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EXPLORING A THERMAL MODEL FOR THE TIME VARIABILITY OF THE RADIO EMISSION FROM THE CEN 1a SYSTEM

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RESUMEN

En este trabajo exploramos la posibilidad de que la emisión variable en el tiempo observada en frecuencias de radio en el sistema CEN 1a tenga un origen térmico. Los flujos observados y los índices espectrales de esta fuente son claramente distintos a los predichos por el modelo estándar de un viento estelar de una estrella masiva, y parecen ser consistentes con emisión térmica ópticamente delgada. Aquí investigamos la emisión libre-libre en radio-continuo de un viento estelar con parámetros de inyección dependientes del tiempo, los cuales tienen como resultado la formación de choques internos que se alejan de la estrella central. Aunque nuestro modelo es capaz de predecir los flujos observados y los índices espectrales de la fuente CEN 1a, éste falla en explicar la variabilidad detectada en el régimen ópticamente delgado. Concluimos que la emisión observada tiene naturaleza compuesta, con contribuciones tanto térmica como no-térmica.

ABSTRACT

In this work we explore the possibility that the observed time variable emission at radio frequencies from the CEN 1a system has a thermal origin. The observed flux densities and spectral indices from this source clearly deviate from the standard stellar wind model around a massive star, and seem to be consistent with optically-thin thermal emission. Here we investigate the radio-continuum free-free emission from a stellar wind with time-dependent injection parameters, which result in the formation of internal shocks that travel away from the central star. Although our model is able to predict the observed flux densities and spectral indices from the CEN 1a source, it fails to explain the detected variability in the optically-thin regime. We conclude that the observed emission has a composite nature, with thermal and non-thermal contributions.

Key Words: radiation mechanisms: thermal — radio-continuum: ISM — shock waves — stars: individual (CEN 1a)

1. INTRODUCTION

The massive radio source CEN 1a (classified as an O4 V star; Hanson, Howarth, & Conti 1997) is one of the components of the massive binary system CEN 1. Located at a distance of 2.1 kpc, this binary star is the main UV photon source that ionizes the HII region M17 (e.g., Hoffmeister et al. 2008). On their own, both components of CEN 1, CEN 1a and CEN 1b, are spectroscopic binaries (Hoffmeister et al. 2008). CEN 1 was detected for the first time at radio frequencies by Rodríguez, González, & Montes (2009), showing that the flux densities observed from both components (CEN 1a and CEN 1b) exceed the expected free-free emission from an ionized wind. An O4 V star has a luminosity of $6 \times 10^5\ L_\odot$ (the average of the values given by Hanson et al. 1997 and Vacca, Garmany, & Shull 1996). Following Kudritzki & Puls (2000) we find that on the average such a star will have a wind terminal velocity of 3×10^3 km s^{-1} and a mass loss rate of $2 \times 10^{-6}\ M_\odot$ yr^{-1}. Using these wind parameters, we estimate the free-free radiation (at radio wavelengths) from a completely

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ionized spherical wind assuming an electron temperature in the wind of 104 K (Panagia & Felli 1975; Wright & Barlow 1975). At 8.46 GHz, we derive an expected flux density of 0.03 mJy. This is more than an order of magnitud below the detected values in CEN 1a and suggests a mechanism different from the classic thermal wind.

More recently, high angular resolution observations (at 4.96 and 8.46 GHz) by Rodríguez et al. (2012) give evidence that, while CEN 1b is a steady source (with a spectrum consistent with optically-thin synchrotron radiation), CEN 1a is strongly variable (but with a flat spectral index, consistent with thermal optically-thin radiation). The observed flux densities and the spectral index from CEN 1a clearly deviate from the values predicted by the standard wind model (Panagia & Felli 1975; Wright & Barlow 1975). In these works, a free-free spectrum $S_\nu \propto \nu^{0.6}$ from an ionized isotropic outflow is predicted. Possible mechanisms that lead to deviations from the 0.6 spectral index are discussed in Leitherer & Robert (1991). Among those are changes in the ionization structures and acceleration and deceleration zones of the wind close to the star.

Deviations from the 0.6 value may also be caused by internal shocks in the wind. Supersonic flows are always subject to the formation of shock waves. Raga et al. (1990) developed models for supersonic outflows ejected from sources with variable velocities. These authors showed that supersonic variations in the ejection velocity of a highly supersonic flow lead to the formation of the so-called working surfaces (structures bounded by two shock fronts) that move inside the flow.

