Radio emission from colliding-wind binaries: observations and models

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Abstract: We have developed radiative transfer models of the radio emission from colliding-wind binaries (CWB) based on a hydrodynamical treatment of the wind-collision region (WCR). The archetype of CWB systems is the 7.9-yr period binary WR140, which exhibits dramatic variations at radio wavelengths. High-resolution radio observations of WR140 permit a determination of several system parameters, particularly orbit inclination and distance, that are essential for any models of this system. A model fit to data at orbital phase 0.9 is shown, and some short comings of our model described.

1 What are colliding-wind binaries?

Observations of WR+O binary systems such as WR140 (Williams et al. 1990; White & Becker, Dougherty et al. 2005), WR146 (Dougherty et al. 1996, 2000; O'Connor et al., these proceedings) and WR147 (Williams et al. 1997) reveal synchrotron emission arising from relativistic electrons accelerated where the massive stellar winds of the binary companions collide - the WCR. There is strong evidence that all WR stars (Dougherty & Williams 2000), and now many O stars (van Loo et al., 2005, and references therein), that exhibit non-thermal emission are binary systems. It is widely accepted that the electrons are accelerated by diffusive shock acceleration (DSA), and CWB systems present a unique laboratory for investigating particle acceleration since they provide higher mass, radiation and magnetic field energy densities than in supernova remnants, which have been widely used for such work.

2 Models of radio emission in CWBs

To date, models of the radio emission from these systems have been based largely on highly simplified models. As a first step toward more realistic models, we have developed models of the radio emission based on 2D axis-symmetric hydrodynamical models of the stellar winds and the WCR. The temperature and density on the hydrodynamical grid (Fig. 1) are used to calculate the free-free emission and absorption from each grid cell. We assume the electrons are accelerated at the shocks bounding the WCR by DSA, and then advected out of the system

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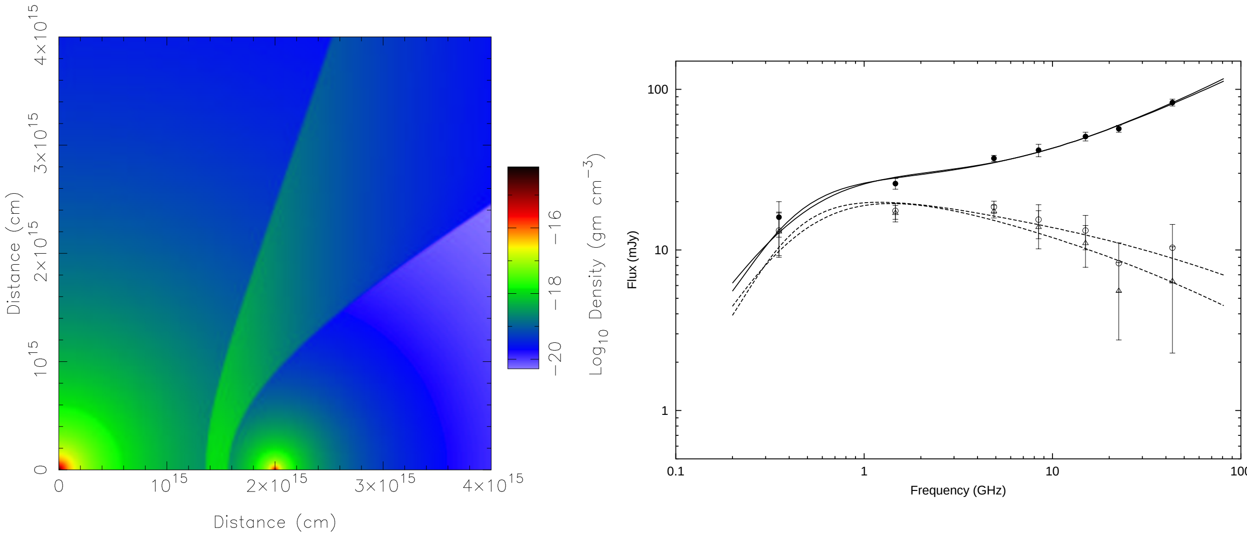

