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Thermal Radio Emission from Radiative Shocks in Colliding Stellar Winds

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Abstract: We present a semi-analytic model for computing the thermal radio continuum emission from radiative shocks within colliding wind binaries. Assuming a thin shell approximation, we determine the contribution of the wind collision region (WCR) to the total thermal emission for close binaries. We investigate the effect of the binary separation and the stellar wind parameters on the total spectrum. In addition, we point out the relevance of taking into account this contribution for the correct interpretation of the observations, and the accuracy of the stellar wind parameters derived from them.

1 Introduction

Stellar winds from hot massive stars, OB and Wolf-Rayet (WR) type stars, emit free-free thermal emission detectable at radio frequencies. For a steady, isothermal, and radially symmetric wind, the radio spectrum is characterized by a spectral index, $\alpha \sim 0.6$ ($S_\nu \propto \nu^\alpha$; Wright & Barlow, 1975; Panagia & Felli, 1975). However, deviations from these assumptions, such as variations in the wind parameters at injection, might alter the value of α (Leitherer & Robert, 1991; González & Cantó 2008). Furthermore, in binary systems, the stellar winds of both stars might collide, resulting in a WCR between the stars (Eichler & Usov 1993). This WCR might also affect the radio spectrum, since its structure might i) alter the symmetry of stellar wind, and, ii) contribute with an extra emission component, which could be thermal and/or non-thermal emission.

Theoretical studies suggest that for wide systems (orbital periods, P ~years) the thermal emission from the WCR might have an important but not dominant contribution to their total emission (see Stevens 1995), being more important for close systems (Pittard et al. 2006). Pittard et al (2006) analyzed the thermal emission arising from an adiabatic WCR, and found that the hot gas within the WCR remains optically thin, with a thermal component of emission with an spectral index ~-0.1. Recently, Pittard (2010) studied the emission from radiative shocks in O+O type systems. They found that the thermal emission from the material within this kind of shocks remains optically thick with spectral indices up to ~ 1.5 for frequencies ~ 50 GHz. Such steep tendency for the spectral index

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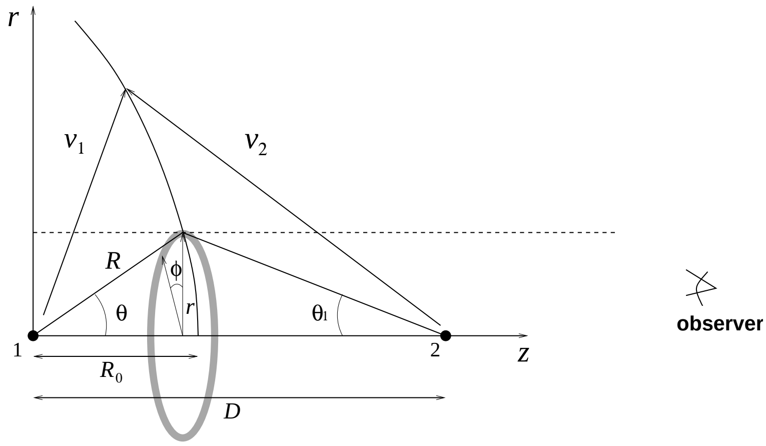

Figure 1: Schematic diagram of the two symmetric winds from stars 1 and 2, having velocities v_1 and v_2, and the thin shell resulting from their interaction. Dotted line represent the line of sight from the observer through the stellar winds, which intersects the thin shell at the impact parameter r.

were reported for WR systems in Montes et al. 2009, which suggest that a thermal component from a radiative WCR could also be taking place in WR stars.

2 Thermal radio-continuum emission from the WCR

2.1 The analytical model

Using the formalism developed by Cantó, Raga, & Wilkin (1996) and Cantó, Raga, & González (2005) we obtain semi-analytic solutions (Montes et al. 2010) from which the free-free thermal emission arising from the interaction region, and its dependence with the stellar wind parameters, can be obtained.

We assume two symmetric and stationary outflows, and use a thin shell approximation to describe their interaction. We define $\dot{m}_1$ and v_1 as the mass loss rate and the velocity of the wind source at the origin of the spherical coordinate system (R, θ, ϕ), and $\dot{m}_2$ and v_2 as the corresponding quantities for the wind from the source located at a distance D. The position of the thin shell can be approximated by the momentum balance curve described by,

$$R(\theta) = D \sin\theta_1 \csc\left(\theta + \theta_1\right), \tag{1}$$

(Cantó et al. 1996). Additionally, the distance to the stagnation point is $R_0 = \beta^{1/2} D/(1 + \beta^{1/2})$, where $\beta = (\dot{m}_1\, v_1)/(\dot{m}_2\, v_2)$ (see Figure 1).

