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Acyclic High-Energy Variability in Eta Carinae and WR 140

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Abstract. Eta Carinae and WR 140 are similar long-period colliding wind binaries in which X-ray emission is produced by a strong shock due to the collision of the powerful stellar winds. The change in the orientation and density of this shock as the stars revolve in their orbits influences the X-ray flux and spectrum in a phase dependent way. Monitoring observations with RXTE and other X-ray satellite observatories since the 1990s have detailed this variability but have also shown significant deviations from strict phase dependence (short-term brightness changes or "flares", and cycle-to-cycle average flux differences). We examine these acylic variations in Eta Car and WR 140 and discuss what they tell us about the stability of the wind-wind collision shock.

1. Eta Carinae: Peculiar Variations at High Energy

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 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). See Davidson & Humphreys (1997) and Corcoran et al. (2010) for references about the system parameters. 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 thermal hard 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). 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). Sporadic variations in the stellar wind from Eta Car A should cause cycle-to-cycle changes in the state of the wind-wind shock which produces the thermal X-ray emission as 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). In the following, Cycle 1 is the orbital

[1]Like AFJ Moffat, RXTE is another honoured retiree; as of this writing, RXTE is scheduled to be turned out to that great pasture in the sky in December 2011.

period centered on the 1997 X-ray minimum, Cycle 2 centered on the 2003.5 minimum, and Cycle 3 centered on the 2009 minimum.

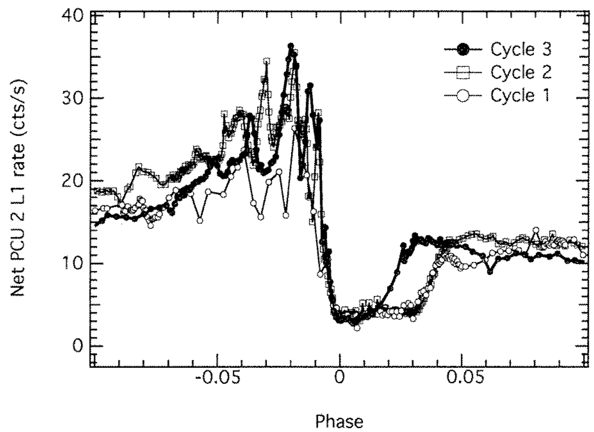

Figure 1. RXTE PCA X-ray fluxes from Eta Car near periastron passage for 3 orbital cycles. The full lightcurve is available in Corcoran et al. (2010), with updates at http://asd.gsfc.nasa.gov/Michael.Corcoran/eta_car/etacar_rxte_lightcurve.

1.1. Examples of Cycle-to-Cycle X-ray Variations

There are a number of examples of X-ray phenomena exhibited by Eta Car which either a) don't follow the (relatively) smooth X-ray variability expected from (relatively simple) models of X-ray emissions from wind-wind collisions or b) show definite changes from cycle to cycle. These are not mutually exclusive categories. The best examples of this are the so-called X-ray "flares" seen most obviously around periastron passage; variations in the flux level approaching apastron; and a striking change in the duration of the X-ray minimum. We discuss each briefly below.

1.1.1. "Flaring"

X-ray "flares" were first noted by Ishibashi et al. (1997) as rather weak, long-duration ($\sim$ 20 days) increases in the "ambient" X-ray flux level in the 2–10 keV band. Early monitoring suggested a recurrence timescale of $\sim$ 85 days, but additional data obtained by RXTE showed that this period was not maintained for the entire orbital cycle. Moffat & Corcoran (2009) analyzed the flare characteristics (separation in time of the flare "peaks", the flare "full-width at half maximum", FWHM, and "flare strength", or peak height $\times$ FWHM) as a function of time, mean anomaly and true anomaly. Both the time separation of the flare peaks and the flare FWHM decrease sharply from apastron to periastron. Interestingly, the flare strength does not seem to vary greatly around the orbital cycle - there are low-peak-level, long duration flares near apastron, and high-peak, short duration flares near periastron, but the product remains roughly constant. Moffat & Corcoran considered 3 simple models for the flare behavior: variations caused by clumps in the wind of one or both stars, large-scale structures ("co-rotating interaction regions") in the wind of the primary, and (briefly) instabilities in the wind-wind collision. Their analysis suggested that a model in which large ($\gtrsim$ 1AU) homologously-expanding clumps in the primary wind colliding with the wind-wind shock interface was arguably the best to explain the observed behavior of the X-ray flares, though the other two models could not be strongly ruled out.

