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PARTICLE ACCELERATION IN THE COLLIDING WIND BINARY WR 140

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RESUMEN

Los sistemas de estrellas masivas WR+O presentan un plasma a alta temperatura, calentado por shocks, en la región donde el viento de la estrella WR colisiona con el de su compañera binaria – o región de colisión de vientos (WCR). La WCR es una fuente de emisión térmica (por ejemplo, rayos X duros) y no-térmica (emisión sincrotrón). Esta última surge de electrones y iones acelerados a energías relativistas. Estas binarias de vientos en colisión constituyen un laboratorio excelente para estudiar la aceleración de partículas a masas y densidades de energía fotónica y magnética mayores que las que existen en remanentes de supernovas. Los modelos recientes de emisión no-térmica en WR 140 han ayudado al entendimiento de este proceso.

ABSTRACT

Massive WR+O star systems produce high-temperature, shock-heated plasma where the wind of the WR star and that of its binary companion collide – the wind-collision region (WCR). The WCR is a source of thermal (e.g. hard X-rays) and non-thermal (e.g. synchrotron) emission, the latter arising from electrons and ions accelerated to relativistic energies. These colliding wind binaries (CWBs) provide an excellent laboratory for the study of particle acceleration at higher mass, photon and magnetic energy densities than exist in SNRs. Recent models of the non-thermal (NT) emission from WR 140 have provided insight into this process.

Key Words: radio continuum: stars — stars: individual (WR 140)

1. INTRODUCTION

WR 140 (HD 193793) is the archetype of long-period CWB systems. It consists of a WC7 star and an O4-5 star in a highly eccentric orbit ($e \approx 0.88$), and exhibits dramatic variations in its emission from near-IR to radio wavelengths (Williams et al. 1990; White & Becker 1995), and also at X-ray energies (Zhekov & Skinner 2000; Pollock et al. 2002, 2005) during its 7.9-year orbit. The variability appears to be linked to the WCR, which experiences significant changes as the stellar separation varies between 2 and 30 AU. The orbit modulation of the synchrotron flux has yet to be understood, but is likely due to a number of mechanisms. The changing free-free opacity along the line of sight through the extended stellar winds is certain to play a role, as will the strong inverse Compton cooling of the NT electrons. In addition, the intrinisic synchrotron luminosity and the spectral index of the NT electron energy distribution may alter. Recently developed models of CWBs that are based on hydrodynamical simulations of the stellar winds and the WCR have provided a more accurate representation of the thermal and NT emission (Dougherty et al. 2003; Pittard et al. 2006), and are a first step towards disentangling these mechanisms and ultimately understanding the acceleration processes in detail.

Due to the non-unique solutions which can arise from these models, it is essential that observations across a broad energy spectrum are available to provide as many constraints as possible. Fortunately, recent observations of WR 140 with the VLBA enable a full orbit definition, including inclination, along with robust distance and luminosity estimates (Dougherty et al. 2005). Together, these parameters provide essential constraints that are currently unavailable for any other wide CWB. However, thermal X-ray and NT X-ray and γ-ray observations are also critical to establish some of the model parameters.

2. MODELLING THE NON-THERMAL EMISSION

We have applied our newly developed radiative transfer models of CWBs to WR 140 in order to investigate the emission and absorption processes which act to govern the radio variations. Full details can be found in Pittard & Dougherty (2006). Rather than attempting to model the radio lightcurve in one step, our first aim was to obtain good fits to the radio data at phase 0.837. This phase was chosen on the basis that the observed radio emission is close to maximum, that an X-ray spectrum exists, and that orbital-induced curvature of the WCR is negligible.

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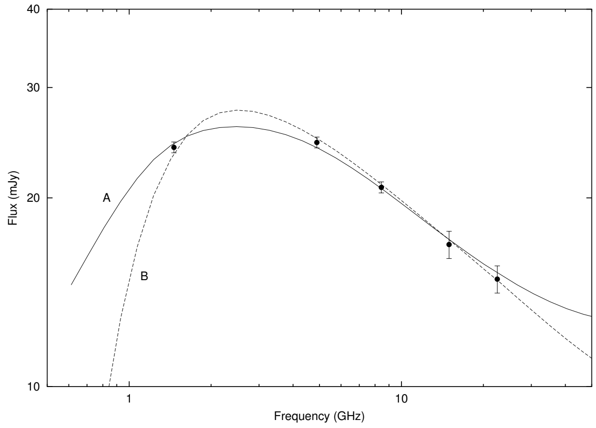

Fig. 1. Model fits to radio data of WR 140 at orbital phase 0.837. In model A $\eta = 0.22$, while model B has $\eta = 0.02$. The latter is preferred (see text for details).

