Interactions in Massive Colliding Wind Binaries

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1 Introduction

The most massive stars (M> $60 M_{\odot}$) play crucial roles in altering the chemical and thermodynamic properties of their host galaxies. Stellar mass is the fundamental stellar parameter that determines their ancillary properties and which ultimately determines the fate of these stars and their influence on their galactic environs. Unfortunately, stellar mass becomes observationally and theoretically less well constrained as it increases. Theory becomes uncertain mostly because very massive stars are prone to strong, variable mass loss which is difficult to model. Observational constraints are uncertain too. Massive stars are rare, and massive binary stars (needed for dynamical determination of mass) are rarer still; and of these systems only a fraction have suitably high orbital inclinations for direct photometric and spectroscopic radial-velocity analysis. Even in the small number of cases in which a high-inclination binary near the upper mass limit can be identified, rotational broadening and contamination of spectral line features from thick circumstellar material (either natal clouds or produced by strong stellar-wind driven mass loss from one or both of the stellar components) biases the analysis. In the wilds of the upper HR diagram, we're often left with indirect and circumstantial means of determining mass, a rather unsatisfactory state of affairs.

2 Wind-Wind Collisions as a Binary Diagnostic

However, in massive binaries, the strong stellar wind possessed by at least one (and, usually, both) of the stars will interact with the radiation and (in most cases) the wind outflowing from the companion stars surface. Bob Koch and his collaborators, notably Ray Pfeiffer and Ioannis Pachoulakas, recognized this fact long ago [7, 6], and developed surprisingly sophisticated models of the complex radiative transfer through the "moving envelope" (to use Sobolev's terminology) of the binary: in these cases, in which the wind is moving in an azimuthal direction (due to orbital motion) in addition to the radial one.

A particularly interesting case occurs when the stellar wind from one star collides with a companion star's wind. The shock-heated gas (typically at temperatures of millions of Kelvin) produced in this collision generates intense X-ray emission that provides a useful diagnostic of wind mass-loss rates and densities. If the cooling of the shocked gas is dominated by adiabatic expansion, then simple scaling laws show that the X-ray luminosity of this gas varies inversely with stellar separation. This change in emission, and the variable overlying wind absorption which changes with our viewing angle to the X-ray emitting gas, produces an orbital dependence which can be usefully analyzed to constrain the dynamical properties of the system, and, in the best case, constrain the mass of one or both components.

2.1 Eta Carinae: A Test Case

Eta Carinae (= HD 93308) is a long-period ($P = 2022$ days) colliding wind binary with an extremely bright unstable Luminous Blue Variable primary (Eta Car A) which has a dense ($\dot{M} \sim 10^{-3}$ $M_\odot$ yr^{-1}), slow ($V_\infty \approx 500$ km s^{-1}) wind. Eta Car A is one of the most massive and luminous stars in the Galaxy, and as such has been an object of intense scrutiny since the mid-1800's. Eta Car A is orbited by a fainter, hotter, lower mass, *unseen* companion (Eta Car B) possessing a less dense ($\dot{M} \sim 10^{-5}$ $M_\odot$ yr^{-1}) but much faster ($V_\infty \approx 3000$ km s^{-1}) wind in a very eccentric orbit ($e \sim 0.9$ or thereabouts). Because of the large eccentricity, changes in separation (by a factor of 20) and viewing geometry produce phase-dependent variability in nearly all bands of the EM spectrum, especially in the thermal X-ray region. This cyclical variability makes Eta Carinae a fine laboratory for studying hypersonic astrophysical shocks, the generation of high-energy thermal radiation, and (possibly) the production of non-thermal high energy emission due to Fermi acceleration of charged particles and inverse-Compton scattering of seed photospheric photons [4]. However, Eta Car A is also a dramatic and sporadic variable in its own right, prone to episodes of extreme brightening and mass loss (the best example of this is the "Great Eruption" of 1843, at which time the star spewed forth $\gtrsim 10M_\odot$ of stellar material which now forms its dusty shroud). Sporadic variations in the stellar wind from Eta Car A should cause cycle-to-cycle changes in the state of the wind-wind shock. The phase-dependent and secular X-ray variations of the thermal X-ray emission have been studied in great detail by the Proportional Counter Array (PCA) on board the Rossi X-ray Timing Explorer [RXTE; 1] for the last 3 stellar orbital cycles (from 1996 to 2011; Figure 1). We define Cycle 1 to be the orbital cycle centered on the 1997 X-ray minimum, Cycle 2 centered on the 2003.5 minimum, and Cycle 3 centered on the 2009 minimum.

Table 1: Parameters for the Eta Carinae System

	X-ray Value	Non-X-ray Value
Mass Loss Rate ($M_\odot$ yr^{-1})	2.5×10^{-4} & 10^{-5}	10^{-3} & —
Terminal Velocity (km s^{-1})	500 & 3000	500 & —
Escape Velocity (km s^{-1})	200 & 1200	200 & —

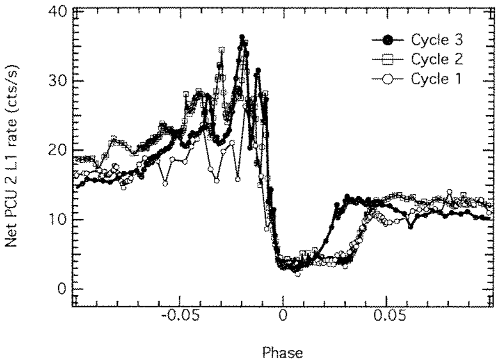

Figure 1: RXTE PCA X-ray fluxes from Eta Car near periastron passage for 3 orbital cycles. The full lightcurve is available in [2], with updates at http://asd.gsfc.nasa.gov/Michael.Corcoran/eta_car/etacar_rxte_lightcurve.

