RevMexAA (Serie de Conferencias), **15**, 56–58 (2003)

RADIO EMISSION MODELS OF COLLIDING-WIND BINARIES

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RESUMEN

Presentamos cálculos preliminares de la distribución espacial de la emisión a radiofrecuencias de un sistema binario WR+OB con vientos en colisión basados en simulaciones hidrodinámicas de alta resolución y en soluciones a la ecuación de transferencia radiativa. Explicamos tanto la emisión térmica como la emisión sincrotrónica suponiendo una equipartición entre las densidades de energía magnética y de las partículas relativistas, y que esta última es una fracción sencilla de la densidad de energía térmica de las partículas. Presentamos unos intentos preliminares de modelar el radiocontinuo del sistema binario muy abierto WR 147, y presentamos algunos pensamientos sobre como modelar la curva de luz a radiofrecuencias del sistema de vientos en colisión arquetipo, WR 140.

ABSTRACT

We present initial calculations of the spatial distribution of the radio emission from a WR+OB colliding wind binary (CWB) system based on high-resolution hydrodynamical simulations and solutions to the radiative transfer equation. We account for both thermal and synchrotron radio emission assuming equipartition between the magnetic and relativisitic particle energy densities, and that the latter is a simple fraction of the thermal particle energy density. We present preliminary attempts to model the radio continuum of the very wide system WR 147, and present some thoughts on modeling the radio light curve of the archetype CWB, WR 140.

Key Words: **STARS: WR — STARS: MASS LOSS**

1. INTRODUCTION

Observations of some early-type stars reveal them to be sources of both thermal and synchrotron radio emission. Thermal emission typically exhibits brightness temperature $\sim 10^4$ K and spectral index $\alpha \sim +0.6$ ($S_\nu \propto \nu^\alpha$) at centimeter wavelengths. In contrast, synchrotron emission is characterized by high brightness temperatures ($\geq 10^6$ K) and flat or negative radio spectral indices. In addition to magnetic fields, synchrotron emission requires a population of relativistic electrons, widely thought to be accelerated in shocks. For single stars, shocks arise due to wind instabilities (e.g., Lucy & White 1980), while for massive binary systems stationary shocks occur where the winds of the two stars collide (Eichler & Usov 1993).

Observations of the WR+OB binary systems WR 146 (Dougherty et al. 1996; Dougherty, Williams, & Pollacco 2000) and WR 147 (Williams et al. 1997; Niemela et al. 1998) provide direct imaging evidence that the wind-wind collision region is the origin of synchrotron emission. In both these WR stars the thermal emission is coincident with the position of the WR star, while the synchrotron emission arises between the binary components at a position consistent with the pressure balance of the two stellar winds. There is strong evidence that all WR stars that exhibit synchrotron emission are binary systems (Dougherty & Williams 2000), and this is also possibly the case in O stars cf. Cyg OB2 #5 (Contreras & Rodríguez 1999).

In this paper we describe some preliminary work on modeling the radio emission from colliding wind systems. To date, modeling has been restricted to the radiometry from such systems. Typically, the stellar wind envelope is assumed to be radially symmetric, such that relatively simple analytical solutions are maintained. Although these models may successfully recover the radiometry (e.g., Skinner et al. 1999; Monnier et al. 2002), the single-valued free-free opacity along the line of sight to the synchrotron emission region is an over-simplification considering the observed extended synchrotron emission from both WR 146 and WR 147 . Furthermore, in a colliding wind binary (CWB) the assumption of radial symmetry fails in the collision zone.

No attempts have yet been made to construct synthetic radio images based on more realistic density and temperature distributions. This is surely imperative with the advent of spatially resolved observations, where direct comparison between models and observations may be expected to increase our understanding of this phenomenon. In making

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the first steps toward addressing this situation, we have calculated the free-free and synchrotron emission arising from an early-type binary system under various simplifying assumptions. Our approach extends and improves on previous work by including the ability to simulate both the free-free *and* synchrotron emission and absorption from the stellar winds and wind-wind collision region based on hydrodynamical simulations of the density and pressure distribution. The radiative transfer equation is then solved to generate synthetic images.

