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COLLIDING WIND SIGNATURES IN EARLY-TYPE BINARIES

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RESUMEN

Las observaciones de estrellas binarias de tipo temprano permiten no sólo establecer propiedades fundamentales de las estrellas masivas en forma independiente de modelos, sino que proveen además información importante sobre las interacciones de sus vientos estelares. Indicios de interacciones entre vientos han sido encontradas a lo largo de un rango considerable de longitudes de onda y energías, desde el dominio de radio a rayos X, y posiblemente rayos gamma. En esta contribución se discuten algunos resultados del estudio de las interacciones de vientos en estrellas binarias WR y de tipo O.

ABSTRACT

Observations of early-type binaries not only allow us to establish the fundamental properties of massive stars in a model-independent fashion, but furthermore provide important information on the interactions of their stellar winds. The signatures of wind-wind interactions have been found over a broad range of wavelengths and energies, from the radio domain to X-rays and possibly γ-rays. In this review, I discuss some results of the study of wind interactions in Wolf-Rayet and O-star binaries.

Key Words: binaries: spectroscopic — radiation mechanisms: non-thermal — stars: winds, outflows — stars: early-Type — x-rays: stars

1. INTRODUCTION

In massive binary systems where two stars with highly energetic stellar winds are bound by gravitation, the interaction of the stellar winds has important consequences. The concept of wind-wind collisions has been introduced theoretically by Prilutskii & Usov (1976) and Cherepashchuk (1976). The usual picture is that of an interaction zone limited by two hydrodynamic shocks. At each shock front, part of the kinetic energy of the inflowing wind is thermalized. The relative strength of the winds entering the collision region is expressed by the so-called wind momentum ratio $\eta = \dot{M}_2\,v_2/\dot{M}_1\,v_1$ where $\dot{M}_i$ and v_i are respectively the mass loss rate and pre-shock wind velocity of component i. This parameter determines the location and the shape of the interaction region. For $\eta = 1$ (equal wind strengths), the wind interaction zone is expected to be roughly planar and to be located midway between the binary components. For $\eta < 1$, the wind collision region is wrapped around the star with the weaker wind. To first approximation, the shape of the wind collision zone is a cone with an opening angle set by the value of η (Eichler & Usov 1993).

The most obvious physical consequences of the wind-wind interaction can be summarized as follows:

- the spherical symmetry of the stellar winds of the individual binary components is broken;
- the density of the post-shock plasma is increased compared to the pre-shock density;
- the plasma immediately behind the shock is heated to temperatures of several 10^6 K;
- the hydrodynamic shock can act as an acceleration site for relativistic particles.

In the following, I discuss each of these effects in turn, emphasizing each time the wavelength domains over which these effects produce the most prominent observational signatures.

2. THE LOSS OF SYMMETRY OF THE WIND

One of the most obvious consequences of a wind interaction is the loss of the spherical symmetry of the winds: the interaction creates a cavity in the most energetic wind and confines the less energetic one. This situation has important consequences for the profiles of spectral lines that form in the wind. The deficit of emission over certain ranges of radial velocities compared to a spherically symmetric wind of a single star leads to a phase-dependent deformation of the line profile, regardless of any putative extra-emission from the wind interaction zone itself.

Consider for instance a UV resonance line forming only in the wind of one of the binary components. The velocity extent of the P-Cygni absorption trough and hence the apparent terminal velocity as deter-

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mined from the observed line profile depend on the orbital phase. In addition, the strength of the absorption components can vary as a result of selective atmospheric eclipses. This phenomenon occurs in WR + O binaries when the WR star is in front and the continuum light of the O-star is absorbed at specific wavelengths by the WR wind (Koenigsberger & Auer 1985).