Figure 1: Left: Density distribution of a model CWB. The WR star is at (0,0) and the O star companion at $(0, 2 \times 10^{15})$ cm. Right: Models of the radio spectrum of WR147. The total (solid) and synchrotron (dashed) emission are shown for two possible models.

in the post-shock flow. At the shocks, the energy distribution of the relativistic electrons is specified by a power-law i.e. $n(\gamma) \propto \gamma^{-p}$. This spectrum evolves away from a simple power law as the electrons cool via several processes, including inverse-Compton and Coulombic cooling. The models take all these effects into account, including the impact of Razin effect. The synchrotron emission and self-absorption from each cell within the WCR are then calculated from the local energy distribution of non-thermal electrons. For more details see Dougherty et al. (2003) and Pittard et al. (2005).

We have applied these models to observations of WR147 (Fig. 1) and WR146 (see O'Connor et al., these proceedings) with some success. The models of WR147 are not as well constrained by the available data as those from WR146. O'Connor et al. (these proceedings) point out that models of WR146 would be much better if the spectra steepened at high frequencies, and if the WCR emission was less extended. We continue to investigate these issues.

3 Observations and models of WR140

The development of more realistic models of the radio emission from CWBs was motivated, in part, by the difficulties earlier work had with modelling the radio variations observed in WR140 (Williams et al., 1990; White & Becker, 1995). In spite of the wealth of multi-frequency observations of WR140, a number of critical system parameters are either unknown (e.g. system inclination), or weakly constrained (e.g. distance and luminosity class of the companion). Recent radio observations now provide these key constraints.

3.1 Modelling constraints from observations

A 24-epoch campaign of VLBA observations of WR140 was carried out between orbital phase 0.7 and 0.9. An arc of emission is observed, resembling the bow-shaped morphology expected for the WCR (Fig. 2). This arc rotates from "pointing" NW to W as the orbit progresses (Fig. 3) which, in conjunction with the observed separation and position angle of the two stellar components at orbital phase 0.3 (Monnier et al. 2004), leads to a solution for the orbit

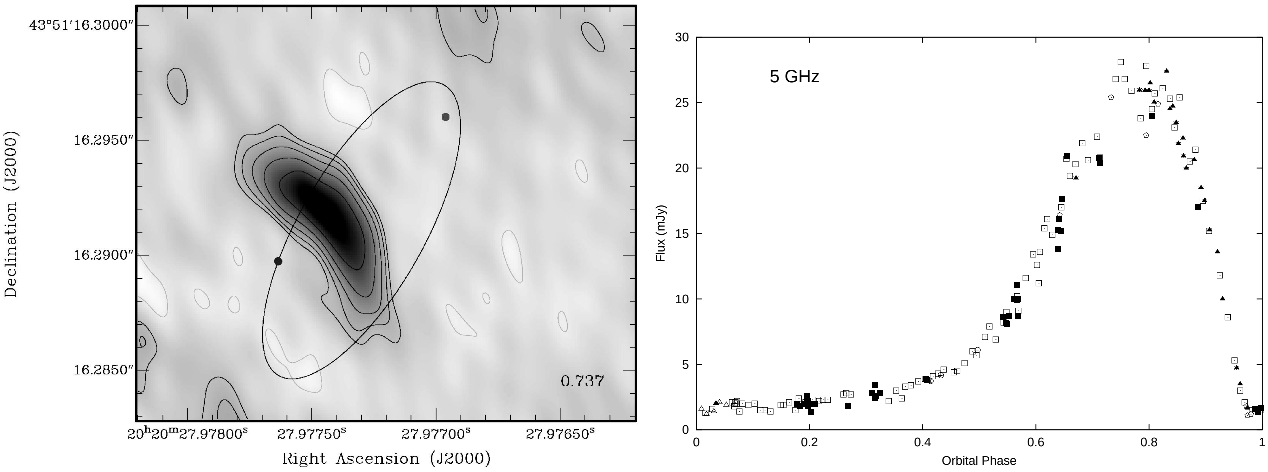

Figure 2: Radio observations of WR 140. Left: 8.4-GHz VLBA observation at orbital phase 0.737, with the deduced orbit superimposed. Right: 5-GHz flux as a function of orbital phase from orbit cycles between 1978-1985 (pentagons), 1985-1993 (squares), 1993-2001 (triangles), and the current cycle 2000-2007 (circles). Open symbols are from the VLA, and solid symbols from the WSRT.