These assumptions allow us to find an analytic expression for the emission measure of the WCR as a function of θ and θ_1, $EM(\theta, \theta_1)$. In this way, the optical depth of the WCR, in the direction perpendicular to the thin shell, can be written as $\tau_{WCR,\perp}(\theta, \theta_1) = EM(\theta, \theta_1)\, \chi(\nu)$, where $\chi(\nu)$ =8.436 $\times 10^{-7}\, \nu^{-2.1}$, where ν is the frequency in Hz.

2.2 The radio spectra of binary systems

The radio continuum flux from a system located at a distance L from the observer can be calculated by,

$$S_\nu = 2\pi B_\nu \left(\frac{R_0}{L}\right)^2 \int_0^{\tilde{r}(\theta_\infty)} [1 - \mathrm{e}^{-\tau(\theta,\theta_1)}]\, \tilde{r}\, d\tilde{r} \tag{2}$$

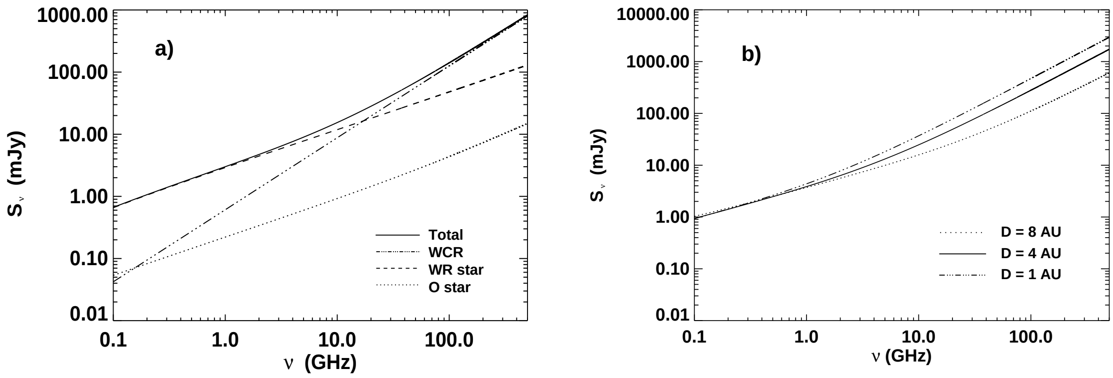

Figure 2: a) Predictions from the analytical model presented in Section 2 of the thermal radio spectrum of a binary system with $\beta = 0.25$, $D = 4$AU, $v_1 = v_2 = 10^3 \mathrm{km\,s^{-1}}$, $\dot{M}_1 = 1.25 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$, and $\dot{M}_2 = 5 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$. All the emission components, and the total spectrum are plotted. b) Total thermal emission for systems at different separation D, considering the terminal wind velocities $v_1 = v_2 = 10^3 \mathrm{km\,s^{-1}}$, and mass loss rates $\dot{M}_1 = \dot{M}_2 = 5 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ ($\beta = 1$).

where $\tau(\theta, \theta_1) = \tau_{WCR}(\theta, \theta_1) + \tau_{w,1}(\theta) + \tau_{w,2}(\theta)$ is the total optical depth along the line of sight, $B_\nu = 2kT\nu^2/c^2$ (being k the Boltzmann's constant, and c the speed of light) is the Planck function in the Rayleigh-Jeans approximation, and $\tilde{r}(\theta_\infty)$ is the impact parameter at the asymptotic angle θ_∞ of the thin shell, which corresponds to $R \rightarrow \infty$.

In Figure 2-a we show the total thermal spectrum from a binary system with typical WR+O type star parameters. All the individual contributions to the emission are plotted. The shock emission remains optically thick with $\alpha_{WCR} \sim 1.1$, and the stellar wind components shows the expected $\alpha \sim 0.6$ behavior. In this way, the total spectrum shows a stellar wind behavior at low frequencies, changing to one dominated by the shock at high frequencies. Therefore, the impact of the WCR over the total spectrum is seen as an excess of emission at high frequencies (with respect to that expected for a single stellar wind spectrum). This result is similar to that found by Pittard (2009) from hydrodynamic simulations for radiative O+O systems.

From equation (3), for the case $\tau_{WCR} >> 1$ it can be seen that $S_\nu \propto R_0^2 \propto D^2$, in contrast with the D^{-1} dependence for adiabatic shocks (Pittard et al. 2006). Figure 2-b shows the increase of the WCR contribution when the distance between the stars D is increased.

3 Applicability of the model

This model can be applied to WR binary systems that satisfy $P > 15$ days, where the wind acceleration region and braking effect, which could be relevant in shorter period systems (Gayley, Owocki, & Cranmer, 1997), can be neglected. On the other hand, Parkin & Pittard (2008) found, for a WR system, that the cooling is important for orbital periods $\lesssim 1$ year. Thus, the systems we are considering have a period between 15 days and 1 year.