More recently, Cantó, Raga, & D'Alessio (2000) presented a formalism for solving the equations for hypersonic flows with time-dependent injection velocities, based on momentum conservation for the internal working surfaces. They obtained parametric analytic solutions for the dynamical properties of the working surfaces given the specific variability of the flow parameters (injection velocity, mass injection rate and (or) injection density).

González & Cantó (2002) applied this formalism to estimate the thermal radio-continuum emission from shocked stellar winds in low-mass stars, where the ionization and radiation are produced by internal working surfaces in the winds. In another work, González & Cantó (2008) studied the free-free radiation at radio wavelengths from an outgoing working surface in a stellar wind ejected from a massive star. These authors considered that the central star keeps both the wind and the compressed shell inside the working surface fully ionized. Here, we investigate the variability in the flux densities and the spectral index from such a system, and compare our predictions with the radio source CEN 1a.

This paper is organized as follows. In § 2, we describe the model. The comparison of the model predictions with the observations of the CEN 1a system is shown § 3. Finally, in § 4 we give our conclusions.

2. THE MODEL

Consider an isotropic ionized wind with time-dependent injection parameters. For times $t < 0$, the wind velocity and the mass loss rate are v_0 and $\dot{m}_0$, respectively. Suddenly, at time $t = 0$, the wind velocity is increased to av_0 ($a > 1$) while the mass loss rate remains constant. This kind of variability in the flow parameters, which has been previously investigated in González & Cantó (2002), Cantó et al. (2005), and González & Cantó (2008), produces instantaneously (at the base of the outflow) an internal working surface that moves with an intermediate constant velocity $v_{\rm ws} = a^{1/2} v_0$. Neglecting the stellar radius, the position of the shell is simply $r_{\rm ws} = v_{\rm ws}\, t$. In addition, we adopt the approximation that the width of the working surface is negligible with respect to the distance from the central star (the effect that the shell becomes physically thicker as it evolves is ignored in this work; see González 2002).

Given $r_{\rm ws}$ and $v_{\rm ws}$, one can calculate the optical depth of the working surface along a line of sight that intersects the shell, and thus, its contribution to the total emission. According to González & Cantó (2008), the radio-continuum flux from the shocked wind located at a distance D from the observer can be calculated by integrating the intensity over the solid angle, that is,

$$S_\nu = 2\pi B_\nu \left(\frac{r_{\rm ws}}{D}\right)^2 \int_0^\infty \left[1 - e^{-\tau(\tilde{q})}\right] \tilde{q}\, d\tilde{q}\,, \qquad (1)$$

where B_ν is the Planck function in the Rayleigh-Jeans approximation ($= 2kT_e\nu^2/c^2$ with k being Boltzmann's constant, T_e the electron temperature and c the speed of light), and $\tilde{q} = q/r_{\rm ws}$ an adimensional impact parameter. For $\tilde{q} \le 1$, the total optical depth has the contribution of both the fast and the slow winds and also of the working surface, $\tau(\tilde{q}) = \tau_{\rm ew}(\tilde{q}) + \tau_{\rm ws}(\tilde{q}) + \tau_{\rm iw}(\tilde{q})$, while for $\tilde{q} > 1$ it only has the contribution of the external wind, $\tau(\tilde{q}) = \tau_{\rm ew}(\tilde{q})$[4].

As pointed out by González & Cantó (2008), the contribution of the working surface to the total emission occurs near a critical frequency that, in time,

[4]The expressions for $\tau_{\rm ws}(\tilde{q})$, $\tau_{\rm ew}(\tilde{q})$, and $\tau_{\rm iw}(\tilde{q})$ are given by equations 7, 11 and 12 of González & Cantó (2008).