These effects were modelled by Stevens (1993) for resonance lines using Monte Carlo simulations of the radiative transfer in an axisysmmetric colliding wind binary. Generally speaking, for any line that forms over a significant part of the wind, important line profile variability is expected in a close binary system (with orbital separations of a few stellar radii, i.e. of order of the radius of the line emitting region). This effect is not restricted to UV P-Cygni lines (e.g. N IV $\lambda\,1718$, Stevens 1993), but concerns also optical (e.g. Hα, He II $\lambda\,4686$) and near-infrared (e.g. He I $\lambda\,10830$, Stevens & Howarth 1999) emission lines.

3. THE ENHANCED DENSITY OF THE POST-SHOCK PLASMA

For an ideal gas undergoing a strong shock, the Rankine Hugoniot relations predict a density increase by a factor 4 across the hydrodynamic shock front. This effect has several potential consequences. The type of radiation emitted depends on the post-shock plasma temperature and hence on the efficiency of radiative cooling (Stevens et al. 1992). If radiative cooling is very slow, the post-shock plasma will essentially evolve adiabatically and emits radiation mainly in the X-ray domain (see § 4). If, on the contrary, the post-shock plasma cools down rapidly, one expects to observe the signature of the enhanced density over a wide range of wavelengths. For instance, the ρ^2 dependence of the intensity of recombination lines possibly leads to a localized extra emission of lines in the optical, UV and infrared domains. A semi-analytical geometrical model of such an extra emission arising from the wind interaction zone has been constructed by Lührs (1997) and was subsequently applied to a number of early-type binaries, mainly of spectral type WC + O. For the latter systems, the discrete extra emission features are seen to move on top of the very broad WC emission lines that are typical of these objects. The 'motion' of these emission features as a function of orbital phase can be used to constrain some of the properties of the shock cone (such as the opening angle, the Coriolis deflection, the orbital inclination,..., see Lührs 1997). At this stage, it has to be stressed that the assumption of an underlying undisturbed flat-topped profile is only valid if the colliding wind region lies sufficiently far away from the WR star so that the symmetry of the line emission region in its wind is preserved. To overcome this limitation, Hill et al. (2002) designed a numerical model based on the Lührs (1997) formalism but accounting for the variations of the underlying emission profile and for turbulence in the wind and the wind interaction zone. These authors used their model to fit the C III $\lambda\,5696$ emission line in the spectra of θ Mus (WC6 + OB), WR 42 (WC7 + O) and WR 79 (WC7 + O).

In a more general situation, where the extra emission arises only from a narrow part of the interaction zone and where the underlying emission lines are rather narrow, the extra emission leads to complex changes of the line morphology. It is quite often impossible to distinguish the effects of an extra emission from the profile variations due to the loss of spherical symmetry.

To illustrate the complexity of the line profile variations observed in some close binaries, I show in Figure 1 the case of the O4 If$^+$ + O7.5(f) binary LSS 3074 ($P_{\rm orb} = 2.1851$ days; Gosset et al. 2005). In the spectrum of this system, the He II $\lambda\,4686$ line evolves from a broad and skewed emission (around $\phi = 0.0$) into a double-peaked feature with rather narrow individual peaks and the strongest peak closely following the orbital motion of the primary (at phases near 0.5). There is no emission directly moving with the secondary. A possible interpretation could be that due to the proximity of the two stars the primary wind only fully develops (and hence emits) in directions away from the secondary. Towards the secondary component, the primary wind would encounter either the wind or the surface of the secondary and hence the only emission there should be produced by the material compressed in the wind interaction zone. In between these two physical regions shock heating could lead to a higher than normal ionisation, preventing the formation of optical recombination lines.

Another consequence of the increased density in the wind interaction zone is the production of dust, either episodically or continuously, in binaries harbouring a WC component. These aspects are reviewed by Williams (2008).

