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HIGH ENERGY INTERACTIONS IN MASSIVE BINARIES: AN APPLICATION TO A MOST MYSTERIOUS BINARY

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Abstract. Extremely massive stars ($50M_\odot$ and above) are exceedingly rare in the local Universe but are believed to have composed the entire first generation of stars, which lived fast, died young and left behind the first generation of black holes and set the stage for the formation of lower mass stars suitable to support life. There are significant uncertainties about how this happened (and how it still happens), mostly due to our poor knowledge of how stars change mass as they evolve. Extremely massive stars give mass back to the ISM via strong radiatively-driven winds and sometimes through sporadic eruptions of the most massive and brightest stars. Such mass loss plays an important role in the chemical and dynamical evolution of the local interstellar medium prior to the supernova explosion. Below we discuss how high energy thermal (and, in some cases, non-thermal) emission, along with modern simulations in 2 and 3 dimensions, can be used to help determine a physically realistic picture of mass loss in a well-studied, mysterious system.

Key words: stars: massive - stars: η Car - stars: binaries - X-rays

1. Introduction

Very massive stars are rare in the local Universe. Assuming a Salpeter IMF with a lower stellar mass limit of $0.06M_\odot$, the fraction by number of stars with mass above $50M_\odot$ is only 0.02%. Despite this scarcity, very massive stars are important stellar constituents of galaxies. Mass loss from such stars, which starts as a massive, radiation-driven stellar wind and which ends with the final explosion of the star at the end of nuclear burning, contributes crucially to the chemical evolution of the interstellar medium in the host galaxy. Understanding how these massive stars evolve and lose mass is a key astrophysical problem, and a frustratingly difficult one at that. The most fundamental and essential measurement is to determine the stellar mass as a function of time, and how this changes with time. A realistic understanding of the ways in which very massive stars lose their mass and evolve to the supernova/hypernova event requires calibrating the mass of the star as it traverses the HR diagram. For most stars, this calibration is normally best accomplished through dynamical mass determinations by analysis of photospheric radial velocity variations and photometric eclipses in binaries. However, for those stars possessing strong winds, photospheric lines are often severely contaminated by wind lines, if the photosphere lines can be seen at all. For the most interesting phases of massive star evolution (at least in terms of mass loss), the Wolf-Rayet (WR) and Luminous Blue Variable (LBV) phases, mass loss rates are of the order of $10^{-3} - 10^{-5} M_{\odot}$ yr^{-1} and the wind is sufficiently thick to hide the stellar photosphere completely. In addition to these line-driven winds, mass can be lost through continuum-driven winds at high bolometric luminosities, and by eruptions in extreme, Luminous Blue Variable (LBV) stars. The cause of LBV eruptions is unclear, but they may be a sign of pulsational-pair instability (Barkat *et al.*, 1967; Woosley *et al.*, 2007) near the core of the star, as has recently been suggested for the "supernova imposter" SN2009ip (Pastorello *et al.*, 2010), a star which showed evidence of LBV-type eruptions in 2009 before its explosion as a true supernova in 2012.

2. Winds in Collision, and Their Consequence

Winds from massive binaries will collide either with the wind or surface of the companion star. This collision will produce directly observable effects that can be analyzed to reveal key information about the system and stellar parameters. At the most basic level, the collision will make the wind aspherical, since a "wind cavity" forms around the weaker-wind star. Additionally, the winds will get compressed at the point of collision, and the wind in the collision zone will be shock heated. This shock heating can produces a useful astrophysical diagnostic: strong, observable X-ray emission. X-rays are produced since the temperature of the shocked gas in the post-shock region is given approximately by

$$T_{ps} \approx 1.51 \times 10^7 (\frac{V_s}{1000 \text{ km s}^{-1}})^2 \text{ K},$$

(assuming solar abundances) and wind speeds are typically $V_s > 1000\,\mathrm{km\,s^{-1}}$, resulting in lots of high temperature ($T \sim 10^7$ K) X-ray emitting gas. Also, the observed X-ray emission is expected to vary as the stars revolve in their orbits. In contrast, single massive stars, which produce X-ray emission from large numbers of distributed clumps of shocked gas due to the stellar wind Line De-Shadowing Instability (Lucy and Solomon, 1970), are generally rather faint ($L_x \approx 10^{-7} L_{bol}$ or less), soft ($T <$ few$\times 10^6$ K) non-variable X-ray sources. So the detection of strong, periodically variable, high-temperature thermal X-ray emission can be a good sign of the presence of a wind-wind collision, and thus of the presence of an otherwise hidden companion star. However, it's important to note here that confinement of the wind by a strong magnetic field can also produce bright, hard, periodic X-ray emission in single (for example, the magnetic rotator θ^1 Ori C, Gagné *et al.*, 2005) and binary (for example, Plaskett's Star, Grunhut *et al.*, 2012) massive stars, though the frequency of (non-compact) hot magnetic stars is much smaller than the frequency of massive binaries.

