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3D modelling of the massive star binary systems Eta Carinae, WR 22, and WR 140

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Abstract: Massive stars possess powerful stellar winds. Wind-wind collision in a massive star binary system generates a region of thermalized plasma which may emit prolifically at X-ray wavelengths. Results are presented from 3D adaptive-mesh refinement (AMR) hydrodynamical models which include radiative cooling and the radiative driving of the stellar winds. The models provide an exceptional insight into the turbulent nature of the wind-wind interaction regions. The X-ray emission from the hydrodynamical models is then calculated, allowing detailed comparisons with observational data. Preliminary results from investigations of Eta Carinae, WR 22, and WR 140 are discussed.

1 Introduction

In a binary system consisting of two hot massive stars the collision of the hypersonic winds generates a region of thermalized plasma which emits at X-ray wavelengths (e.g. Stevens, Blondin & Pollock 1992). X-ray observations therefore provide a direct probe of the wind-wind collision region (WCR) and can be used to infer details about the pre-shock winds (e.g. Pittard & Corcoran 2002). Depending on the parameters of the winds and the orbit, the dynamics of the post-shock gas in the WCR can cover a diverse range (Stevens et al. 1992). For instance, in long-period binaries (i.e. on the order of years) the post-shock gas is expected to be quasi-adiabatic for the most part, whereas in short-period (i.e. $\sim$ few days) systems the post-shock gas is expected to be highly radiative. Highly eccentric systems, such as η Car, WR 140, and WR 22, provide the interesting prospect of transitioning between these two extremes as, given the relatively small separation of the stars at periastron, the WCR may reside deep in the wind-acceleration regions. Considering that the pre-shock wind velocity strongly influences the stability of the WCR through the effectiveness of radiative cooling, periastron passage in these systems may also be chaotic. Furthermore, the high contrast in wind ram pressures characteristic of WR+O binary systems (e.g. WR 140 - Williams et al. 1990; Zhekov & Skinner 2000; Pollock

Table 1: Adopted system and stellar parameters. P is the orbital period, e is the orbital eccentricity, a is the semi-major axis of the orbit, and $\dot{M}_i$ and $v_{\infty i}$ are the mass-loss rate and terminal wind speed for star i. References are noted in parentheses, and are as follows: 1 = Damineli et al. (2008), 2 = Hillier et al. (2001), 3 = Parkin et al. (2009), 4 = Pittard & Corcoran (2002), 5 = Rauw et al. (1996), 6 = Rauw (1997), 7 = Crowther et al. (1995), 8 = Gosset et al. (2009), 9 = Williams et al. (1990), 10 = Marchenko et al. (2003), 11 = Pittard & Dougherty (2006).

System	P (d)	e	a (AU)	$\dot{M}_1$ ($M_\odot$ yr^{-1})	$v_{\infty 1}$ (km s^{-1})	$\dot{M}_2$ ($M_\odot$ yr^{-1})	$v_{\infty 2}$ (km s^{-1})
η Car	2024 (1)	0.9 (1)	16.64 (2)	4.8×10^{-4} (3)	500 (4)	1.4×10^{-5} (3)	3000 (4)
WR 22	80.325 (5)	0.559 (5)	1.68 (5)	1.6×10^{-5} (6)	1785 (7)	2.8×10^{-7} (8)	2100 (8)
WR 140	2900 (9)	0.881 (10)	16 (10)	4.33×10^{-5} (11)	2860 (11)	8.0×10^{-7} (11)	3100 (11)

et al. 2005; Pittard & Dougherty 2006) places the WCR close to the O star, and a stable wind-wind momentum balance may not occur. In such cases the WR wind may be radiatively braked prior to reaching the O star (Gayley, Owocki & Cranmer 1997).

Here we present preliminary results from hydrodynamic models aiming to explore the aforementioned possiblities. The remainder of this work is structured as follows: in Sect 2 we describe the model, results are presented in Sect. 3, followed by conclusions in Sect. 4.

2 The model

We model the colliding winds by numerically solving the time-dependent equations of Eulerian hydrodynamics in a 3D Cartesian coordinate system. For this purpose we use the AMR hydrodynamics code FLASH (Fryxell et al. 2000) into which we have implemented customized units for radiative driving, gravity, orbital motion, and radiative cooling. A description of the numerical methods used can be found in Pittard (2009) and Parkin et al. (2010, in prep). The adopted system and stellar parameters are listed in Table 1.