4. THE HOT POST-SHOCK PLASMA

When the stellar wind encounters the hydrodynamic shock, part of its kinetic energy is converted into heat following the relation $T = 3\,\overline{m}\,v_j^2/16\,k$ where $\overline{m}$ and v_j are the average mass per particle

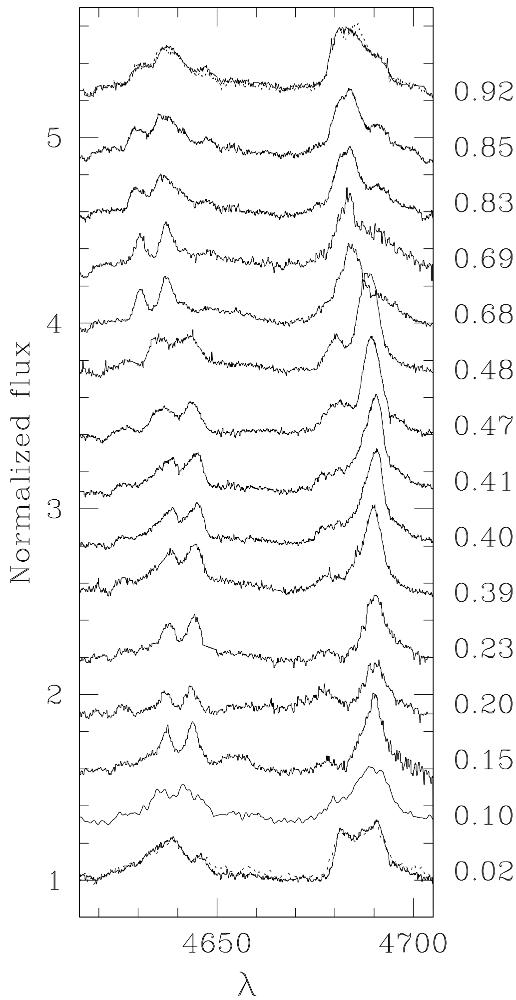

Fig. 1. Phase-locked profile variations of some emission lines in the blue optical spectrum of LSS 3074. The orbital phases are indicated on the right.

and the pre-shock velocity, k being the Boltzmann constant. This translates into a significant increase of the post-shock plasma temperature, up to several million degrees. As a consequence, the wind interaction zone could contribute significantly to the X-ray emission from an early-type binary system. This emission has been the subject of quite a number of theoretical modelling efforts including semi-analytical (e.g. Eichler & Usov 1993; Antokhin et al. 2004) as well as purely numerical (i.e. hydrodynamical) approaches (e.g. Stevens et al. 1992; Walder & Folini 2003). The X-ray luminosity of the shock region depends on the efficiency of cooling. For a highly radiative system, $L_X \propto \dot{M}\, v^2$ (Pittard & Stevens 2002). If both winds are adiabatic, $L_X \propto \dot{M}^2/(dv^{3.2})$ (Stevens et al. 1992). Hydrodynamic models are well suited to describe the X-ray emission of adiabatic wind interactions, but often fail to handle the radiative case, usually associated with short period binary systems, since the typical cooling length becomes so short that it cannot be resolved by the models. A semi-analytical approach to the X-ray emission of radiative systems was therefore designed by Antokhin et al. (2004).

A number of early-type binary systems, spanning a range in orbital as well as stellar parameters, have been observed with *XMM-Newton* and *Chandra*. Phase-locked variations of the X-ray flux were detected for many of them, including HD 5980, the first system outside our Galaxy where such variations were observed (Nazé et al. 2007). The X-ray emission from the wind-wind collision is expected to vary as the stars revolve around each other for several reasons:

- because of the changing circumstellar optical depth along the line of sight towards the shock;
- because in eccentric colliding wind systems, the variation of the orbital separation as a function of orbital phase should lead to a modulation of the X-ray flux.

The first effect stems from the rather large intrinsic opacity of the wind material to photoelectric absorption at energies below ~ 1 keV. In short-period early-type binaries, the wind interaction zone is buried rather deeply inside the optically thick part of the winds, thus leading to a substantial modulation of the observable X-ray flux especially in the softer energy range. This effect has been observed in γ^2 Vel (WC8 + O7.5 III, $P_{\rm orb} = 78.5$ days, $e = 0.4$) where the X-ray flux significantly increases over a relatively short phase interval when the O-star with its less opaque wind passes in front of its WC8 companion and the wind interaction region (Willis et al. 1995; Rauw et al. 2000; Schild et al. 2004).