2. MODELING THE CWB RADIO EMISSION

The input for our model calculations is from a hydrodynamic model of a wind-wind collision (Pittard & Stevens 1997), calculated using VH-1, a piecewise-parabolic method code with a Lagrangian remap. We assume that the stellar winds are spherically symmetric and collide at their terminal speeds to generate an axisymmetric region of hot gas. We use WR or Solar abundances for the winds, as appropriate. Such models are commonly applied to the analysis of X-ray observations of CWB systems (cf. Pittard & Corcoran 2002; Pittard et al. 2002)

The 2-D grid of density and pressure from VH-1 is read into a radiative transfer ray-tracing code that generates synthetic images of the model under the assumption of cylindrical symmetry. Expressions for the thermal emission and absorption coefficients are taken from Rybicki & Lightman (1979, hereafter RL79) equations 5.14b and 5.18b, respectively. The synchrotron emission is modeled in a "standard" manner assuming equipartition between the energy density of the relativistic particles ($U_{\rm rel}$) and the magnetic field ($U_{\rm B}$), and that $U_{\rm rel}$ is proportional to the thermal energy density, $U_{\rm th}$ i.e., $U_{\rm B} = U_{\rm rel} = fU_{\rm th}$, where $U_{\rm th} = P/(\Gamma-1)$ (P is the gas pressure and Γ is the adiabatic index, taken to be 5/3). In the models discussed here, we assume a truncated power-law distribution of electrons, $N(E)\,dE = CE^{-p}\,dE$ between energies $\gamma_{\rm max}$ and $\gamma_{\rm min}$, though any energy distribution can be used. For a power-law distribution, the emission is given by RL79 equation 6.36. We assume $p = 2$ (giving a spectral index of -0.5) and impose the limits $\gamma_{\rm max} = 4000$ and $\gamma_{\rm min} = 1$ on the electron energy distribution. To be complete, we also include synchrotron self-absorption (RL79 equation 6.53).

2.1. *WR 147*

As a first step, we have attempted to model the radio emission from WR 147. In this system, the two stars are separated by 410 AU/ cos(i), where i

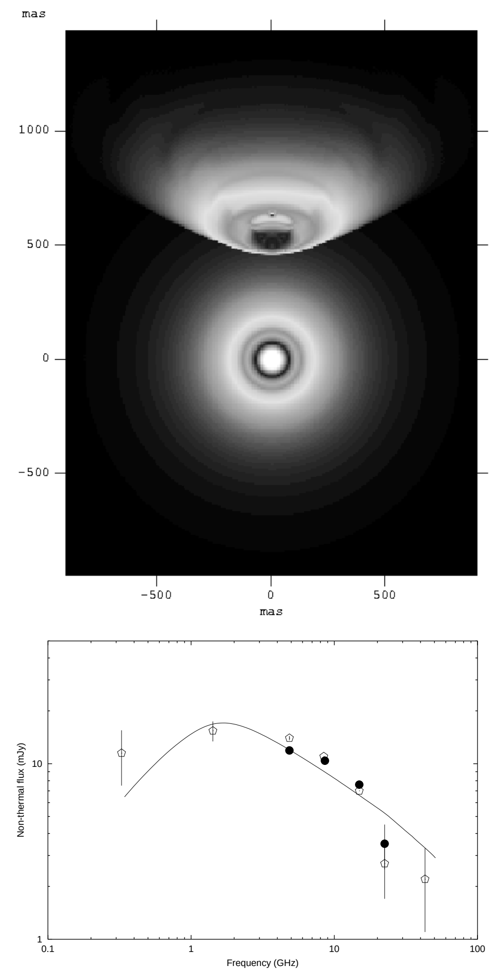

Fig. 1. Synthetic image of WR 147 at 5 GHz (top) and spectrum of WR 147N (bottom). The solid line represents the model spectrum and the solid points are the radiometry of WR 147N from direct observation. The open hexagons are points inferred from the total flux measurements minus an extrapolated thermal power-law model (Setia-Gunawan et al. 2001). The low-frequency turnover is due to free-free absorption by the stellar wind.

