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ON THE SIZE OF THE NON-THERMAL COMPONENT IN THE RADIO EMISSION FROM CYG OB2 #5

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RESUMEN

Cyg OB2 #5 es un sistema binario de contacto con emisión variable de radio. Esta emisión tiene un estado bajo de flujo dominado por el viento estelar ionizado y un estado alto de flujo, donde una componente no-térmica adicional aparece. Ahora se sabe que las variaciones tienen un período de 6.7 ± 0.2 años. La componente no-térmica ha sido atribuida a varios agentes: una envolvente en expansión eyectada periódicamente por la binaria, emisión de una región de choque de vientos, o una estrella con emisión no-térmica en órbita excéntrica alrededor de la binaria. La determinación del tamaño angular de la componente no-térmica es crucial para discriminar entre estas posibilidades. Presentamos un análisis de datos de archivo del VLA hechos a 8.46 GHz en 1994 (en estado bajo) y 1996 (en estado alto), que nos permiten sustraer el efecto de la componente térmica persistente y estimar un tamaño angular $\leq 0\rlap{.}''02$ para la componente no-térmica. Este tamaño compacto favorece la explicación en términos de una estrella con emisión no-térmica o de una región de choque de vientos.

ABSTRACT

Cyg OB2 #5 is a contact binary system with variable radio continuum emission. This emission has a low-flux state where it is dominated by thermal emission from the ionized stellar wind and a high-flux state where an additional non-thermal component appears. The variations are now known to have a period of 6.7 ± 0.2 yr. The non-thermal component has been attributed to different agents: an expanding envelope ejected periodically from the binary, emission from a wind-collision region, or a star with non-thermal emission in an eccentric orbit around the binary. The determination of the angular size of the non-thermal component is crucial to discriminate between these alternatives. We present the analysis of VLA archive observations made at 8.46 GHz in 1994 (low state) and 1996 (high state), that allow us to subtract the effect of the persistent thermal emission and to estimate an angular size of $\leq 0\rlap{.}''02$ for the non-thermal component. This compact size favors the explanation in terms of a star with non-thermal emission or of a wind-collision region.

Key Words: radio continuum: stars — stars: individual (Cyg OB2 #5)

1. INTRODUCTION

Cyg OB2 #5 (V729 Cyg, BD +40 4220) is an eclipsing, contact binary system consisting of two O-type supergiants with a 6.6-day period (Hall 1974; Leung & Schneider 1978; Rauw, Vreux, & Bohannan 1999; Linder et al. 2009). As several other luminous O-star systems in the Cyg OB2 association, this source was found to show evidence of variable radio emission (Persi et al. 1985, 1990; Bieging, Abbott, & Churchwell 1989). The radio emission appears to have two states: a low-flux state of ~ 2 mJy at 4.8 GHz where the spectral index is consistent with thermal emission from an ionized stellar wind, and a high-flux state of ~ 8 mJy at 4.8 GHz where the spectral index is flatter than in the low state. The variations were proposed to have a 7-year period (Miralles et al. 1994) and have been attributed

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TABLE 1

ARCHIVE DATA USED

Epoch	Project	Frequency (GHz)	On-source Time (min)	Phase Calibrator	Bootstrapped Flux Density (Jy)	Beam Angular Size[a]
1994 Apr 09 (1994.27)	AR277	8.46	37	2007+404	2.84 ± 0.01	$0\rlap{.}''18 \times 0\rlap{.}''16$; -43°
1996 Dec 28 (1996.99)	AR277	8.46	45	2007+404	2.89 ± 0.01	$0\rlap{.}''30 \times 0\rlap{.}''21$; -85°

[a]Major axis × minor axis; position angle, for a (u, v) weighting of ROBUST = 0 (Briggs 1995).

to variable non-thermal emission from an expanding envelope arising periodically in the binary (Persi et al. 1990; Bieging et al. 1989; Miralles et al. 1994).