Concerning the second effect, theoretical models predict a dependence of the intrinsic X-ray emission of the wind-wind collision on the orbital separation (d). For instance, in the adiabatic regime, it is expected that the emission varies as $1/d$. Such a relation might apply to the eccentric system HD 93403 (O5.5 I + O7 V, $P_{\rm orb} = 15.1$ days, $e = 0.23$; Rauw et al. 2002), but does not hold for HD 152248 (O7.5(f) III + O7(f) III, $P_{\rm orb} = 5.8$ days, $e = 0.13$; Sana et al. 2004) nor Cyg OB2 #8a (O6 I + O5.5 III, $P_{\rm orb} = 21.9$ days, $e = 0.24$; De Becker et al. 2006). In the latter two systems, the X-ray flux is actually lower at phases near periastron, probably because the stellar winds do not reach their terminal velocities before colliding and the wind interactions are still in the radiative regime. For typical mass loss rates of O-type stars, the transition between the radiative and adiabatic regime thus apparently occurs for orbital periods of a few weeks. Due to the larger mass loss rates of Wolf-Rayet stars, the transition from the radiative to the adiabatic regime in WR + O binaries should occur at longer orbital periods. Indeed, no d^{-1} scaling was seen in γ^2 Vel (Rauw et al. 2000) nor in WR 22 (Gosset et al. 2003) which both have orbital periods near 80 days.

A very interesting case to consider in this context is the WN6ha star WR 25. Based on its rather unusual X-ray brightness, and variability (see e.g. Pollock & Corcoran 2006, and references therein) WR 25 had often been suspected to be a colliding wind binary. However, it is only through the recent work of Gamen et al. (2006, 2008) that the binarity of this system was established and that a first orbital solution became available ($P_{\rm orb} = 208$ days, $e \simeq 0.35$, Gamen et al. 2006). Folding the X-ray data of this system with the ephemerides, one finds that WR 25 might actually display a d^{-1} modulation of its X-ray flux (see Figure 2). Figure 2 further indicates a deficit of the X-ray flux, compared to the d^{-1} expectation, shortly after periastron passage. This is likely due to the eclipse of the wind interaction zone by the wind of the WN6ha star. Furthermore, near phase 0.8, we see an excess of the emission that is strongest in the softer energy band (0.5 – 2.4 keV). The latter orbital phase corresponds to our line of sight towards the system crossing the less opaque O-star wind.

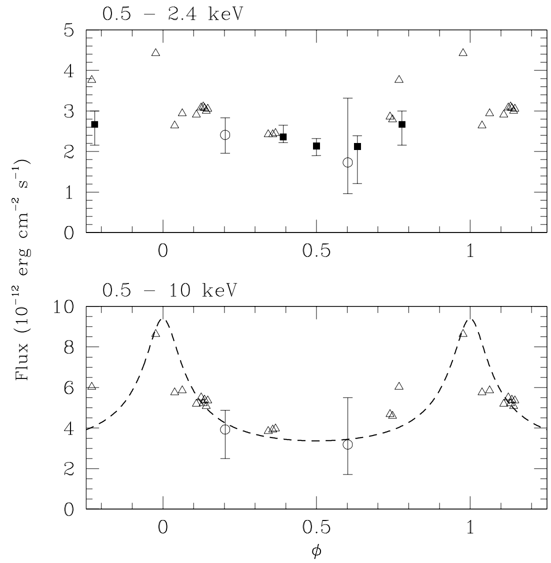

Fig. 2. X-ray light curve of WR 25 over the *ROSAT* (top panel) and *XMM-Newton* (bottom panel) energy ranges (work done in collaboration with Y. Nazé and E. Gosset) as a function of orbital phase. The d^{-1} relation is shown in the lower panel for illustration (note that this is not a fit to the data). Squares, circles and triangles stand respectively for *ROSAT*, *ASCA* and *XMM-Newton* data. Note that the error bars on the *XMM* data are smaller than the symbols.