3.1 The case of WR 98

WR 98 (HD 318016) is a system identified as a double-line binary (WN7o/WC+O8-9) with an orbital period, $P = 47.8$ days (Gamen & Niemela 2002). Montes et al. (2009) reported variability in both flux density and spectral index, which they interpreted as the result of a WCR contribution. We apply our model and fit the flux densities obtained for which their determination of the spectral index

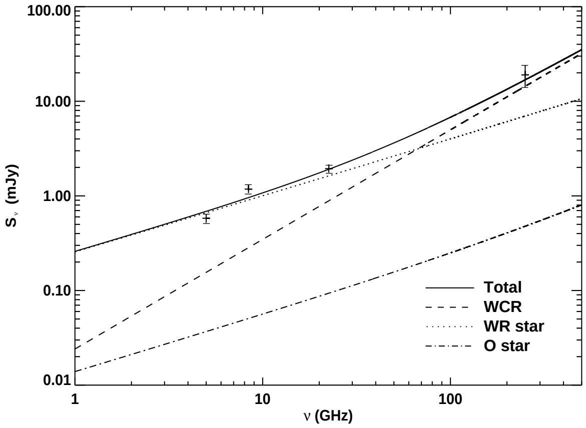

Figure 3: Fit of the radio observations of the binary system WR 98 including the WCR thermal component. Flux densities, $S_{5\,\mathrm{GHz}} = 0.58 \pm 0.06$ mJy, $S_{8.4\,\mathrm{GHz}} = 1.18 \pm 0.05$ mJy, $S_{23\,\mathrm{GHz}} = 1.94 \pm 0.05$ mJy from Montes et al. (2009), and $S_{250\,\mathrm{GHz}} = 19 \pm 5$ mJy from Altenhoff et al. (1994) are plotted.

suggest a thermal spectrum, with $\alpha \sim 0.64$ (see Figure 3). For the WR star, we have assumed a mass loss rate $\dot{M}_{WR} = 3.0 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ (upper limit derived by Montes et al. 2009), and a terminal velocity $v_{WR} = 1200\,\mathrm{km\,s^{-1}}$ (Eenens & Williams, 1994). The best fit to the observations was found using the O star parameters $\dot{M}_O = 4.0 \times 10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$ and $v_O = 1800\,\mathrm{km\,s^{-1}}$, which are reasonable values for an O type star. We assume a separation, $D = 0.5$AU (see Gamen & Niemela 2002), and calculate $\beta = 0.2$, and $R_0/D = 0.3$. From our model we predict that the WCR might start to contribute to the spectrum at a frequency of $\nu \sim 70$ GHz, and reach an excess of emission at 250 GHz of a factor of 2 that from the stellar winds (~ 7 mJy), which is similar to the flux density at 250 GHz, $S_{250\,\mathrm{GHz}} = 19 \pm 5$ mJy, reported by Altenhoff, Thum, & Wendker (1994).

4 Discussion and Conclusions

Steep spectral indices in both WR and O type stars have been observed (Montes et al. 2009; Benaglia 2010). In particular, for WR stars, Nugis, Crowther, & Willis (1998) analyzed their spectrum from mm to IR frequencies, finding spectral indices between 0.6-1.0, with cases where α increases at high frequencies. Although several processes have been used to explain such behavior, our model predicts the WCR to have a similar impact over the radio-mm spectrum.

At this time, the impact of the WCR over the radio spectrum has only been inferred from the analysis of non-thermal emission, detectable mainly at low frequencies. In this way, for those close systems where the non-thermal emission is expected to be absorbed and only the thermal stellar wind emission is thought to be detected, this model also predicts an impact from a WCR contribution. Furthermore, as well as in the case of the non-thermal emission, the thermal contribution from the WCR is expected to be modulated by the orbital motion (Pittard 2010), resulting in this way in a variable thermal contribution. Therefore, observational studies to identify a modulated thermal excess of emission might represent a new method to unveil close binary systems from radio observations, this time at high radio frequencies (a few cm down to a few mm). Those close systems like WR 113, and WR 141, where steep spectral indices have been observed (Montes et al. 2009), are excellent candidates for this kind of study.

On the other hand, in order to compare the spectrum behavior in close systems with respect to those in wide systems and single stars, a statistical study of the emission at frequencies ($\gtrsim 50$ GHz) is required. This study might reveal a steep tendency for the spectral index in close systems, unveiling in this way a binary influence as result of the process described here. However, at this moment there is a poor sample of O and WR stars (those with the strong winds) observed at high frequencies, so that this kind of study is not possible to perform, and high-frequency observations are required.

Furthermore, as was pointed out for WR 98 in Section 4, the total flux density at 250 GHz was estimated to be a factor of 2 higher than that from a single stellar wind, as result of the WCR contribution. Therefore, this possible extra contribution must be taken into account for a mass loss rate determinations from these frequencies. This effect could be even higher than in the example of WR 98, as was pointed out by Pittard (2010) from his estimates of the WCR contribution in radiative O+O systems.

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