to analyze the characteristics of the thermal jet of Z CMa, we have employed the task IMFIT of AIPS in all three data epochs to fit and deconvolve the dimensions of the source. The results are summarized in Table 1.

After analyzing these results and taking into account the continuum images, we see that within observational error, we do not find large variations in the parameters of the jet, at the 20% level.

Taking into account these results, the mass loss rate of the jet can be determined considering the following equation (Eislöffel et al. 2000)

$$\dot{M}_{-6} = 1.9\ v_8\ x_0^{-1}\ S_{\rm mJy}^{0.75}\ \nu_9^{-0.45}\ d_{\rm kpc}^{1.5}\ \theta_0^{0.75}\ , \qquad (1)$$

where $\dot{M}_{-6}$ is the mass loss rate in $10^{-6}\ M_\odot\ {\rm yr}^{-1}$, v_8 is the thermal jet velocity given in 10^3 km s^{-1}, x_0 is the ionization fraction, S_{mJy} is the flux density in mJy, ν_9 is the frequency in GHz, $d_{\rm kpc}$ is the distance in kpc (which was taken to be 1.15 kpc), and θ_0 is the opening angle in radians.

The opening angle can be estimated by means of

$$\theta_0 = 2\ tan^{-1}\left(\frac{\theta_{min}}{\theta_{maj}}\right), \qquad (2)$$

where θ_{maj} and θ_{min} are the major and minor axis of the jet-like structure, respectively. In Table 2 we show the obtained results. We have assumed in eq. (1) $x_0 = 1$ and $v_8 = 1$ (probably an upper limit for the jet velocity). The mass loss rate is then of the order of $1{\times}10^{-6}\ M_\odot\ {\rm yr}^{-1}$

In order to study the spectral index of the jet from Z CMa, in Figure 4 we show the spectrum of Z CMa at millimeter and centimeter wavelengths, employing our 3.5 and 6 cm data, and other data from the literature that we summarize in Table 3.

TABLE 2

DERIVED QUANTITIES FOR THE Z CMA THERMAL JET

Epoch	ν(GHz)	θ_0 (rads)	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})
1982.1	4.885	0.98	1.75
1983.9	4.885	0.78	1.15
1993.8	8.415	0.72	1.10

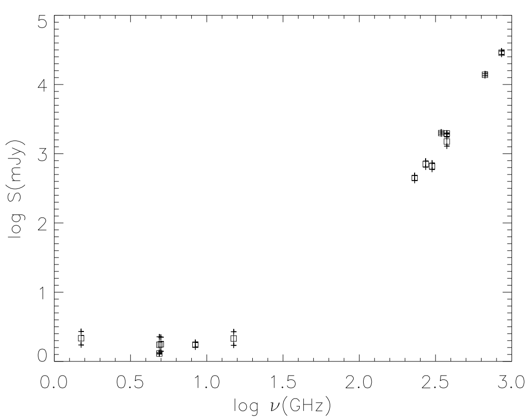

Fig. 4. Spectrum of Z CMa at centimeter and millimeter wavelengths employing the data of Table 3.

At centimeter wavelengths, the spectrum of Z CMa jets is almost flat, suggesting optically-thin free-free emission.

TABLE 3

FLUX DENSITIES OF Z CMA

ν(GHz)	S_ν (mJy)	Reference
1.5	2.16± 0.21	a
4.885	1.30± 0.10	b
4.885	1.73± 0.17	b
5.0	1.77± 0.18	a
8.415	1.74± 0.06	b
15.0	2.14± 0.21	a
230.7	446± 16	c
272.7	708± 31	e
300.	660± 30	d
344.8	1990± 30	c
375.	1500± 100	d
375.	1960± 13	e
667.	13840± 200	e
857.	28800± 700	e

References: (a) Cohen & Bieging (1986), (b) this paper, (c) Reipurth et al. (1993), (d) Weintraub et al. (1991), (e) Dent et al. (1998).

4. DISCUSSION

4.1. *The Secondary Peaks*

Several authors reported that they found a secondary radio or optical source to the east of the core of the Z CMa thermal jet (Bieging et al. 1983; Cohen & Bieging 1986; Finkenzeller & Mundt 1984). However, this fact was not confirmed by other observations.

In our 3.5 cm data, we find that the Z CMa thermal jet has an elongated shape, in the NE-SW direction, with a prominent extension to the SW. To the East and North, there are two emission structures (labeled as "A" and "B" in Fig. 1, respectively), with positions that differ slightly from the ones reported by Bieging et al. (1983). The "A" structure (see Fig. 1) appears connected with the jet of Z CMa.