The thermal X-ray flux is used to obtain a family of solutions with varying WR and O-star mass-loss rates as a function of wind momentum ratio, η. With these constraints, fits to the radio emission (see Figure 1) lead us to favour models with a relatively small value of η (e.g. 0.02), on the basis that the required line-of-sight angle is more consistent with the orbital solution of Dougherty et al. 2005. Unfortunately, the VLBA images do not have the sensitivity to directly constrain the value of η due to the rapid decline in the surface brightness of the WCR with off-axis distance. In these models, free-free absorption is responsible for the turnover between 1.6 and 5 GHz – the Razin effect can be ruled out because it places an unacceptably large fraction of energy into NT electrons. The post-shock B-field at the apex of the WCR is estimated to be about 1 G, while somewhat less than 1% of the total available energy is transferred to NT electrons.

A key finding is that the slope of the energy spectrum of the NT electrons, p, is flatter than the canonical value anticipated for diffusive shock acceleration (i.e. $p < 2$). Several mechanisms can produce such distributions. The most likely are re-acceleration at multiple shocks within the WCR (e.g. Schneider 1993), and second-order Fermi acceleration resulting from magnetic scattering off turbulent plasma (e.g. Scott & Chevalier 1975; Dolginov & Silant'ev 1990). Both of these processes could occur together if the WCR is highly structured, as occurs naturally when clumps within the winds impact the WCR and introduce vorticity (Pittard 2007). Magnetic reconnection, perhaps through resistive MHD, is another possibility. Reconnection probably occurs throughout the volume of the turbulent WCR, and not just at a hypothetical contact discontinuity, and may provide additional energy for generating and maintaining the magnetic fluctuations which drive stochastic acceleration.

A remaining problem is that the B-field and p are somewhat ill constrained by the radio data alone. However, their degeneracy is broken at γ-ray energies, and thus tighter constraints can be made if future observations with GLAST are utilized. While we generally predict lower γ-ray fluxes than previous works, detectability should not be an issue. However, we conclude that WR 140 is unlikely to be detected as a TeV source with VERITAS-4, though it may be brighter at phases closer to periastron. Since the high stellar photon fluxes prevent the acceleration of electrons beyond Lorentz factors $\gamma \gtrsim 10^5 - 10^6$, TeV emission from CWB systems will provide unambiguous evidence of pion-decay emission from accelerated ions.

3. FUTURE DIRECTIONS

While these models have provided key insights into the particle acceleration process(es) occuring in WR 140, much work remains. In forthcoming work we will apply our model to other orbital phases, and will investigate the effects of particle acceleration *within* the WCR.

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DISCUSSION

G.E. Romero - What is the maximum energy you get for protons, and how do you estimate this energy: from proton losses or from the size constraints?

J. Pittard - $\gamma_{\max} \sim 10^5$, at the phase we modelled ($\phi = 0.837$). We determined $\gamma_{\max}$ by comparing the timescales for the proton acceleration to their advection timescale out of the system (see Pittard & Dougherty 2006).

G.E. Romero - Electromagnetic cascades should be important at $E > 10 - 50$ GeV, and will affect the spectrum shape at GLAST energies, at least during periastron passage.

P. Williams - What happens to clumps entering the shock if the conditions are not adiabatic?

J. Pittard - Rolf Walder has simulated a case where the wind collision region is almost radiative. Then if the pre-shock flow is clumpy, the higher density of the clumps pushes the post-shock gas into the radiative limit. The wind collision region then collapses into a thin dense sheet which may break up into clumps. So in this case the post-shock structure is not smoother than the pre-shock wind, unlike when the post-shock flow remains adiabatic.

Sergio, Fernanda and Norbert making plans for a free afternoon.