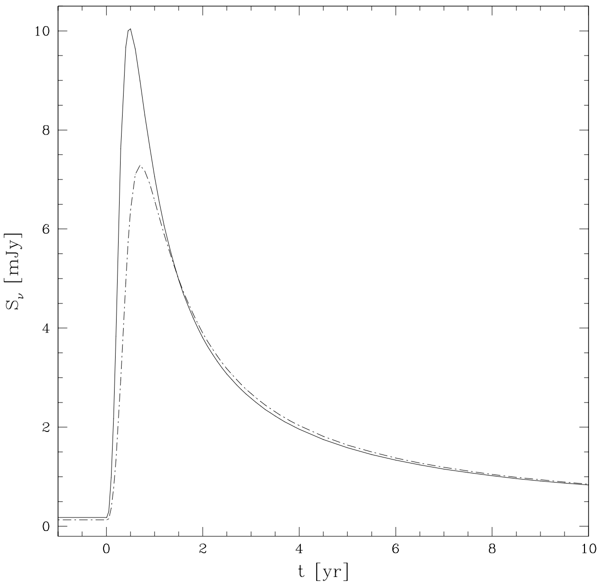

Fig. 1. Predicted radio-continuum fluxes at 8.46 GHz (solid line) and 4.96 GHz (dot-dashed line) as functions of time from the CEN 1a system. We have assumed an isotropic stellar wind with constant mass-loss rate $\dot{m}_0 = 3.9 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, and an initial ejection velocity $v_0 = 1800\ \mathrm{km\ s}^{-1}$ which suddenly changes to $av_0 = 3240\ \mathrm{km\ s}^{-1}$. The source is located at a distance $D = 2.1$ kpc from the observer. The behavior of the plot is described in the text.

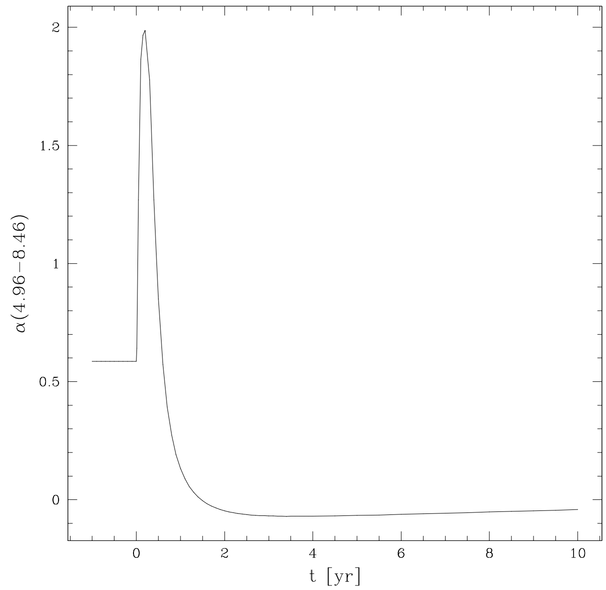

Fig. 2. Spectral index between 4.96 GHz and 8.46 GHz as a function of time for the model described in Figure 1. The physical description of the plot is given in the text.

moves toward lower frequencies. Let ν_0 be a fixed frequency. Then, before the working surface is formed (at a time $t = 0$) the flux $S_1(\nu_0)$ must be consistent with the predicted value by the standard wind model for the slow initial wind. Once the working surface is formed (at a time $t = 0$), the flux steadily increases reaching a maximum value while the spectral index $\alpha \to 2$. For later times, as the working surface moves away from the star, it becomes optically thin ($\alpha \to -0.1$), while the flux $S_2(\nu_0)$, with $S_2(\nu_0) < S_1(\nu_0)$ for constant mass-loss rate, will approach again the value predicted by the standard wind model, but corresponding to the faster wind.

3. RADIO-CONTINUUM EMISSION FROM THE CEN 1A SYSTEM

To explore the possibility that the time variable emission from CEN 1a has a thermal origin, we apply the model described in § 2 for computing the free-free radiation at radio frequencies from this source. As mentioned above, CEN 1a shows a flat radio spectrum that seems to be consistent with optically-thin thermal emission, but it is strongly time-variable (Rodríguez et al. 2012).

Let us suppose that, for times $t < 0$, the wind velocity is constant, with a value $v_0 = 1800\ \mathrm{km\ s}^{-1}$. At time $t = 0$, the ejection velocity is suddenly increased to $av_0 = 3240\ \mathrm{km\ s}^{-1}$ ($a = 1.8$)[5]. The mass-loss rate $\dot{m}_0 = 3.9 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ is assumed to be constant. This variation in the wind velocity produces instantaneously, at the base of the outflow, a working surface that travels with constant velocity $v_{\mathrm{ws}} = a^{1/2} v_0 = 2415\ \mathrm{km\ s}^{-1}$, which is intermediate between the low-velocity and high-velocity outflows (see, also, González & Cantó 2002). Since the shell velocity is constant, its position is simply $r_{\mathrm{ws}} = v_{\mathrm{ws}}\, t$, where we suppose that the stellar radius is much smaller than the radius of the emitting region of the wind.

