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X-raying the wind interactions of massive binaries

What we have learned from 25 years of observations

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Abstract. The collision of radiatively-driven stellar winds in massive binary systems should produce a strong X-ray emission. This emission is expected to display a phase-locked modulation due to a changing orbital separation (in eccentric systems) and/or a changing optical depth along our line of sight towards the wind interaction region. The current generation of X-ray satellites allowed the study of a number of massive binaries. They notably demonstrated that not all O + O binaries are X-ray bright and that some systems display rather complex orbital variations. In this contribution, we highlight the properties of a few systems that were recently studied with *XMM-Newton*.

Key words: stars: early-type – stars: winds – X-rays: stars

1. Introduction

Hot, massive stars of spectral-type O have energetic stellar winds that are driven by their huge radiation pressure (Vink, 2022). These winds associate considerable mass-loss rates of order $10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$ and large velocities of several $1000\,\mathrm{km\,s^{-1}}$. Because the majority of these O-type stars reside in binary or higher multiplicity systems (Sana et al., 2012), the stellar winds of the stars in those systems are bound to interact with each other. When the winds collide, their huge kinetic energy is transformed into heat leading to post-shock plasma temperatures of millions of K (Stevens et al., 1992). The collision of stellar winds in O + O binary systems should thus produce a hot plasma emitting copious X-rays, and these systems should exhibit X-ray over-luminosities compared to single O-type stars. Owing to the orbital motion of the stars, the observable X-ray emission is further expected to be modulated by the variations of the orbital separation (in eccentric systems) and/or the changing optical depth along our line of sight towards the wind interaction region (Pittard & Parkin, 2010).

The actual emission and its variability depend on the efficiency of cooling processes via radiative recombination and inverse Compton scattering (Stevens et al., 1992; Pittard, 2009; Mackey et al., 2023). These cooling processes are usually rather efficient in the wind interaction zones of close, short-period binaries and this should lead to strong hydrodynamic instabilities that reduce the X-ray emission of the wind interaction zone (Kee et al., 2014). On the contrary, wide, long-period binaries often feature an adiabatic wind interaction zone which should be more stable and is expected to display an X-ray emission that varies as $1/r$ where r is the instantaneous orbital separation between the binary components (Stevens et al., 1992). Whilst some prominent colliding wind binaries host Wolf-Rayet stars (e.g., WR 140, V 444 Cyg) the focus of the present contribution is on O + O binary systems.

2. The X-ray emission of massive binaries

The X-ray emission of massive stars was serendipitously discovered with the *EINSTEIN* satellite in the late 1970s (Harnden et al., 1979; Seward et al., 1979). Many of the brighter sources found among the O-type stars in these early observations were indeed binaries (Chlebowski, 1989). The *EINSTEIN* data already unveiled the existence of a simple scaling relation between the X-ray and bolometric luminosities of O-type stars ($L_X/L_{bol} \sim 10^{-7}$), and this relation was confirmed and refined by observations with subsequent satellites such as *ROSAT* and most recently *Chandra* and *XMM-Newton* (Berghoefer et al., 1997; Nazé, 2009). Over the last two and a half decades, the current generation of X-ray satellites shed new light on the X-ray properties of massive stars in general and massive binaries in particular (for reviews see e.g., Rauw & Nazé, 2016; Rauw, 2022, and references therein). The emerging global picture of colliding wind systems is more complicated than anticipated: whilst some emblematic systems are indeed bright and variable X-ray emitters, not all O+O binaries display a strong X-ray emission. Indeed, observations of large samples of O-type stars showed no strong difference in L_X/L_{bol} between known binaries and presumably single O-type stars (e.g., Nazé, 2009; Rauw et al., 2015). As it turns out, X-ray over-luminosity of massive binaries is more the exception rather than the rule!

In long-period eccentric systems, this situation could partially result from a selection effect. To illustrate this, we consider the system HD 168112 (O4.5IV((f)) + O5.5V(n)((f)) which has an orbital period of 514 d and an eccentricity $e = 0.75$ Blomme et al. (2024). The X-ray emission of this systems displays a well-defined $1/r$ variation as expected for an adiabatic wind-wind collision (Rauw et al., 2024a). However, if we consider that a system would be classified as overluminous if its X-ray luminosity exceeds the canonical $L_X/L_{bol} \sim 10^{-7}$ by at least a factor of two, then HD 168112 meets this criterion only during about 10% of its orbital period, when the stars are close to periastron. Over the rest of the orbit, the emission is fully consistent with the level expected without any colliding wind contribution. Therefore, a single snapshot X-ray observation of such a long period eccentric system could easily miss the detection of the emission from the wind interaction zone if it would not be taken at times close to periastron.