3 Results

3.1 η Carinae

Possibly the largest and finest example of a pre-hypernova candidate, η Car presents a rare but exceptional opportunity to test our current understanding of stellar evolution in the upper Hertzsprung-Russell diagram. X-ray emission from η Car is indicative of a highly eccentric, long-period binary system (Table 1). The binary model is relatively successful in explaining the majority of the X-ray lightcurve (e.g. Okazaki et al. 2008, Parkin et al. 2009). However, when the spatial extent of the X-ray emission region and energy dependence of the emission and absorption are taken into consideration (Parkin & Pittard 2008, Parkin et al. 2009), the width of the observed X-ray minimum cannot be reproduced by an eclipse of the X-ray emitting plasma alone. Furthermore, the observed X-ray emission in the 7-10 keV band was over-estimated by an order of magnitude if the pre-shock winds were assumed to be at terminal velocity. One potential cure for this discrepency would be a disruption of the WCR apex, initiated by effective radiative cooling of the companion's wind (Davidson 2002, Parkin et al. 2009, Parkin et al. 2010, in prep).

In our recent work, tests with static stars at a periastron separation and radiatively-driven stellar winds reveal that the companion star's pre-shock wind speed is reduced from $3000\ \mathrm{km\,s^{-1}}$ to $\simeq$

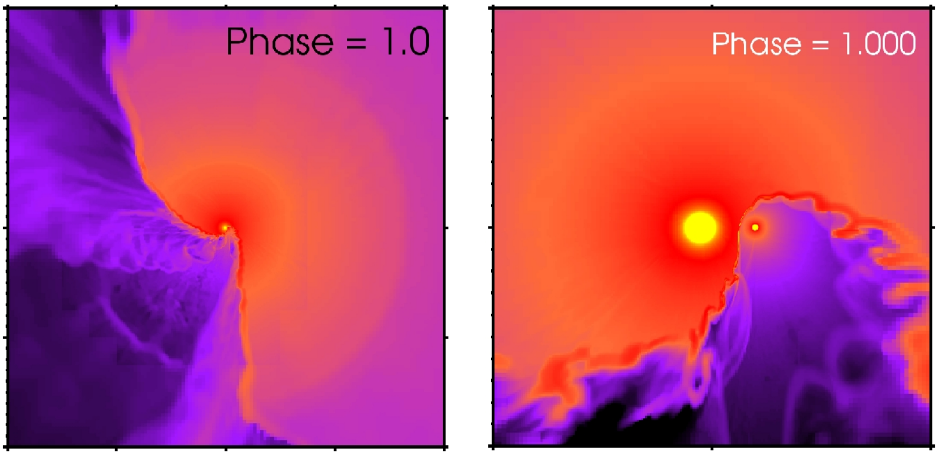

Figure 1: Snapshots of the gas density in the orbital $(x - y)$ plane from the radiatively-driven winds simulation of η Car at $\phi = 1.0$. At periastron ($\phi = 1.0$) the primary is to the left, and the companion is to the right, of the image centre. The plots show a region of $\pm 2 \times 10^{15}$ cm (left panel) and $\pm 5 \times 10^{14}$ cm (right panel).

2200 km s^{-1} by radiative inhibition (Stevens & Pollock 1994). Consequently, radiative cooling in the post-shock gas becomes important, driving the runaway growth of non-linear thin-shell instabilities (NTSI - Vishniac 1994) which massively distort the WCR. Subsequent vigorous oscillations lead to the collision of dense fragments of the WCR against the companion star. Compared to a simulation with terminal velocity winds, the aforementioned disruption leads to a reduction in the 7-10 keV X-ray flux by a factor of 8, thus providing a plausible explanation for the observed X-ray minimum.

However, in large-scale simulations (Fig. 1), the inclusion of orbital motion of the stars reduces the impact of radiative inhibition and increases the acquired pre-shock velocities. As such, the post-shock gas temperature and cooling time see a commensurate increase, and sufficient gas pressure is preserved to stabilize the WCR against catastrophic instability growth.