In Figures 1 and 2 we present the results of our model for the flux densities at 4.96 GHz and 8.46 GHz and the corresponding spectral index. For times $t < 0$, the fluxes at both frequencies are consistent with the values obtained from an ionized spherical wind (with a velocity of $1800\ \mathrm{km\ s}^{-1}$). At a time $t = 0$, when the shocks are produced, the fluxes rapidly increase reaching the peak values $S_{4.96} \simeq 7.3$ mJy, and $S_{8.46} \simeq 10$ mJy as well as the spectral index $\alpha \to 2$. For later times, the flux

[5] Although this kind of speed increase is not expected in a normal star, we explore this possibility in an attempt to find a thermal explanation for the observed radio emission from CEN 1a.

densities decrease more slowly, while the spectral index diminishes to −0.1. Eventually, the spectral index will again approach the value 0.6, but the fluxes will correspond to the faster wind with velocity of 3240 km s^{-1}.

We note that the model is able to predict both the observed flux densities from CEN 1a, $S_{4.96} =$ 2.69 mJy and $S_{8.46} = 2.58$ mJy, and the corresponding spectral index, $\alpha(4.96-8.46) \simeq -0.08$, at a time $t \simeq 3$ yr of the dynamical evolution of the working surface. However, the observed variability from this source over timescales of one month cannot be explained by this model in the optically-thin regime. The fast time variability, with the flux density increasing in time, can be explained in the initial, optically-thick regime, but the model fails to explain the observed flat spectral index. Therefore, we conclude that the observed radio emission from CEN 1a most probably has a non-thermal nature, and that the observed flat spectrum is consistent with a combination of synchrotron emission and free-free absorption, as noted before (see Rodríguez et al. 2009).

Our thermal model implies that a significant increase in flux density over time periods of months will also result in an optically-thick ($S_\nu \propto \nu^2$) spectrum. However, this is clearly not the case in CEN 1a. Also, in the case of Cyg OB2 No. 9 this behavior is not present. This star increased its 3.6 cm flux density from 1.87 ± 0.01 mJy on 1992 May 30 to 3.20 ± 0.06 on 1993 January 1 (van Loo et al. 2008). However, in this last epoch its 6-cm flux density was 3.09 ± 0.01 mJy, implying again a flat spectrum like in the case of CEN 1a. Another example of this behavior is HD 168112, which increased its 3.6 cm flux density from 0.30 ± 0.05 mJy on 1992 May 30 to 3.42 ± 0.09 on 1993 January 1 (Blomme et al. 2005). In this last epoch its 6-cm flux density was 4.24 ± 0.11 mJy, consistent with a flat spectrum like in the case of CEN 1a and Cyg OB2 No. 9.

4. CONCLUSIONS

In this article, we investigate the time variation of the thermal radio emission from shocked stellar winds in massive stars. We apply the model developed by González & Cantó (2008) for calculating the free-free emission at radio frequencies from outflows with time-dependent injection parameters. Assuming a sudden increase in the ejection velocity, we investigate the predicted light curve from this kind of systems. We show that the contribution of the internal shocked layer rapidly increases the total emission reaching a maximum value in the optically thick phase, after which the layer becomes optically thin and the emission decreases more slowly. Thus, the model predicts a fast variation in the flux density in the optically-thick regime. The flux densities before the layer is formed and at large enough times correspond to the predicted values by the standard wind model of an ionized flow.

In particular, we try to model the CEN 1a system as a thermal source. This system shows a radio spectrum that seems to be consistent with optically thin thermal emission, but is strongly time-variable over timescales of months. Although our model can explain simultaneously the observed flat spectrum at 4.96 GHz and 8.46 GHz, it predicts larger timescales in the optically thin regime, as well as decreasing fluxes (while increasing fluxes are observed). Finally, we conclude from our thermal emission model that the CEN 1a spectrum most probably can be explained as a composite spectrum, with a thermal plus a non-thermal contribution arising from the wind collision region in a massive binary system. This interpretation supports the conclusion of Hoffmeister et al. (2008) that CEN 1a is a spectroscopic binary. Radio observations of very high angular resolution (VLBI) are required to image the non-thermal wind collision region.

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