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Interactions in massive Binary Systems

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Abstract. In binary systems consisting of two massive stars, the interaction of the powerful stellar winds of the two components produces signatures over a broad range of wavelengths. Many observational and theoretical studies of this phenomenon have been performed over the last two decades. In very close massive binary systems, mass exchange due to Roche lobe overflow can also occur and the signatures of the two phenomena are sometimes hard to distinguish. In this review, I discuss some recent developments in the study of both phenomena.

1 Theoretical Models of Interactions in early-type Binaries

Early-type stars of spectral types O and Wolf-Rayet (WR) feature extremely powerful radiatively driven winds that combine tremendous mass-loss rates (10^{-8} – $10^{-4}\,\mathrm{M_\odot\,yr^{-1}}$) and highly supersonic wind velocities (from about 1000 to several $1000\,\mathrm{km\,s^{-1}}$). In binary systems harbouring two such stars, these winds are forced to interact. In most cases, this interaction takes the form of a wind - wind collision where the position and shape of the contact surface between the winds are set by the condition that their momenta balance each other. The wind interaction region is limited by two hydrodynamical shocks, one on either side of the contact surface, where the inflowing gas abruptly decelerates and its kinetic energy is converted into heat. Immediately behind the shocks, the post-shock gas is thus compressed and much hotter with respect to the pre-shock gas. What happens to the shock-heated gas in the post-shock region depends critically upon the efficiency of radiative cooling (Stevens, Blondin, & Pollock 1992; Pittard & Stevens 2002).

Substantial efforts have been invested over the last two decades to develop increasingly sophisticated hydrodynamical models of wind - wind interactions. Among the more recent developments are the inclusion of clumping (Walder & Folini 2002; Pittard 2007) and of the Coriolis force (Lemaster, Stone, & Gardiner 2007; Okazaki et al., 2008; Parkin & Pittard 2008), to cite only a few. One major problem that remains to be solved is the failure to numerically resolve the cooling layers of the post-shock gas in systems where radiative cooling is important.

Besides the wind-wind interaction described above, another type of interaction that can occur in (short period) early-type binaries is the exchange of matter and angular momentum through a Roche lobe overflow (RLOF) process. This process has important consequences for the evolution of the system (see the reviews of Vanbeveren and Pols in this volume) and will manifest itself in the observational properties of the binaries. In the past, it has often been argued that the presence of a strong radiation field and a substantial stellar wind could alter the RLOF interaction in early-type binaries. In this respect, an extremely important theoretical result was obtained from hydrodynamical simulations by Dessart, Langer, & Petrovic (2003) who showed that radiation and wind momenta are actually irrelevant for the general dynamics of an accretion stream that continues to move along a ballistic trajectory.

Mass exchange in early-type binaries has different characteristics than in late-type systems. As a matter of fact, in a close O + O binary system, both components have rather large radii and there is generally not enough space for an accretion disk to form. Hence the stream of transferred material should impact directly onto the mass gainer. Finally, it has to be stressed that the angular momentum that is transferred can spin up the accretor to critical rotation thereby stopping the accretion process.

2 Observations of Colliding Winds

2.1 Observational Signatures of Wind - Wind Interactions

As a result of the temperature and density increases in the wind interaction zone, one expects to find a number of observational features that reflect the presence of a wind - wind collision (see also Rauw 2008):

At the shock front, part of the kinetic energy is converted into heat and the temperature of the post-shock gas is therefore of the order of several million degrees. This hot gas produces an X-ray emission that comes on top of the intrinsic X-ray emission produced by the components of the binary system (see e.g., Pittard & Stevens 2002). The observable X-ray emission is often variable, either as a result of the changing optical depth along the line of sight towards the observer, or as a result of the changing orbital separation between the components. Phase-modulated X-ray emission has been observed for a number of colliding wind systems in our Galaxy (see e.g., Rauw 2008 and references therein), but also for one system in the Small Magellanic Cloud (Nazé et al. 2007). One open issue is the fact that the observed X-ray overluminosity of colliding wind systems is frequently much lower than expected on theoretical grounds (see e.g., Pittard et al. 2000; De Becker et al. 2004; Nazé 2009).

If radiative cooling is efficient in the interaction region, the gas in the post-shock region flows along the contact surface and radiatively cools until it reaches temperatures that allow the recombination of certain elements, thereby producing extra emission, mainly in optical recombination lines. The Doppler shifts of these excess emissions reflect the gas velocity component along the line of sight. As the orientation of the stars with respect to the observer changes with orbital phase, phase-locked line-profile variability is produced (see Fig. 1). When this effect is not properly taken into account, it can result in a distorted radial velocity curve and hence erroneous orbital parameters. Conversely, this property can be used to investigate the shape of the interaction region either by assuming a simple geometrical model deviced by Lührs (1997, see also Hill et al. 2000, Falceta-Gonçalves, Abraham, & Jatenco-Pereira 2006) or by applying a Doppler tomography technique (see e.g., Thaller et al. 2001, Rauw et al. 2005).