is the inclination angle. In such a wide system the relative position of the stars and the wind-collision region is stationary on the timescale of tens of years and can be adequately modeled in 2-D axisymmetry. Further, in such a system the inverse Compton (IC) lifetime is long compared to the dynamical time, and the density in the collision zone is such that synchrotron self-absorption (SSA) is not a factor.

We adopt the following system parameters for our models of WR 147: $\dot{M}_{\rm WR} = 2\times10^{-5}\,M_\odot\,{\rm yr}^{-1}$, $\dot{M}_{\rm O} = 3.8\times10^{-7}\,M_\odot\,{\rm yr}^{-1}$, $v_{\infty,{\rm WR}} = 950\,{\rm km\,s}^{-1}$, and $v_{\infty,{\rm O}} = 1000\,{\rm km\,s}^{-1}$, giving a wind momentum ratio $\eta = 0.02$. In these models we adopt $D_{\rm sep} = 6.1\times10^{15}$ cm, a separation derived assuming an inclination $i = 0°$ to the line of sight. The model flux was normalized (via the proportionality constant f) using the 5 GHz data point (see Figure 1) with $f = 6.3 \times 10^{-3}$. The results are shown in Fig. 1 and it can be seen that for an initial attempt the model fit is remarkably consistent with the data. For a more detailed discussion of this work see Dougherty et al. (in preparation).

2.2. *Thoughts on Modeling WR 140*

In systems with eccentric orbits that are much more compact than WR 147, the variation of the stellar separation, D, will cause a change in the observed synchrotron luminosity, since the *intrinsic* synchrotron emission will vary as $D^{-1/2}$ (assuming $U_{\rm rel} \propto U_{\rm th}$ and the shocks are adiabatic) and the absorption (both free-free and SSA) increases with decreasing D. For small separations, radiative cooling of the shocked gas and IC cooling may also become important. Thus, observations of such systems may place constraints on the nature of the accelerated electrons, and may potentially provide further insight to the underlying acceleration mechanism. WR 140 is an ideal object for such study—it has a highly eccentric orbit (~ 0.84) and an orbital period of 7.9 yrs, giving a range of separation of 2.3 to 27 AU between periastron and apastron, and the observed synchrotron emission changes dramatically throughout the orbit (Williams et al. 1990; White & Becker 1995).

Adopting appropriate system parameters for WR 140 (Williams et al. 1990), we have attempted to model the radio light curve. From comparison of the observations with results from our models, our first conclusion is that the free-free opacity does *not* govern the behavior of the light curve, especially at orbital phases between 0.1 and 0.7, a point originally made by Williams et al. (1990) using a simple model of the system. Furthermore, it is also clear that the *intrinsic* synchrotron luminosity does not behave as $D^{-1/2}$!

Additional mechanisms must therefore be at play. At apastron, we determine an equipartition field of ~ 0.1 G. Assuming that the O-star (the dominant radiation field in the wind-collision region) has a radius of $10\,R_\odot$ and $T_{\rm eff} \sim 40,000$ K, then for relativistic electrons radiating at 5 GHz at a distance of 4.3 AU from the O-star the IC cooling time is $\sim$ 140 hrs, similar to the flow time. However, at periastron where the O-star is only at a distance of 0.38 AU and with an estimated $B_{\rm eq} \sim 1$ G, the cooling time is only $\sim$ hours—significantly shorter than the flow time. Additionally, it can be demonstrated that at orbital phases close to periastron, the density is sufficiently high that SSA is significant. These effects and radiative shock cooling (and possibly others!) need to be incorporated in any realistic model of WR 140, which we are currently pursuing.

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