X-ray emission produced by the collision of winds in massive binaries offers an important diagnostic of both the thermodynamic state of the winds (densities, temperatures) and the orbit of the two stars. This is because the X-ray emission from the shocked gas depends on the local wind density and velocity at the collision point, and these quantities can vary in a predictable way if the orbit is eccentric. In addition, the observed X-ray emission from the shocked region is absorbed by any overlying wind material, and this material is no longer spherically symmetric (if it ever was) but is distorted by the cavity around the weaker-wind star. X-ray absorption can thus be used to determine the extent of this cavity, and this yields information on the relative wind momentum ratio $\eta = \dot{M}_1 V_1 / \dot{M}_2 V_2$, where $\dot{M}$ and V_∞ are the mass loss rates and wind velocities, respectively, for star 1 and star 2. Discussions of the theory of wind-wind collisions and X-ray production have a rather extensive history (Cherepashchuk, 1967, 1976; Stevens *et al.*, 1992; Usov, 1992).

2.1. Eta Carinae: X-raying the Most Mysterious Star

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 ($\dot{M} \sim 10^{-3}$ $\mathrm{M_\odot\ yr^{-1}}$), 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. As shown most clearly by X-ray observations, η Car-A is orbited by a fainter, hotter, lower mass, companion (η Car-B) which so far has not been directly seen at any wavelength. As discussed by Pittard and Corcoran (2002), X-ray spectra suggest that this star possesses a less dense ($\dot{M}_B \approx 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$) 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 (Leyder *et al.*, 2010).

Eta Ca A is also a dramatic and sporadic Luminous Blue Variable (Davidson and Humphreys, 1997, and references therein), prone to episodes of extreme brightening and mass loss. The classical example of one of these major outbursts is the "Great Eruption" of 1843, at which time the star spewed out $> 10M_\odot$ of stellar material, which now forms its dusty shroud. The star underwent a smaller outburst in 1890, and since then has been relatively quiet. The reason for these outbursts is unknown, but what is generally acknowledged is that these outburst events require an extreme physical mechanism, since the Great Eruption produced $\sim 10^{50}$ ergs of energy, comparable to a supernovae.

The wind-wind collision is a sensitive diagnostic of the instantaneous state of the stellar mass loss from η Car-A, and therefore 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; Bradt *et al.*, 1993) for the last 3 stellar orbital cycles (from 1996 to 2011[1]; Figure 1). For convenience, Cycle 1 is the orbital cycle centered on the 1997 X-ray minimum, Cycle 2 is centered on the 2003.5 minimum, and Cycle 3 is centered on the 2009 minimum.

As discussed in Pittard and Corcoran (2002); Parkin *et al.* (2009); Russell *et al.* (2011), the X-ray variations can be modelled to yield values of the

[1]Sadly, *RXTE* mission operations terminated on January 4, 2012.

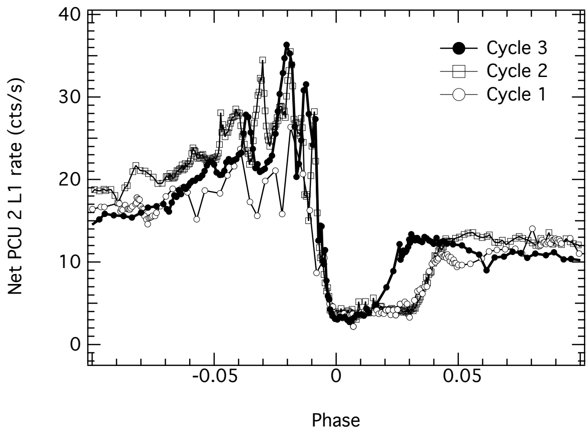

Figure 1: RXTE PCA X-ray fluxes from Eta Car near periastron passage for 3 orbital cycles. The full lightcurve is available in Corcoran *et al.* (2010) and http://asd.gsfc.nasa.gov/Michael.Corcoran/eta_car/etacar_rxte_lightcurve.

stellar wind parameters of the companion star, η 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 η Car-A. Table I lists parameters derived from analysis of the X-ray spectra and lightcurve (Pittard and Corcoran, 2002; Parkin *et al.*, 2009) for both stars.