In relatively wide binary systems harbouring a carbon-rich Wolf-Rayet star of spectral type WC, the increased density in the wind interaction zone can lead either to episodic or persistent production of dust. In the former case, dust is produced around periastron passage in highly eccentric systems leading to episodic IR outbursts (e.g., Williams et al. 1990; Williams, Rauw, & van der Hucht 2009), whilst in the latter case, the combination between rotation and advection of the dust leads to the formation of spiral features that can be seen as so-called pinwheel nebulae in the near infrared (Tuthill, Monnier, & Danchi 1999).

The hydrodynamical shocks in colliding wind binary systems are thought to be efficient sites for the acceleration of relativistic particles (e.g., Pittard & Dougherty 2006; De Becker 2007 and references therein). The relativistic electrons produce a phase-dependent non-thermal (synchrotron) radio emission that is observed in addition to the thermal free-free emission produced in the winds of these stars (e.g., van Loo et al. 2008). The presence of these relativistic electrons in combination with the strong UV radiation fields of massive stars should also yield hard X-rays and soft γ-ray emission through inverse Compton scattering. So far, such a non-thermal high-energy emission has only been detected in the case of η Carinae (Leyder, Walter, & Rauw 2008; Tavani et al. 2009).

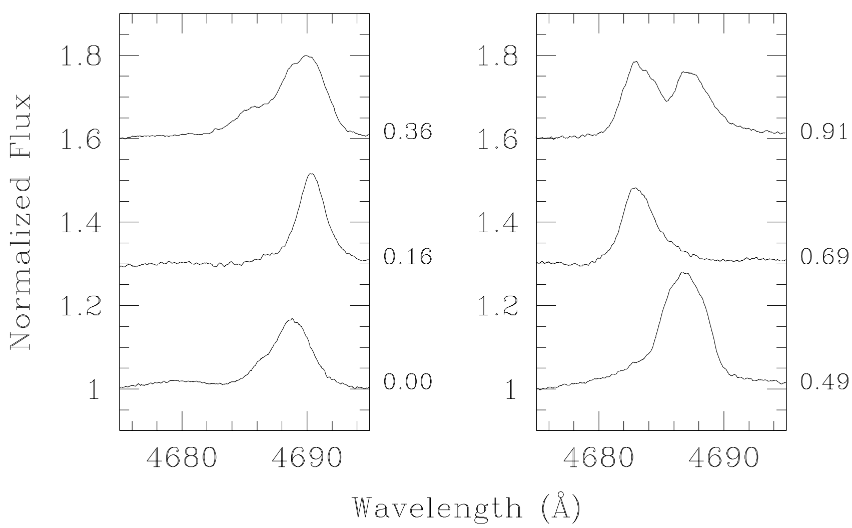

Figure 1. He II λ 4686 emission line profile variability in the optical spectrum of 29 CMa (O8.5 + O9.7, $P_{\rm orb}$ = 4.4 days; Linder et al. 2009, in preparation). The orbital phases are indicated on the left of each spectrum and phase 0.0 corresponds to the conjunction with the primary star being in front. For clarity, the various spectra are shifted by 0.3 continuum units.

2.2 A few specific Examples

In this subsection, we briefly illustrate the confrontation between the predictions of theoretical models and the actual observations.

Let us first consider the effect of the Coriolis force. Whilst the consequences of the orbital velocities on the outermost regions of the wind interaction zone are well illustrated by the spiral shape of the pinwheel nebulae (e.g., Tuthill et al. 1999), their impact on the inner parts of the wind - wind interaction is more difficult to investigate observationally. Lemaster et al. (2007) performed

3-D hydrodynamical simulations of an adiabatic (i.e. with no radiative cooling) colliding wind binary system. In a system with a circular orbit and undergoing a strong Coriolis deflection, the column density towards the center of mass of the system, where the hottest, X-ray brightest material is expected, was found to peak slightly after quadrature phase (around $\phi \sim 0.2 - 0.4$ and $0.7 - 0.9$). These phases should thus correspond to a peak in the absorption of the observed X-ray emission. To first order, such a situation probably applies to the very massive eclipsing Wolf-Rayet system WR 20a (WN6ha + WN6ha, $P_{\rm orb} = 3.7$ days) were the X-ray flux was found to be 20 - 30% lower near quadrature than around conjunction (Nazé, Rauw, & Manfroid 2008), although in this case the X-ray emitting region must be quite extended as indicated by the lack of an X-ray eclipse. The signature of the Coriolis deflection was also observed in the Doppler map of the optical emission lines of this system (Rauw et al. 2005).