The presence of the eastern component can be explained by two scenarios. In the first one, Z CMa (already a subarcsecond binary) has a third stellar component 1$''$.5 to its east. However, in the radio the secondary component presents variations in position, flux density and morphology (this probably being the reason why it is detected in some observations, but not in others), making the stellar interpretation unlikely. In the second scenario, this "secondary peak" is actually ionized material which was ejected by the central core of Z CMa and is moving away from it, and it is just a coincidence that the position of the Eastern features "D" and "A"(observed at 1982.1 and 1993.8 epochs, respectively) result similar.

4.2. *The Orientation of the Jet*

In Table 2, we see that the position angle obtained from the 3.5 cm data (65°) is consistent with the value of 60°of the optical jet detected by Poetzel et al. (1989) and the CO outflow reported by Evans et al. (1994). The PA of 65°, obtained from our 3.5 cm data is also almost perpendicular to the angle of the accretion disk claimed to have been detected by Malbet et al. (1993), by means of infrared observations. However, as we noted, these observations have been questioned by Tessier et al. (1994).

Comparing the values of the position angle obtained at the 1982.1, 1983.9, and 1993.8 epochs (see Table 2), we note that there are apparent variations of the order of 10°; however, these variations are not statistically significant since the errors are of the same order.

4.3. *Which Component Drives the Outflow?*

As mentioned, there is uncertainty on which of the two components of the binary is driving the jet. To address this problem, we made a high angular resolution map using only our 1994 A configuration data and uniform weighting. We precessed the map from equinox 1950.0 to equinox 2000.0 using the task REGRD in AIPS. In 1998 August, after our our observations were made, the position of the phase calibrator 0727–115 was refined to achieve an accuracy of $\sim 0.''002$. This refinement of the position ($\Delta\alpha = +0.^{s}006$; $\Delta\delta = +0.''05$) was also applied to the map, resulting in the image shown in Figure 5. This compact radio source is the “base” of the jet, and shows a core with an extension to the northeast. The peak of this core is located at $\alpha(2000) = 07^{h}\ 03^{m}43.^{s}163$; $\delta(2000) = -11°33'06.''21$. To obtain the position of the optical component we used the results of the Hipparcos survey (Perryman et al. 1997) that give for Z CMa $\alpha(2000) = 07^{\rm h}\ 03^{\rm m}43.^{\rm s}1619$; $\delta(2000) = -11°33'06.''209$, with an error of $\sim 0.''001$. The position of the infrared companion was obtained from the offsets given by Thiebaut et al. (1995). As can be seen in Fig. 5, the core of the radio jet seems to coincide well with the optical component, supporting the proposition of Lamzin et al. (1998) that this is the component driving the outflow.

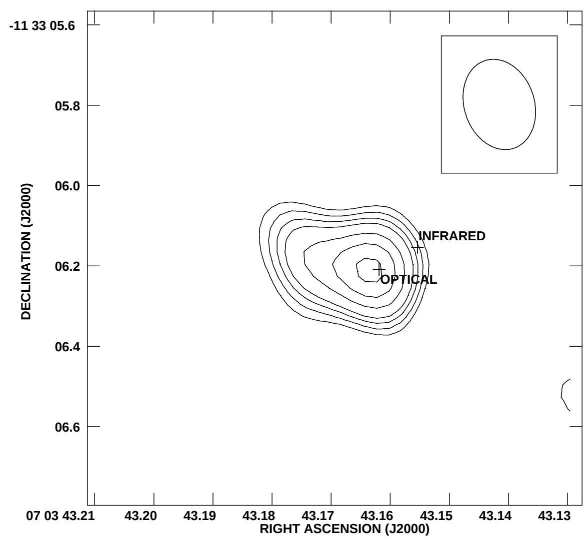

Fig. 5. Contour map of the radio continuum of Z CMa at 3.5 cm, obtained with the A configuration of the VLA and uniform weighting. The crosses mark the positions of the optical and infrared components. The contour levels correspond to (−3, 3, 4, 5, 6, 8, 10, and 12)×0.055 mJy/beam, the rms noise of the map. The angular resolution is $0.23'' \times 0.17''$, PA=18°.

5. CONCLUSIONS

We have obtained high angular resolution ($0.''45$) images at 3.5 cm and 6 cm of the young star Z CMa, employing the VLA.

Analysis of our data at 3.5 cm and 6 cm indicates that the thermal emission of Z CMa exhibits a jet-like shape in direction NE-SW. We determined the position angle of the axis of this radio source and found that is coincident within error with those reported in optical and molecular (CO) observations. Then this radio feature is the radio thermal counterpart of the optical jet and the CO outflow (reported by Poetzel et al. 1989; Evans et al. 1994, respectively).

We also have detected some faint radio features which probably are the results of periodic emission of material from the central core of Z CMa.

Z CMa is actually a binary system in which one of its components is visible in the optical, and the other one was detected in infrared observations. From our high resolution image at 3.5 cm (using the A configuration of the VLA), we found that the optical component of the Z CMa binary system is the star that actually drives the jet (see Fig. 5) detected in radio, optical and CO observations.

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