1.1.2. Flux Level Variations

RXTE has also observed variations in the flux level away from periastron, at phases when the stars are far apart and the wind has settled down from the contortions of periastron passage. Comparison of the three orbital cycles seen so far by RXTE show striking changes in the "quiescent" flux level. Perhaps significantly, at a phase interval near apastron ($\phi \sim 0.4$), Cycle 2 and Cycle 3 show a similar 2-10 keV X-ray flux level in the orbital phase interval $0.4 \lesssim \phi \lesssim 0.6$, despite strong differences in flux outside this interval[2] In the run-up to periastron passage ($0.7 \lesssim \phi \lesssim 0.9$, before the onset of strong flaring), the flux in Cycle 2 was significantly higher then the flux from either Cycle 1 or Cycle 3 (which were similar in flux level for this phase interval). This lasted until the onset of strong flaring after $\phi \approx 0.9$, at which time the Cycle 3 level reached and eventually surpassed the Cycle 2 level. After periastron the flux levels show a higher level of discrepancy. In the phase interval $0.1 \lesssim \phi \lesssim 0.4$ Cycle 1 was brighter in the 2–10 keV band than Cycle 2, which was brighter than Cycle 3. This may indicate a temporal trend so that the post-minimum flux is dropping significantly with time. Since the 2–10 keV flux is a measure of the shocked fast wind from the companion star, this could indicate some waning of the mass loss rate from the companion.

1.1.3. Changes in X-ray Minimum Duration

While the morphology of the minimum – its start, minimum flux level, and egress – were strikingly similar in Cycle 1 and Cycle 2, the Cycle 3 minimum was about 1/3 shorter than the earlier ones. The cause of this change has not yet been conclusively demonstrated. A drop in mass loss rate from the LBV primary star has been a suggested culprit, though this is not confirmed, and ground based spectroscopy of the H-δ line by Damineli and collaborators (these proceedings) does not support any significant change in the primary's wind density.

2. WR 140: A Shock Physics Laboratory

WR 140 (= HD 193793; WC7+O4-5) is arguably the best example we have 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 confusing thick circumstellar material near 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 (Dougherty et al. 2005) 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.

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[2]Unfortunately cycle 1 observations did not start until orbital phase $\phi = 0.66$.

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[3]. 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.

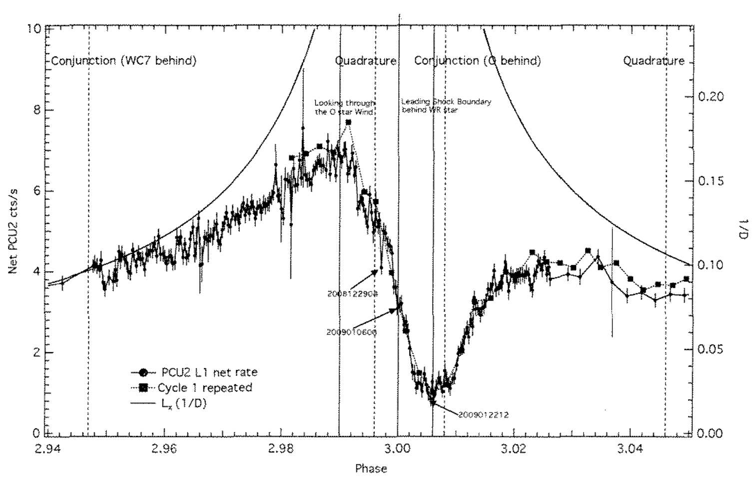

Figure 2. RXTE PCA fluxes from WR 140 near X-ray minimum. The black circles are observations taken in 2009, while the data marked by the square symbols are the observations of the 2001 minimum, shown for comparison. UT dates of observations from 2009 are indicated, along with important orbital phases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

Modeling the system with smoothed particle hydrodynamics calculations similar to those used to model the X-ray flux variations in Eta Car have had some success. As shown in Russell et al. (2011), 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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[3]see http://asd.gsfc.nasa.gov/Michael.Corcoran/wr140/wr140_rxte_lightcurves/index.html for the latest RXTE data

2.2. Cycle-to-Cycle Variations

There are some slight variations in the flux level after periastron passage if we compare the 2001 and 2009 data. Otherwise the data from the two cycles are remarkably similar. In particular the timing of the ingress and egress from the X-ray minimum, the height of the maximum X-ray flux, and the depth of the minima, all agree with each other. This statement can be extended to the spectral variation of the X-ray emission; the X-ray color shows remarkably good agreement between the 2001 and 2009 cycle, especially around periastron. There are only mild variations in X-ray flux seen prior to the 2009 X-ray minimum; there are no strong flaring episodes of the type exhibited by Eta Car.

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. This is not the case with Eta Car, a star that's notoriously badly behaved in almost every epoch and almost every energy band. Indeed the behavior of Eta Car's X-ray flux arguably shows the smallest amount of cycle-to-cycle variability compared to other wavebands. 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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