In addition, Abbott, Bieging, & Churchwell (1981) and Miralles et al. (1994) reported on the existence of a radio "companion" 0.8 arcsec to the NE of the main radio source (which is associated with the eclipsing binary). Observations by Contreras et al. (1997) revealed that this radio source has an elongated shape and lies in-between the short-period binary and a third star, which was first reported by Herbig (1967). Contreras et al. (1997) suggested that the proposed NE radio companion actually corresponds to the wind interaction zone between the binary system and the tertiary component. Recently, Kennedy et al. (2010) reanalysed all VLA observations of Cyg OB2 #5 and showed that the primary radio source, associated with the eclipsing binary, varies with a period of 6.7±0.2 yr while the flux from the secondary NE source remains constant in time. These authors proposed that the variations in the main radio component can be represented by a simple model in which a fourth star (with constant non-thermal emission) moves around the eclipsing binary in an eccentric orbit and the varying radio emission results from the variable free-free opacity of the wind between the star and the observer (Kennedy et al. 2010). These authors estimate a major axis of 14 AU for the star with non-thermal emission. In this scenario, we have a quadruple star system: the contact binary, the star with non-thermal emission in a 6.7 yr orbit around the contact binary, and the NE component.

To advance our understanding of the nature of the time-variable non-thermal emission, a determination of the angular size of the source producing it is needed. Using VLA data taken at 8.46 GHz in 1991 October 3 (when Cyg OB2 #5 was in the high radio state), Miralles et al. (1994) estimated an angular size of $0\rlap{.}''046 \pm 0\rlap{.}''006$ for the whole (non-thermal plus thermal components) emission. Using MERLIN data taken at 4.8 GHz in 1996 November 14 (when Cyg OB2 #5 was again in the high radio state), Kennedy et al. (2010) estimated an angular size of $\sim 0\rlap{.}''077$ for the whole (non-thermal plus thermal components) emission associated with the primary radio component. Since the thermal contribution comes from the ionized wind that is known to be extended, these size estimates can be considered as upper limits to the size of the non-thermal emission. In this paper we present the analysis of archive 8.46 GHz continuum observations made with the Very Large Array (VLA) of the NRAO[3] in the A configuration toward Cyg OB2 #5 in two epochs. During 1994 April 9 (1994.27), the source was in the low radio state and only the thermal emission from the ionized stellar wind was present. These observations were used to estimate the characteristics of the persistent thermal component. During 1996 December 28 (1996.99), the source was in the high radio state, with both the thermal and non-thermal components present. Using the information obtained from the 1994 data, it is possible to subtract in the (u, v) plane the contribution from the thermal component and obtain a more stringent estimate of the angular size of the non-thermal emission.

2. DATA REDUCTION

The archive data were edited and calibrated using the software package Astronomical Image Processing System (AIPS) of NRAO. The parameters of the observations are given in Table 1. The absolute amplitude calbrator for both epochs was 1331+305, with an adopted flux density of 5.21 Jy. The (u, v) data were self-calibrated in amplitude and phase. An image was made with the 1994.27 (u, v) data and the clean components of this image were subtracted from the 1996.99 (u, v) data using the AIPS task UVSUB. The resulting (u, v) data, that we refer to as 1996.99-1994.27, were analyzed both in the image and in the

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(u, v) planes. In the image plane a compact, basically unresolved source is observed. A Gaussian ellipsoid fit to this source in the image plane using the AIPS task JMFIT indicates maximum possible deconvolved angular dimensions of $0\rlap{.}''035 \times 0\rlap{.}''029$ (major axis $\times$ minor axis) for the source. However, White & Becker (1982) have shown that it is better to study the angular dimensions of marginally resolved sources directly in the (u, v) plane. We then fitted directly the (u, v) data in two dimensions using the AIPS task UVFIT and a Gaussian ellipsoid model. The fit gave $0\rlap{.}''023 \pm 0\rlap{.}''013 \times 0\rlap{.}''023 \pm 0\rlap{.}''019$ (major axis $\times$ minor axis) for the source. This result indicates that the source is very compact and that, within the error, it shows no strong departures from a circular morphology. We then adopt as an estimate of the Gaussian angular size (full width at half maximum) of the source the geometric mean of the major and minor axes, that gives $\theta_G = 0\rlap{.}''023 \pm 0\rlap{.}''012$.

The angular size determined for the non-thermal emission depends on the model assumed to fit the (u, v) data. A model of a circular disk with constant brightness gives an angular diameter of $\theta_D = 0\rlap{.}''019 \pm 0\rlap{.}''010$. Given that the errors are comparable to the measurements, we will take this determination as an upper limit, $\theta('') \leq 0\rlap{.}''02$, to the angular size of the non-thermal emission.

