Wolf-Rayet Stars
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Studies of WR+O colliding-wind binaries

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Two of the main physical parameters that govern the massive star evolution, the mass and the mass-loss rate, are still poorly determined from the observational point of view. Only binary systems could provide well constrained masses and colliding-wind binaries could bring some constraints on the mass-loss rate. Therefore, colliding-wind binaries turn out to be very promising objects. In this framework, we present detailed studies of basic observational data obtained with the *XMM-Newton* facility and combined with ground-based observations and other data. We expose the results for two particularly interesting WR+O colliding-wind binaries: WR 22 and WR 21a.

1 Introduction

Massive stars (OBs and their descendants WR stars) are very important objects that play a major role in the chemical evolution of galaxies, but also in the dynamical evolution through their influence, positive or negative, on star formation and through the shaping of their environment. Despite this importance, several aspects of their live remain poorly known. Two of the main parameters that govern their evolution, the mass and the mass-loss rate, are still poorly determined from the observational point of view. A good observational determination of masses can only be obtained through the study of binary systems. In massive systems, the winds of both components do collide somewhere in-between the two stars. This collision zone, at least near its apex, is then emitting in the X-ray domain. The shape of the collision zone is dependent on the relative importance of individual winds, possibly providing constraints on the relative mass-loss rates. The X-ray flux characteristics are dependent on the wind and their variations along the orbital cycle bear also information on the individual mass-loss rates. Therefore WR+O and O+O colliding-wind binaries are key objects to constrain evolution of massive stars.

From the formation point of view, the origin and the nature of the most massive stars are also poorly known. In the quest of young massive stars, some astronomers are studying the O2 and O3 stars. However, some people think that, very early, the very massive stars appear as disguised in hydrogen-rich, late WN stars even if they are still in the core-hydrogen-burning evolutionary status. These stars of spectral type WNLh are now recognized as key objects to understand the beginning of the evolution of massive stars. Some of these objects are also belonging to binary systems. In the following, we will illustrate the potentialities of the WNLh+O systems by reporting some results of the study of two of them: WR 22 that we observed and studied some time ago and WR 21a which in some sense is a newcomer in the game.

2 The case of WR 22

WR 22 is a WN7h+O binary star with a period of 80.33 days. Actually, this star has been the first discovered WR+O binary system where the mass of the WR turned out to be strongly in excess of the O one (Rauw et al. 1996). Concomitantly, this primary WNLh star was recognized as strongly massive with a keplerian mass somewhere between 56 and 72 $M_\odot$ (Rauw et al. 1996; Schweickhardt et al. 1999). If at 72 $M_\odot$, the star is most probably not a pure WR but rather a core-H burning object (Rauw et al. 1995, and references therein). WR 22 has been observed with the *XMM-Newton* facility and its X-ray lightcurve tentatively interpreted (Gosset et al. 2009). This lightcurve presents no variation in the hard band, whereas some variable absorption is detected in the soft and middle band. Indeed, the system is eccentric and roughly seen from the apastron side. When the O star goes from apastron to periastron, it is going deeper and deeper into the WR wind. Therefore, the two possible X-ray sources (the O star itself and the collision apex situated very close to the O star on the main axis of the binary) are also diving into the WR wind. Thus, the X-ray emission should be more and more absorbed, which seems to be the case. This configuration offers the possibility to perform some scanning of the WR wind structure.

In the following, we will restrict ourselves to the problem of the mass-loss rate of the WR star that can be deduced from the absorbing column. Assuming a classical velocity law for the wind, it is possible to express the density in the wind as a function of the distance to the WR. The various intervening parameters are the velocity law, the radius of the WR and the mass-loss rate. The last one is the most important one. The absorbing column can be estimated by integrating, along the line of sight from the observer to the X-ray emission zone, the density being estimated at each step as a function of the distance to the WR. Gosset et al. (2009) performed the work and concluded that the adopted mass-loss rate was a factor of two too large to explain the observed soft X-ray absorption. These conclusions could result from a too simple model used by Gosset et al. (2009). However, a more sophisticated model based