5. ACCELERATION OF RELATIVISTIC PARTICLES

Relativistic particles can be produced through diffusive shock acceleration. In this process, the particles gain energy through the first order Fermi mechanism as they cross and re-cross a hydrodynamic shock front. This mechanism involves a hydrodynamic shock and colliding wind binaries are therefore ideal sites for the production of relativistic particles.

The observational signature of relativistic electrons is best seen as non-thermal (synchrotron) radio emission. A fraction of the massive stars detected at radio wavelengths displays indeed a highly variable radio emission with a negative spectral index and a level exceeding the flux expected from thermal free-free emission (see e.g. Williams 1996). Most (if not all) of these objects are binary systems (e.g. Dougherty & Williams 2000). A spectacular confirmation of the link between colliding winds and non-thermal radio emission was presented by Dougherty et al. (2004) who obtained *VLBA* observations of WR 140 (WC7 + O4-5, $P_{\rm orb} = 7.94$ yrs, $e = 0.88$) between the orbital phases 0.74 and 0.97. The radio emission at 8.4 GHz was resolved as a bow-shaped arc that was seen to rotate as the orbit progresses.

Due to the huge opacity of a spherically symmetric and smooth stellar wind at radio wavelengths, only wide (i.e. long-period) binaries, where the wind collision zone is located well outside the radio photosphere, should produce an observable synchrotron emission. Yet, in the case of the O6 I + O5.5 III system Cyg OB2 #8a ($P_{\rm orb} = 21.9$ days, $e = 0.24$, De Becker et al. 2004), the 6 cm radio flux varies with the orbital cycle (Blomme 2005) although the radio photosphere of both components exceeds the orbital dimensions by a large factor. Based on the opacity of the winds of its components, one would not expect to detect any observable synchrotron emission from this system. The clear detection of such an emission is therefore puzzling. A possible way out might be a porous wind consisting of optically thick clumps, rather than a homogeneous spherically symmetric outflow.

Sophisticated theoretical models for non-thermal phenomena in colliding wind binaries, including the

Razin effect, inverse Compton scattering and relativistic bremsstrahlung, were presented by Pittard et al. (2006) and Pittard & Dougherty (2006). However, these models are ill-constrained by the radio data alone. High-energy data should in principle provide clues on how to discriminate between the different models. In fact, the interplay between the strong flux of photospheric UV photons emitted by early-type stars and the relativistic electrons should produce inverse Compton X-rays and γ-rays. Still, the current sensitivity and/or angular resolution of γ-ray observatories are not sufficient to derive actual measurements of the high-energy emission of colliding wind systems. For instance, using the IBIS instrument onboard *INTEGRAL*, only upper limits of the soft γ-ray flux could be inferred for most systems (Leyder & Rauw 2006) except perhaps for η Car + WR 25 (Leyder et al., in preparation).

6. CONCLUDING REMARKS

There exists nowadays a large body of papers dealing with the observational signatures of the wind-wind interaction in early-type binaries. Several aspects of the phenomenon have been investigated, but a number of new questions have been raised that will request more sophisticated theoretical models (e.g. to resolve the cooling layers in the wind interaction region and to understand the origin of excess optical line emission from this region) and/or more sensitive observatories such as *GLAST*, *XEUS* or *Con-X* to collect high-quality γ-ray and X-ray data of these systems (e.g. to search for the non-thermal high-energy emission).

On behalf of the Liège hot star group, I would like to express our deepest sorrow about Virpi Niemela's passing away shortly after the end of the Cariló meeting. We all owe her so many things and we will all miss her. I would like to express my gratitude to my colleagues of the Liège group for their help in preparing this review. This work is supported by the FNRS (Belgium), including a travel grant to Argentina, as well as through the XMM and INTEGRAL PRODEX contract (Belspo).