3. INTERPRETATION

The small angular size found for the non-thermal component, $\theta('') \leq 0\rlap{.}''02$, can be used to discuss the nature of the non-thermal component. An expanding envelope ejected periodically from the binary (Persi et al. 1990; Bieging et al. 1989; Miralles et al. 1994) would have to be bigger than the radio photosphere to be outside the optically thick region around the contact binary system. We can use the results for the 1994 data discussed in the Appendix A to estimate that the radio photosphere at 8.46 GHz has an angular size of $\theta('') \simeq 72$ milli-arcseconds. We then conclude that an envelope cannot explain the observations since the non-thermal emission would be significantly larger than observed. Recently, Pittard (2010) has proposed that the time variable emission observed in O+O binaries can come from the thermal emission from the wind-collision region between the stars. In the case of Cyg OB2 #5 the wind-collision region between the members of the contact binary is probably a strong emitter, but lies deep inside the radio photosphere of the system, although it is known that the radio photospheres can be clumpy or asymmetric, allowing the detection of sources embedded in it (e.g. WR140; White & Becker 1995). The wind-collision region could also be located between the contact binary and a third star. Kennedy et al. (2010) discussed the variations arising from non-thermal emission in a wind-collision region between the contact binary and a third star. They demonstrate that thermal emission variations that may arise in such a wind-collision region will not have sufficient amplitude to account for the variations, and conclude that the thermal-emission Pittard models would predict smaller flux changes than observed. The Kennedy et al. (2010) models also account well for the variable radio emission. We then favor the possibility of a third star with non-thermal emission in orbit around the contact binary, as proposed by Kennedy et al. (2010), or a wind-collision region.

Despite the fact that the non-thermal emission from young, low-mass stars is typically associated with gyrosynchrotron emission from Lorentz γ factors of a few (e.g. Ray et al. 1997), while the emission from massive stars is believed to be synchrotron from relativistic electrons with very large γ factors (e.g., Pittard & Dougherty 2006), we cannot rule out the possibility that the non-thermal emission from Cyg OB2 #5 is being produced by a young, low-mass star (i.e. a Tauri star) that formed coevally with the rest of the system. The non-thermal emission from young, low-mass stars is usually very compact. For the T Tau Sb star, with a mass of 0.6 $M_\odot$, Loinard et al. (2005, 2007) estimate an angular size of 0.5 mas, that at a distance of 147.6 pc corresponds to a radius of ~ 8 $R_\odot$. For the more massive S1 star (6 $M_\odot$) in Ophiuchus, Loinard et al. (2008) estimate an angular size of 0.95 mas, that at a distance of 116.9 pc corresponds to a radius of ~ 12 $R_\odot$. At the larger distance of 925 pc (Linder et al. 2009), we expect a non-thermal star associated with Cyg OB2 #5 to have an angular size well below a milli-arcsecond.

Cyg OB2 #5 will be again in high state during 2010 and 2011 and a very long baseline interferometry study is needed to determine accurately the angular size and morphology of the compact non-thermal emission.

4. CONCLUSIONS

We present the analysis of VLA archive data of the Cyg OB2 #5 system taken during the high (1996) and low (1994) radio states. This analysis allows the subtraction, in the (u, v) plane of the persistent thermal component and a better estimate of the angular dimensions of the non-thermal component. We obtain an upper limit, $\theta('') \leq 0\rlap{.}''02$ for the angular size of the non-thermal emission. Cyg OB2 #5

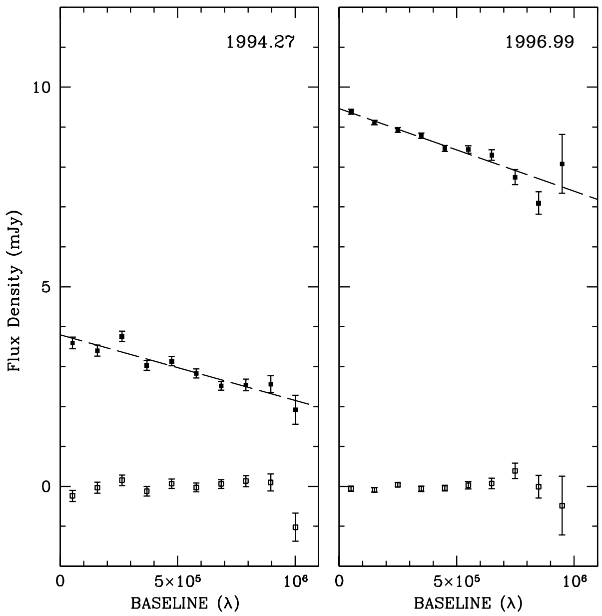

Fig. 1. (Left) Real (filled squares) and imaginary (empty squares) components of the emission at 8.46 GHz for 1994 April 9. The dashed line is the least squares fit to the real component. (Right) Same as in the left panel for 1996 December 28. The imaginary component is consistent with zero, indicating that the source is symmetric about the phase center (the origin of the visibility plane) and has no significant structure on these spatial scales.