Some eccentric colliding wind systems display hysteresis-like variations in their X-ray flux instead of the simple $1/r$ relation. This phenomenon is observed in systems with relatively short orbital periods such as HD 166734 (O7.5If + O9I(f), $P = 34.5$ d, $e = 0.62$, Nazé et al., 2017) and Cyg OB2 #8a (O6I + O5.5III, $P = 21.9$ d, $e = 0.18$, Mossoux et al., 2020). For a same value of r, these systems display a stronger emission at the phase before periastron than at the symmetric phase after periastron. In those binaries, the cooling regime probably changes from essentially adiabatic around apastron to radiative near periastron. The instabilities that occur in the radiative wind interaction zone around periastron could then lead to a collapse of the shock onto the star with the weaker wind (Nazé et al., 2017). This situation can even result in accretion of clumps of wind material onto the star with the weaker wind (Kashi, 2020). For instance, in the case of HD 166734, Kashi (2020) estimated that about $1.3 \times 10^{-8}\,M_{\odot}$ would be accreted at each orbital cycle. Once the stars move again away from each other the wind-wind interaction takes some time to rebuild, thus explaining the hysteresis behaviour.

However, not all short-period eccentric O+O systems follow the above description. For instance, HD 93205 (O3V + O8V, $P = 6.08$ d, $e = 0.37$, Morrell et al., 2001) displays a very different X-ray light curve (Fig. 1) when the data from twenty years of *XMM-Newton* observations are folded with the ephemerides of Morrell et al. (2001). Indeed, in this system, the strongest X-ray emission is observed after periastron. Whilst this could hint at a different origin for the X-ray variations, we stress that the ephemeris of this system need revision. Indeed, Morrell et al. (2001) diagnosed a rather significant apsidal motion at a rate of $1.95°\,yr^{-1}$ and this secular precession of the orbit could impact our interpretation of the X-ray light curve of this system.

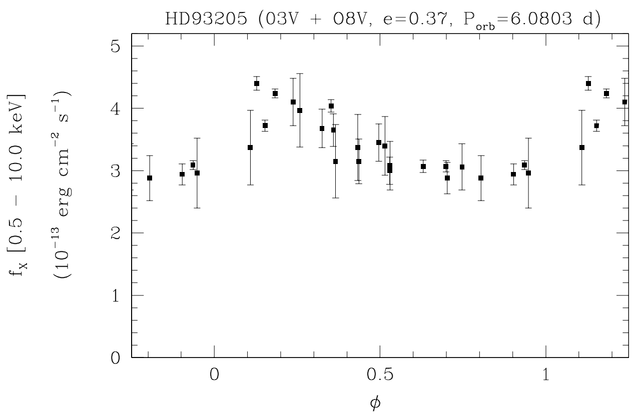

Figure 1. Variations of the observed X-ray flux of HD 93205 as a function of orbital phase according to the ephemerides of Morrell et al. (2001).

X-ray spectral variations in systems with circular orbits can be used to probe the properties of the stellar winds. For instance, in the case of HDE 228766 (Of^+/WN8ha + O7III-I, P = 10.7 d, Rauw et al., 2014), X-ray observations performed at both conjunction phases and one quadrature phase were used to investigate the variations of the X-ray flux as a function of energy. The observation with the Of^+/WN8ha star in front displayed a heavily attenuated X-ray spectrum, especially at low energies. The observed energy dependence of this attenuation was found to be in excellent agreement with the theoretically expected energy dependence of the opacity of the wind of this star. A significantly more complicated situation was found for HD 149404 (O7.5I(f) + ON9.7, P = 9.8 d, Rauw et al., 2024b). The variations of the X-ray emission between the conjunction phases with either the O7.5I(f) or the ON9.7 star in front have a lower amplitude and are grey as they do not display any significant energy dependence. The only way to explain this situation is to assume that these variations are dominated by occultation rather than absorption effects. Occultation can come from the stellar bodies, but given the low orbital inclination ($\leq 31^\circ$) such a scenario seems rather unlikely. An alternative could be that the winds of the stars would consist of optically thick clumps. Indeed, in such a case, the ensuing attenuation of the X-ray emission would depend on the geometrical cross section of the clumps and not on their opacity.

3. Conclusions and future perspectives

The X-ray data on O+O binaries that were collected with *XMM-Newton* and *Chandra* considerably changed our understanding of wind-wind collisions. Among the most important findings, we can cite

- the fact that the majority of these binaries are not X-ray overluminous,
- the fact that wide eccentric systems with adiabatic wind interactions follow a $1/r$ X-ray flux dependence as predicted by theory,
- the fact that the wind interaction zones in shorter period eccentric systems switch between adiabatic and radiative regimes, possibly with accretion at periastron,
- the possibility that optically-thick clumps could be responsible for the grey flux attenuation seen in some systems, whilst others display instead a strongly energy dependent wind opacity as expected for photoelectric absorption by a stellar wind.

More detailed studies become possible, notably thanks to JAXA's *XRISM* mission and its high-resolution spectrograph *Resolve*. Whilst they will focus on a few bright sources, more targets will become accessible thanks to ESA's next X-ray observatory *Athena*. Indeed, some colliding wind binaries exhibit a strong

Fe XXV line at an energy of 6.7 keV. The formation of this line requires temperatures that are only reached in the plasma of the wind-wind collision and not in the winds of single massive stars. This line thus offers an excellent diagnostics of the physical conditions of the shocked plasma (Mossoux & Rauw, 2021). These binaries will be ideal targets for high-resolution X-ray spectroscopy with the *X-IFU* microcalorimeter spectrograph onboard *Athena* (Barret et al., 2023).

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