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DISCUSSION

A. Daminelli - Our BeppoSAX data (Viotti et al.) on η Car show a hard tail in X-rays extending up to 100 keV, that looks to be connected with the INTEGRAL data you have shown. Do you expect to see phase locked variability in γ rays?

G. Rauw - In principle yes, but unfortunately to produce the image that I have shown, we had to combine all the existing INTEGRAL observations of the η Car region and we lack the sensitivity to achieve secure detections of the source if we split our data set into smaller time bins.

G.E. Romero - Past Friday the High-Energy Stereoscopic System (HESS) announced the detection of a new very high-energy source. The interesting point is that this source seems to be coincident with WR 20a. The source, however, is apparently extended. Can you comment on this, please?

G. Rauw - WR 20a is located in the Westerlund 2 cluster where there are a dozen O-type stars hotter than spectral type O7. All these stars (or at least some of them) could contribute along with WR 20a to produce a population of relativistic particles which might then actually produce this TeV emission. Some of these objects might be colliding wind binaries since they appear rather bright on Chandra images, but their status need to be investigated in more detail.

A. Herrero - You have shown a cartoon showing the 6-cm photosphere around the Cyg OB2 #8a system. Is that really spherical? Could this photosphere have a contribution from nearby material or external interactions?

G. Rauw - The radio photospere is unlikely to be spherical indeed. The most obvious reason is that in a colliding wind binary we have to deal with the free-free absorption of two stars. However, in the case of Cyg OB2 #8a the parameters of both stars are quite similar and a spherical radio photosphere provides a good first order approximation to illustrate the problem that we have in explaining the observed synchrotron emission. The radio emission by itself must be tied with the binary, because we see it changes with orbital phase of the binary. So there should be little contribution (if any) from outside of the system.

A. Moffat - It cannot be assumed that single stars are spherically symmetric. I suspect that even a modest wind flattening and inclination of rotation axis relative to the orbital axis (of both stars) could have significant effect on the wind-wind collision effect.

G. Rauw - That's very likely indeed. However, what we wanted to see in the case of Cyg OB2 #8a is whether taking the least complicated model with the lowest number of free parameters (i.e. spherical winds) could explain what we observe. The answer seems to be that it cannot!

S. Owocki - First a comment regarding Gloria Koenisberger question. I believe you can get S-shape interaction from two winds with nearly equal momentum. Second, a question: in the two systems with similar parameters and eccentricities but different phase behaviour in light curve, isn't the deviation of the semi-major axis to the line of sight also a key parameter that will affect, e.g. the level of absorption at various phases?

G. Rauw - Comment: yes, we see the S-shaped interaction regions in these systems where the wind momentum ratio is pretty close to unity. Question: in principle, you are right, the inclination should play a role. However, in these two systems, the inclinations are not substantially different (one has i near $35°$ to $40°$, the other probably has $\sim 55°$). So, I don't believe inclination can actually account for all the differences that we do see.

J. Pittard - The problem that you mentioned about getting synchrotron emission at the systems where the optical depths unity surface is larger than the size of the orbit is maybe not so much of a problem. For instance, within the WCR the gas is hot and hence the free-free absorption is low, so if the line of sight is largely through the WCR the synchrotron emission should escape.

G. Rauw - That's true, but for the system Cyg OB2 #8a the orbital inclination is not $90°$ – it is $\sim 35°$ - which means that it is not so obvious that the line of sight is ever directly crossing the WCR, so it may still be hard for the synchrotron emission to get out to the observer.

N. Smith - Just a clarification: what's the orientation in your image of η Car? – because WR 25 should be to the west and a little south – not down to the left.

G. Rauw - The image is shown in Galactic coordinates. Latitude increases to the top and longitude to the right.