3.2 WR 22

The eccentric intermediate period system WR 22 contains one of the most massive Wolf-Rayet stars ever weighed (Rauw et al. 1996 - see also Schweickhardt et al. 1999). A recent analysis of *XMM-Newton* observations of WR 22 by Gosset et al. (2009) characterised the X-ray emission as a two-component spectrum with a soft component at ~ 0.6 keV and a harder component at $\sim 2 - 4.5$ keV, consistent with the colliding winds binary hypothesis. However, difficulties were encountered as wind-wind collision models were found to over-predict the observed X-ray flux by more than two orders of magnitude. The parameters of WR 22 provide the interesting prospect of a transition in the state of post-shock gas between quasi-adiabatic at apastron to highly radiative at periastron, which will considerably affect the resulting X-ray emission. Furthermore, a stable wind-wind momentum balance may be lost leading to a catastrophic reduction in X-ray flux.

Our simulations of WR 22 reveal that when the stellar winds are assumed to be instantaneously accelerated, a stable WCR is established throughout the orbit. In this case the model over-predicts the observed X-ray flux by more than two orders of magnitude. However, when the acceleration of the winds is considered, the character of the WCR changes dramatically between apastron and periastron. As radiative cooling becomes effective in the post-shock O star's wind, the growth of powerful NTSIs massively disrupts the WCR. Shortly before periastron the WCR collapses onto the O star (Fig. 2), and the over-estimate of the observed X-ray flux by the model is reduced to a factor of ~ 4, massively

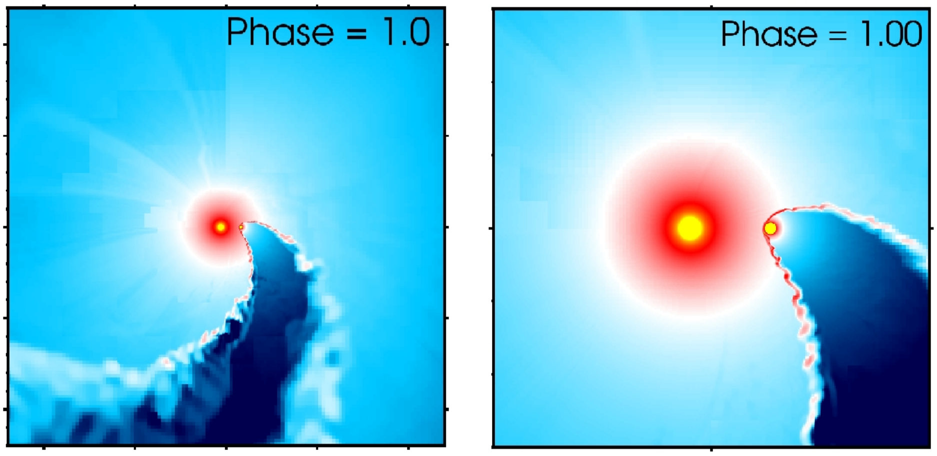

Figure 2: Snapshots of the gas density in the orbital ($x - y$) plane from the radiatively-driven winds simulation of WR 22 at $\phi = 1.0$. At periastron ($\phi = 1.0$) the WR star is to the left, and the O star is to the right, of the image centre. The plots show a region of $\pm 1.2 \times 10^{14}$ cm (left panel) and $\pm 3 \times 10^{13}$ cm (right panel).

improving the agreement[1].

3.3 WR 140

WR 140 represents the archetypal colliding winds binary system: it is a well known non-thermal radio emitter (Dougherty & Williams 2000), an exceptionally bright X-ray source (Pollock et al. 2005; De Becker et al. 2010, in prep), and an episodic dust producer (Williams et al. 2009).

The rapid motion of the stars around periastron contorts the WCR into a spiral structure (Fig. 3). Both winds remain quasi-adiabatic and a stable WCR is established at all orbital phases. Preliminary results of X-ray calculations show that the model provides a reasonable match to the majority of the X-ray lightcurve. However, the rise in X-ray flux prior to periastron is not well matched, and the model lightcurve exhibits no X-ray minimum at periastron. This could be due to our adopted wind parameters - for hydrodynamic models which adopt slightly different wind parameters see the contribution by Russell et al. (2011).