As discussed in [8, 5, 9] the X-ray variations can be modelled to yield values of the stellar wind parameters of Eta Car B, the star which has otherwise not been directly observed. Well-established theoretical relations between wind parameters and stellar escape velocity can then be used to constrain the physical parameters of this hidden companion. In turn, the physical parameters of the companion and the orbital elements so derived from these types of analyses can be used to constrain the stellar and mass-loss parameters of Eta Car A. Table 1 lists parameters derived from analysis of the X-ray spectra and lightcurve [8, 5].

2.2 WR 140: A Shock Physics Laboratory

WR 140 (= HD 193793; WC7+O4-5) is arguably the best known example of a colliding wind system and of the range of phenomena which may be associated with strong, time-variable astrophysical shocks. WR 140's long period ($P = 2897$d) highly eccentric ($e = 0.88$) orbit is congruent to Eta Car's, but the lack of thick circumstellar material around WR 140, and the ability to detect directly both stars in the system, as well as the fact that the shock has been directly resolved by VLBA interferometry [3] means we have a much clearer view of WR 140 and a much more direct understanding of the variations in the wind-wind interaction around the orbit.

2.2.1 Modeling WR 140's X-ray Emission

The PCA on RXTE has measured the X-ray lightcurve of WR 140 for over two cycles[1]. The coverage is not as extensive or complete as it is for Eta Car, however two X-ray minima were measured in detail. Qualitatively, the phase-dependent X-ray variation of WR 140 is similar to that of Eta Car: there's a gradual increase in 2–10 keV X-ray flux from apastron as the stars approach periastron passage; the X-ray flux grows as (roughly) $1/D$ (where D is the separation between the two stars) up through orbital mean anomaly $\phi \approx 0.9$, at which time a deviation from this relation begins; there's a rapid rise to a maximum flux near the time when the X-ray emitting material near the shock cone apex is viewed through the lower density wind of the O4 companion; the X-ray flux falls to a minimum which occurs near the time when the leading edge of the shock cone is occulted by the WR star; and after this minimum, the flux recovers but the recovery is asymmetric, i.e. the level after the minimum is lower than the level at a similar mean anomaly prior to the minimum. Figure 2 shows the observed 2–10 keV X-ray variation for the two periastron passages observed by RXTE.

Modeling the system with smoothed particle hydrodynamics calculations similar to those used to model the X-ray flux variations in Eta Car has had some success. As shown in [9], simple models in which the X-ray flux is localized very near the apex of the shock cone provide good descriptions of the observed variation, though models in which the X-ray emitting region is distributed along the shock cone (as expected in a realistic wind-wind collision) don't describe the observed variations as well.

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[1] see http://asd.gsfc.nasa.gov/Michael.Corcoran/wr140/wr140_rxte_lightcurves/index.html for the latest RXTE data

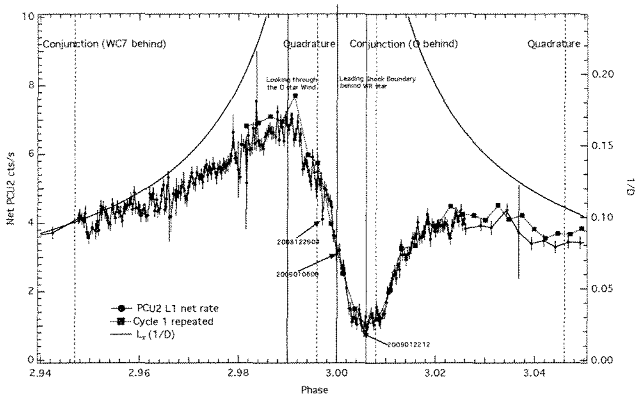

Figure 2: RXTE PCA fluxes from WR 140 near X-ray minimum. The black circles are observations taken in 2009, while the data marked by the square symbols are the observations of the 2001 minimum, shown for comparison. UT dates of observations from 2009 are indicated, along with important orbital phases near periastron passage, which occurs at $\phi = 3.00$.

3 Conclusions

As a canonical colliding wind binary, the X-ray flux behavior of WR 140 around the orbit is remarkably well-behaved even if not yet entirely understood in detail. Important features of its X-ray lightcurve (X-ray extrema, hardness ratio maximum, etc) are well associated with significant orbital events deduced from radial-velocity and radio interferometric studies. In the Eta Car system as well, models of the phase-locked X-ray variations have been useful in determining the system parameters. However, Eta Car is a star that's notoriously badly behaved in almost every epoch and almost every energy band, and indeed the behavior of Eta Car's X-ray flux shows significant non-phase-locked variations. Secular changes in the observed X-ray flux from Eta Car are probably the best indication of a fundamental change in the wind-wind interaction zone. Such change must indicate a real variation in the stellar winds from either or both the primary and secondary.

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