Table I: Parameters for the Eta Carinae System

Parameter	X-ray Value	
	η Car-A	η Car-B
Mass Loss Rate ($M_\odot$ yr^{-1})	2.5×10^{-4}	10^{-5}
Terminal Velocity (km s^{-1})	500	3000
Escape Velocity (km s^{-1})	200	1200

Colliding wind binary models, in which X-ray spectral variability is produced by changes in the shock densities and foreground absorption as the stellar orientation changes (Okazaki *et al.*, 2008; Parkin *et al.*, 2011), are in broad agreement with X-ray fluxes and hardness ratios obtained from 1996–2010 by *RXTE*, though significant discrepancies do exist between the observations and the models. Notable examples of this are the X-ray "flaring" on approach to X-ray minimum (Moffat and Corcoran, 2009), and also the fact that the observed X-ray minimum lasts much longer than simple occultation models predict. Somewhat surprisingly, *RXTE* observations showed that the Cycle 3 minimum was much shorter than either the Cycle 1 or Cycle 2 minima. Since the X-ray minimum begins when the wind-wind shock becomes embedded within the thick inner wind of η Car-A, this change probably represents a decrease in the mass loss rate of one of the stars. Our simple estimate suggests an enormous change in mass loss rate from η Car-A, a factor of $\sim 2-4$, is needed to match the reduced minimum (Corcoran et al. 2010). An independent assessment by Kashi and Soker (2009) came to a similar conclusion. But a factor of two change in mass loss rate should be easily observable in optical spectra if the wind from η Car-A is spherically symmetric. This change is much larger than the $\sim$ 20% decline in mass loss rate derived from optical spectrometry and photometry (Martin *et al.*, 2010), though more recent data reveal a weakening of Hα emission which might indicate a much more substantial change (Mehner *et al.*, 2010). However, spectroscopic monitoring of Balmer Hδ wind lines (Groh *et al.*, 2010) show no strong changes in the inner wind of η Car.

3. The Flow along the Shock

CHANDRA High Energy Transmission Grating Spectrometer (HETGS) observations of the X-ray emission line profiles provide the best information about the flow along the colliding wind boundary and provide unique information regarding relative mass loss rates and the dynamics of the shocked gas. Starting in 2000, we have conducted an HETGS observing campaign to monitor the X-ray line profile variations as η Car-B orbits η Car-A. *CHANDRA* HETG spectra prior to the Cycle 2 minimum showed that the Si XIV and S XVI lines became increasingly blueshifted and broader just before the X-ray minimum in 2003, probably due to the changing orientation of the shock cone relative to the line of sight (see Fig. 2, and Henley *et al.*, 2008) though significant absorption in the otherwise hidden wind of the compan-

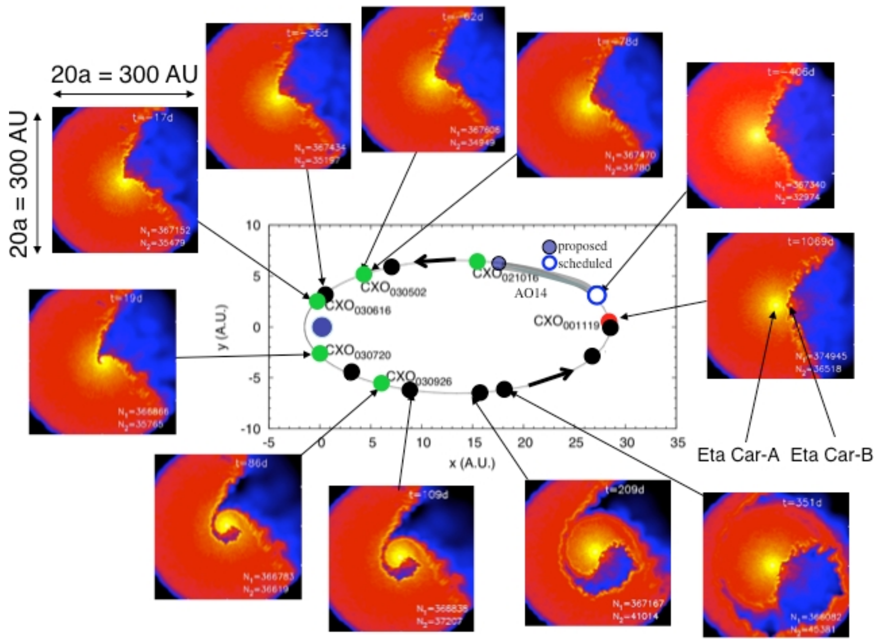

Figure 2: Orbit of the companion star, η Car-B, around the LBV primary, η Car-A. The observer's line of sight is along the $+X$ axis, and inclined by about 40° to the orbital plane (Madura *et al.*, 2011). Along the orbit, images show the projected density in the orbital plane of the interacting winds of η Car-A (yellow-red=high to low density) and η Car-B (blue-black = high to low density) from a 3D isothermal Smoothed Particle Hydrodynamics (SPH) model (Okazaki et al., 2008). The companion's wind forms a low-density "cavity" in the wind from η Car-A which has observable consequences out to 1000 AU.