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APPENDIX A. ONE-DIMENSIONAL ANALYSIS OF THE VISIBILITY FUNCTION

If the sources have approximate circular symmetry, the analysis of the (u, v) data can be made in a one-dimension approximation. To test if this was possible with the data discussed here, the NE component was subtracted in two dimensions in the (u, v) plane of both data sets using Gaussian ellipsoid models to leave only the emission from the main component, the one directly associated with the contact binary. This subtraction was performed using the AIPS task UVMOD. We then fitted the (u, v) data in two dimensions using the AIPS task UVFIT and a Gaussian ellipsoid model. The fits gave $0\rlap{.}''079 \pm 0\rlap{.}''007 \times 0\rlap{.}''066 \pm 0\rlap{.}''008$ (major axis × minor axis) for the 1994.27 data and $0\rlap{.}''045 \pm 0\rlap{.}''006 \times 0\rlap{.}''036 \pm 0\rlap{.}''005$ (major axis × minor axis) for the 1996.99 data. These results indicate that, within error, the emission at both epochs does not show strong departures from a circular assumption. We also note that at a distance of 925 pc (Linder et al. 2009), the semimajor axis of the non-thermal star (7 AU) will subtend an angle of only $0.008''$, below the upper limit of $0.020''$ found for the angular size of the non-thermal component. It is quite possible that this non-thermal star, if present, will introduce asymmetries but future VLBI observations will be needed to test this.

In Figure 1 we present the one-dimensional real and imaginary components of the amplitude as a function of baseline. These values were obtained using the AIPS task UVPLT that averages in circular rings around the origin of the (u, v) plane. Before applying this task, the source emission was centered on this origin.

For a marginally resolved wind source, the real part of the visibility, $V(b)$, can be fitted in one dimension with a linear function (Escalante et al. 1989):

$$V(b) = S_0 - Ab\,, \tag{A1}$$

where S_0 is the flux density at zero spacing (the total flux density), given in mJy, A is the slope of the linear fit, and b is the baseline separation in wavelengths. For 1994 only the thermal (T) emission was present and we obtain $S_0(T) = 3.79 \pm 0.09$ mJy and $A(T) = (1.64 \pm 0.18) \times 10^{-6}$ mJy wavelength^{-1}. For 1996 both the thermal and non-thermal (T+N) emissions were present and we obtain $S_0(T + N) = 9.46 \pm 0.05$ mJy and $A(T+N) = (2.07 \pm 0.14) \times 10^{-6}$ mJy wavelength^{-1}. The fact that both epochs give similar slopes suggests that, as expected, most of the extended emission comes from the thermal component. Subtracting the 1994 fit to the 1996 fit we obtain the non-thermal (N) contribution alone, that is given by $S_0(N) = 5.67 \pm 0.10$ mJy and $A(N) = (0.43 \pm 0.23) \times 10^{-6}$ mJy wavelengths^{-1}. The characteristic angular size of the emitting region is given by (Escalante et al. 1989; Miralles et al. 1994):

$$\theta('') \simeq 1.44 \times 10^5 \, \frac{A}{S_0}\,, \tag{A2}$$

which gives $\theta('') \simeq 0\rlap{.}''011 \pm 0\rlap{.}''006$ for the non-thermal component. It should be noted that our fitting of the non-thermal component to a thermal wind model may not be consistent, since the structure of the visibilities for an optically thin non-thermal source and

TABLE 2

PARAMETERS FROM FITS

Emission[a]	S_0 (mJy)	A (10^{-6} mJy λ^{-1})	θ (mas[b])
T	3.79 ± 0.09	1.64 ± 0.18	62 ± 7
N+T	9.46 ± 0.05	2.07 ± 0.14	32 ± 2
N	5.67 ± 0.10	0.43 ± 0.23	11 ± 6

[a]T = Thermal, N = Non-thermal.

[b]mas = milli-arcseconds.

a partially optically thick stellar wind are not necessarily the same. In Table 2 we summarize the parameters obtained for the thermal and thermal plus non-thermal states, as well as the subtraction that traces the non-thermal emission alone.

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