One of the most challenging cases for hydrodynamical models is the highly eccentric Luminous Blue Variable system η Carinae ($P_{\rm orb} = 5.54$ yrs, $e \simeq 0.9$). In η Car, the secondary wind carves out a cavity in the higher density slower wind of the primary. Over most of the orbit, this cavity has a rather axisymmetrical conical shape. Near periastron, however, the larger orbital speed heavily distorts the structure. The shocked primary wind cools radiatively whilst the shocked secondary wind is adiabatic except maybe near periastron passage[1]. The bulk of the X-ray emission likely arises in the hot shocked secondary wind. The X-ray emission is then attenuated by absorption in the circumstellar material before it leaves the system. Okazaki et al. (2008) and Parkin et al. (2009) performed 3-D hydrodynamical simulations of η Car with different assumptions about the temperature structure of the interaction region. These simulations were confronted with the extensive set of broad-band *RXTE* and *XMM-Newton* data of this system. Most of the features of the X-ray lightcurve can now be explained. The rather flat minimum in the X-ray emission after periastron passage points towards a substantial reduction of the intrinsic X-ray emission which could be due to the wind collision collapsing onto the secondary's surface. However, it has to be stressed that there remain a number of open issues, especially due to the rather poor knowledge of the orbital and physical parameters of η Car, and that other observational diagnostics, such as the analysis of high resolution X-ray line profiles by Henley et al. (2008) yield conflicting conclusions.

3 Observational Hints for Mass Exchange Episodes

For specific early-type binary systems, the existence of a past or ongoing mass exchange can be probed through detailed phase-resolved spectroscopic analyses. For instance, in the case of Plaskett's Star (HD 47129), Linder et al. (2008) investigated a large sample of high-resolution spectra using techniques such as spectral disentangling, Doppler tomography and spectral fitting with a model atmosphere code. This non-eclipsing binary harbours an O8 III-I primary with

[1] Evidence for a change in the shock properties around periastron is also provided by the He II λ 4686 recombination emission line in the optical spectrum which is observed around periastron passage (Steiner & Damineli 2004).

a mass of 52 - 55 $M_\odot$ and a slightly more massive (54 - 58 $M_\odot$) secondary[2]. Disentangled spectra of the primary and secondary are shown in Fig. 2 to illustrate some of the striking features of the system. Indeed, whilst the primary has a moderate rotational velocity ($v \sin i \simeq 65\,\mathrm{km\,s^{-1}}$), the secondary is a much faster rotator ($v \sin i \simeq 300\,\mathrm{km\,s^{-1}}$). The spectrum of Plaskett's Star also displays clear signatures of a flattened secondary wind (likely as a result of the fast rotation of the latter) and of a wind - wind interaction. Most importantly, the primary spectrum is nitrogen enriched by a factor 16 over solar (note the prominent N III lines between 4510 and 4535 Å in Fig. 2), whilst carbon is depleted (0.2 ± 0.1 times solar). Quite surprisingly, the secondary atmosphere seems enriched in helium, whilst nitrogen would be subsolar (Linder et al. 2008). Most of these properties (nitrogen overabundance of the primary, fast rotation of the secondary) suggest that the system is most probably in a post case A RLOF evolutionary stage where the primary star has transferred matter and angular momentum to its, originally less massive, companion. There are however a number of questions that remain to be addressed, such as the chemical composition of the secondary that cannot be explained by present-day binary evolution codes.

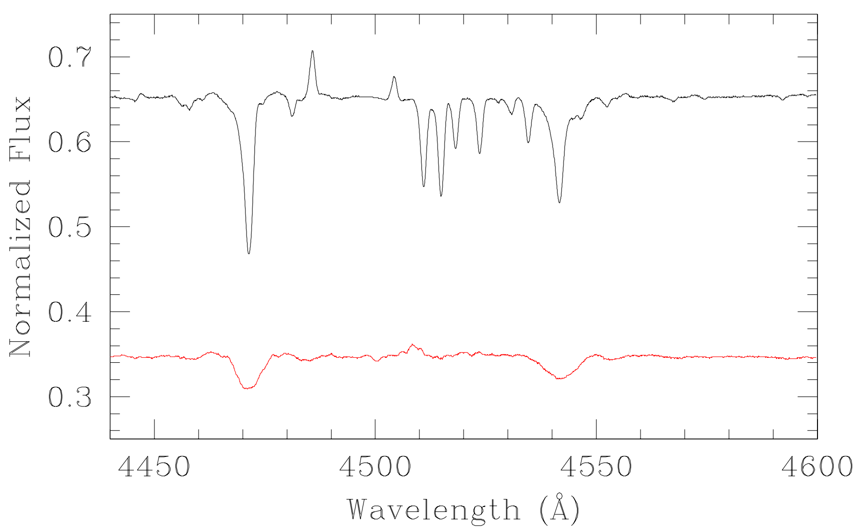

Figure 2. Disentagled spectra of the components of HD 47129 (see also Linder et al. 2008). The relative contributions of the primary and secondary star to the continuum normalized spectrum of the binary are shown.

4 Conclusions

Wind - wind or mass exchange interactions are an important ingredient of early-type binaries and there exists an extensive literature on these topics. The effects

[2] Note that the dynamical masses of the system components are too large for their spectral types. They are evaluated assuming an orbital inclination in the range 69 – 73°.

of these interactions must be accounted for to correctly interpret the spectra of massive binary systems. Conversely, their study provides us with a wealth of information about the physics of stellar winds as well as on the evolution of early-type binaries.

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