inclination of $122\pm5°$ and the orbit semi-major axis of 9.0 ± 0.5 mas. Using the $a \sin i$ derived by Marchenko et al. (2003), we can derive a distance of 1.85 ± 0.16 kpc to WR 140. This represents the first distance derived for CWB systems *independent* of stellar parameters, and together with the optical luminosity of the system implies the O star is a supergiant. In addition, total flux measurements from the VLA (Fig. 2) show that the radio variations from WR 140 are very closely the same from one orbit to the next, pointing strongly toward emission, absorption and cooling mechanisms that are controlled largely by the orbital motion (Dougherty et al. 2005).

3.2 Modelling the radio emission from WR140

Using these new system parameters, we have applied our new radiative transfer models to the spectrum of WR 140 in order to investigate the emission and absorption processes that govern the radio variations. At orbital phase 0.9, an excellent fit to the spectrum is possible (Fig. 3). The free-free flux is negligible compared to the synchrotron flux, which suffers a large amount of free-free absorption by the unshocked O-star wind, as anticipated at this orbital phase since the bulk of the WCR is "hidden" behind the photospheric radius of the O-star wind. The low frequency turnover in this model is due to the Razin effect. Similar fits can be determined for the spectrum at phase 0.8. However, we have difficulty at earlier orbital phases (~ 0.4) if the low frequency turnover is the result of the Razin effect, largely due to the low value of magnetic field strength that is required, and the commensurate extremely high acceleration efficiency that is implied. We are continuing to explore these models.

The manner in which the non-thermal radio emission is calculated gives both the spatial distribution of the magnetic field strength, the intrinsic radio synchrotron luminosity, and the population and distribution of non-thermal electrons. These can provide a robust estimate of the high energy emission from CWBs, which is very relevant given the current and planned high-energy observatories (see Pittard, these proceedings).

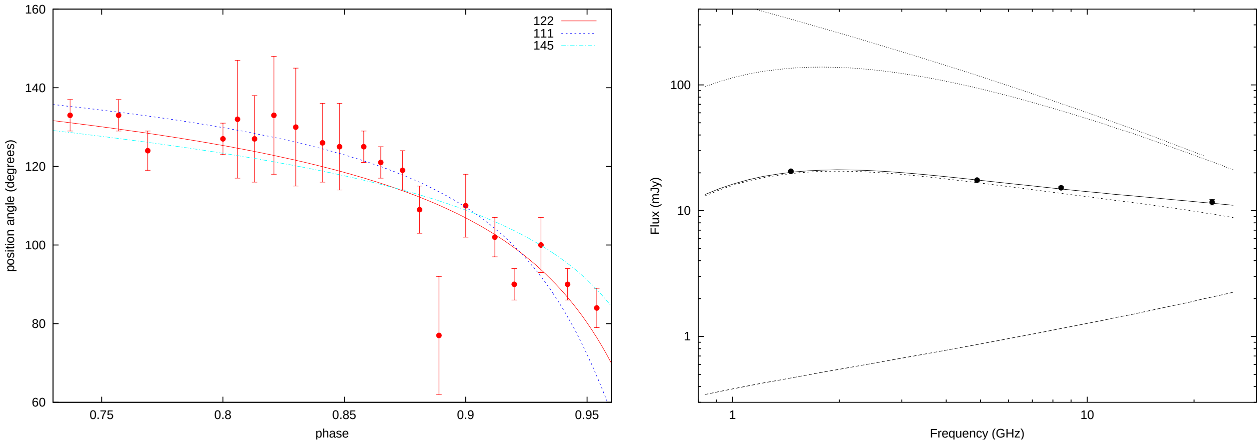

Figure 3: Left: The rotation of the WCR in WR140 as a function of phase, deduced from VLBA observations. Curves derived from known orbital parameters and three inclinations are shown, including the best-fit of 122°. Right: The spectrum of WR140 at phase 0.9. The observations are the solid circles. Various emission components from the model are shown - free-free (long-dashed), synchrotron flux (short-dashed), intrinsic synchrotron flux (dotted), and total flux (solid). The top curve shows the intrinsic synchrotron spectrum without the Razin effect.

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