We note that currently we have only explored models of WR 140 with instantaneously accelerated (i.e. terminal velocity) winds. Considering the ratio of wind ram pressures, the wind acceleration regions may become important for a brief period around periastron passage. As we have seen from our simulations of WR 22, effective radiative cooling of both winds post-shock can jeopardise the stability of the WCR and considerably affect the emergent X-ray flux. Furthermore, rapid radiative cooling of post-shock gas around periastron could provide a means for forming dust. Hence, the importance of the wind-acceleration regions will be explored in future models.

4 Conclusions

Preliminary results from 3D hydrodynamic simulations of the massive star binary systems η Car, WR 22, and WR 140 have been presented which include the radiative driving of the stellar winds,

[1]The approach to radiatively driving the stellar winds in the hydrodynamic simulations is based on the formalism of Castor, Abbott & Klein (1975); a $\beta-$velocity law with $\beta = 1$. Therefore, aspects of WR wind acceleration are not accounted for, e.g. an inner, and outer, wind acceleration region (Hillier & Miller 1999, Gräfener & Hamann 2005). However, the wind-wind collision generally occurs close to the O star, and our conclusions remain uneffected.

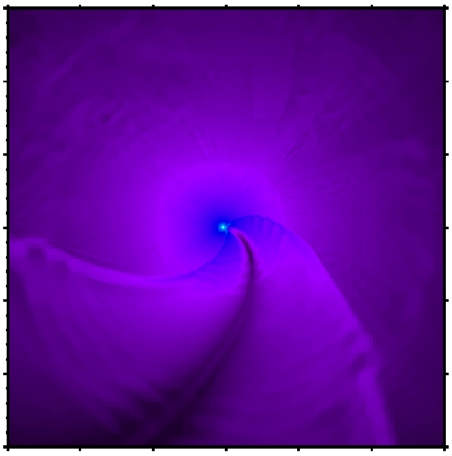

Figure 3: Snapshot of the gas density in the orbital $(x-y)$ plane from the instantaneously accelerated winds simulation of WR 140 at $\phi = 1.0$. At periastron ($\phi = 1.0$) the WR star is to the left, and the O star is to the right, of the image centre. The plot shows a region of $\pm 1.5 \times 10^{15}$ cm - large axis tick marks correspond to a distance of 5×10^{14} cm.

gravity, orbital motion, and radiative cooling. In the systems explored the post-shock gas in the WCRs exhibits a breadth of interesting dynamics. For instance, in WR 22 the transition of the post-shock gas from quasi-adiabatic at apastron to radiative at periastron brings about a dramatic change in the stability of the WCR. Interestingly, transitions in the character of post-shock gas seem to be characteristic of the highly eccentric systems examined.

An extensive study of the dynamics in these systems will be presented in a series of forthcoming papers, along with a detailed comparison between X-ray calculations performed on the models and observations (see e.g. Pittard & Parkin 2010).

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Discussion

I. Stevens: Would you expect to see any observational consequences of wind collapse in, say, the spectrum of the O star, i.e. WR material being dumped onto the surface?
E.R. Parkin: I would expect that there will be some consequence but it will strongly relate to the mixing of the WR wind into the inner wind of the O star. We do not currently resolve the wind acceleration region sufficiently well to examine this effect.

T. Madura: Could you comment on how a latitude-dependent primary wind might affect your results for η Car?
E.R. Parkin: The X-ray emission predominantly originates from the apex of the wind-wind collision region which is close to the orbital plane. Therefore, a latitude dependent primary star wind should not have a considerable effect on the shocks which emit the X-rays. However, the inclination angle of the orbital plane is $\sim 42^\circ$, so X-rays may pass through denser gas towards the pole of the star, thus affecting the degree of attenuation.

W.-R. Hamann: As we had discussed a lot on Monday, mass-loss rates of WR and O stars are still uncertain to some factor 2 or 3, depending on the degree of clumping and the clump sizes. How sensitive are your hydrodynamical simulations to the mass-loss rate, and to possible large-scale wind clumping?
E.R. Parkin: The importance of radiative cooling for the dynamics of postshock gas is directly related to the stellar wind mass-loss rates. Therefore, if you change the mass-loss rates you could significantly change the character of the wind-wind collision region. There is also the effect of clumps in the wind on the shocks. For instance, the processing of clumps in the wind-wind collision region can introduce a large amount of vorticity (Pittard 2011).