ion star is also required. An alternative interpretation (Behar *et al.*, 2007) ascribed the profile changes to accretion events and jets associated with the transient X-ray "flares" seen by *RXTE*, though more recent HETGS spectra obtained at the peak and trough of a flare do not support that conjecture (Moffat and Corcoran, 2009). However, *CHANDRA* HETGS observations in October and December 2008 (just prior to the 2009 X-ray minimum) surprisingly showed that the Si XIII, Si XIV, and S XV line centroids had much lower (blueshifted) velocities compared to observations obtained in the previous cycle, while the S XVI lines seem to be phase-repeatable (Figure 3). Changes in the line profiles suggest a change in the geometry of the colliding wind shock (which in turn is consistent with a change in the momentum balance between the two winds), while differences between lines of different ionization potential indicate the spatial stratification of temperature along the shock boundary.

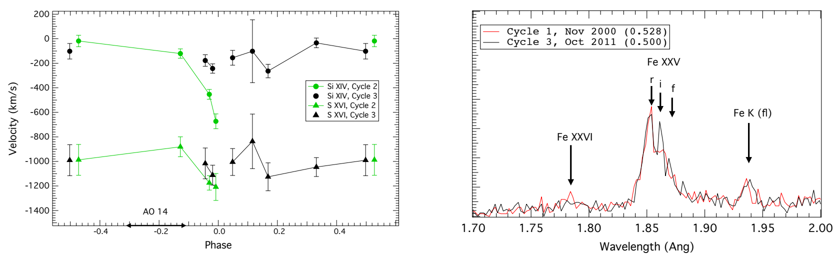

Figure 3: *Left*: Si XIV and S XVI line velocities from HETGS observations of η Car. The S XVI velocities have been shifted downward by 1000 km/s for clarity. Note that the system is too faint and heavily absorbed to obtain HETGS spectra during the X-ray minimum ($0.0 < \phi \lesssim 0.04$). The Si XIV velocities at $\phi \approx -0.02$ in cycle 3 are much less blueshifted than the velocities measured in cycle 2. *Right*: Iron K line region from two *CHANDRA* High Energy Grating spectra near apastron. The red line is the apastron observation from Nov. 2000, while the black line is from the most recent Oct. 2011 spectrum. The spectra have been continuum normalized; the Oct. 2011 spectrum is about 20% fainter in this interval compared to the Nov. 2000 spectrum. The Fe XXVI line, though weak, is significantly stronger in the year 2000 spectrum compared to the 2011 spectrum, and there's indication of a change in the forbidden-to-intercombination ratio in the Fe XXV triplet. This suggests significant thermal evolution in the shocked gas near the wind-wind stagnation point independent of orbital phase.

4. Summary

It's interesting to note that η Car shows phase-locked radial velocity variations (Nielsen *et al.*, 2007), eclipses (Fernández-Lajús *et al.*, 2009) and a composite spectrum (Iping *et al.*, 2005) all of which are due to wind-wind interactions + radiative transfer effects, and are not direct indications of the presence of a companion star. Orbital and stellar parameters derived from standard photometric and spectral analyses of these observations would provide a misleading picture of the system. X-ray observations have given the clearest picture of the system as a massive, colliding wind binary.

X-ray emission from η Car has been used to:

- Constrain the velocity of the companion star's wind & mass-loss rate;
- Constrain the companion star's escape velocity;
- Derive an orbit & the periastron separation;

Our conclusion is that η Car is a strange system consisting of an LBV and a high mass, high luminosity companion with a strong wind in a 2022-day, high eccentricity orbit, where the stars nearly touch at periastron passage. The orbital solution derived from the X-ray data analysis opens the door to a possible stellar interaction when the two stars are close. It's suspected that tidal or radiative interactions between the stars at periastron passage may be important in moderating the physics of the wind-wind collision zone (Parkin *et al.*, 2011), and perhaps even play some role in driving large-scale eruptions from the system (for eg., Smith, 2011). One fruitful area to explore may be the effect of time-dependent tidal interactions near periastron which could perhaps drive oscillatory waves deep in the interior of the primary (à la "heartbeat" stars, discussed elsewhere by Hambleton), perhaps driving the core into the regime of Pulsational Pair Instability if these oscillations compress and heat the nuclear burning region. More work is needed in this area before clear conclusions may be drawn.

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