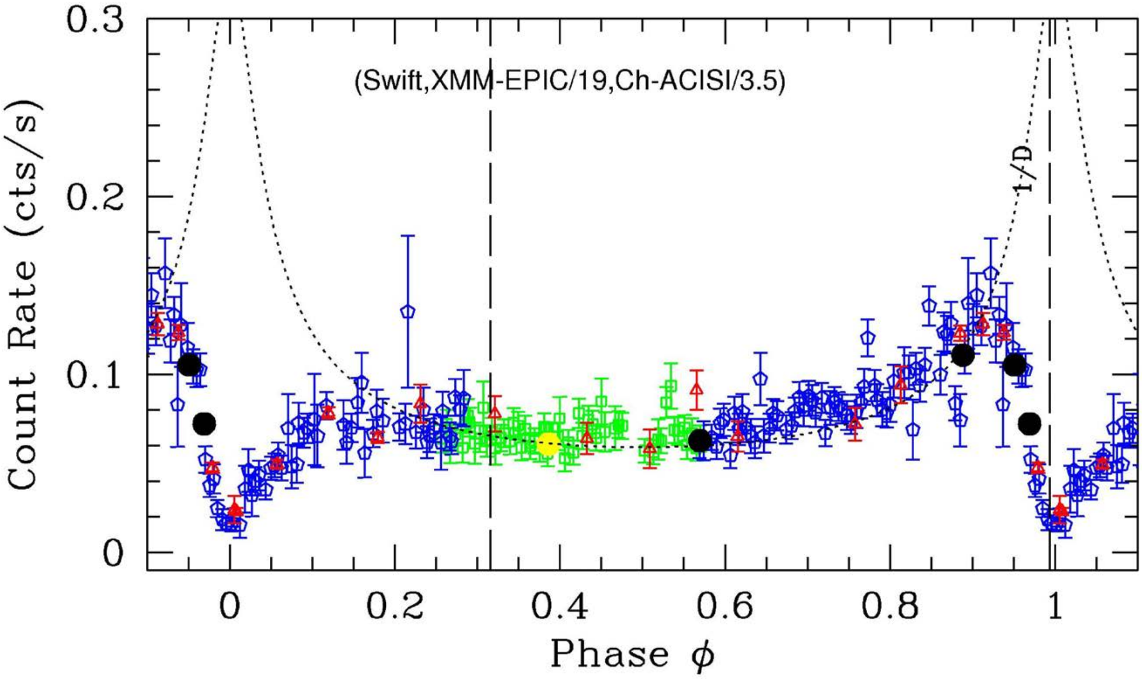

Fig. 1: The X-ray lightcurve of the massive binary system WR 21a presented under the form of count rates as a function of the binary phase. Periastron is at phase 0.0. The filled black circles represent the *XMM-Newton* count rates (divided by 19) whereas the yellow filled circle is from *Chandra* count rates (divided by 3.5). The *Swift* ones are plotted as red triangles for the year 2013, as green squares for the year 2014 and as blue pentagons for 2015. The error-bars represent 1σ standard deviation. The vertical dashed lines mark the position of both conjunctions. The dotted curve is illustrative and represents the canonical $1/D$ evolution of the count rates (see text for details).

on 3D hydrodynamical simulations, arrived from this point of view to similar conclusions (Parkin & Gosset 2011). Two problems occur: the models predict a too large X-ray emission and a too large absorbing column (about a factor of two).

At the time of these works, we supposed that the WN itself was not emitting in the X-ray domain, leading to a lower limit constraint on the fitted mass-loss rate. In addition, since then, WR 22 was observed by the *Chandra* facility in the framework of the CCCP project (Townsley et al. 2011). Within the *XMM-Newton* point spread function, there is actually three sources. The two additional ones were responsible for one fifth of the flux. Therefore, the conclusions needed critical revision.

The *Chandra* observation took place at phase 0.85. We estimated the expected fluxes of WR 22 at that phase from our *XMM-Newton* data. We computed 20% of that flux and attributed this value to the two neighbouring objects. We considered that this contribution is constant and performed again all the fits. The column densities deduced in this way are not strongly different from the previously published ones. A marked exception concerns the spectrum at phase 0.994. In this case, an increase of the column density by 60% is noticed, reaching even 100% if the constant emission component is softer. We also attempted to consider an emission from the WN component of maximum 0.59×10^{-13} erg cm^{-2} s^{-1} (Gosset et al. 2009). In principle, the maximum flux limit could be ten times lower. An increase of the column density is also observed but never markedly exceeding the predicted column (see Fig. 10 of Gosset et al. 2009). Again this does not apply to the observations at phase 0.994 which is impossible to fit properly. We can conclude that the presence of the two neighbouring objects and the possibility to attribute some constant flux to the WN component (the possible WN intrinsic emission does not vary along the orbital cycle), lead to a possible increase of the column densities derived from the fit of the *XMM-Newton* data, by a factor of two but no more. No further information can be extracted from the low S/N spectrum at phase 0.994. Therefore, we can conclude that the derived column density could be in agreement with the physical parameters adopted by Gosset et al. (2009) provided we accept to attribute some emission to the WN component.

3 The new case of WR 21a

In the same context, another very interesting object is WR 21a. The study presented here results from a collaborative work with Y. Nazé; all the details can be found in the related publication (Gosset & Nazé 2015). The object was spectroscopically studied by Niemela et al. (2008) and more recently by Tramper et al. (2015). WR 21a is a WN5h+O3V binary system with an eccentricity $e = 0.693$, and bearing minimum masses of 65.3 and 36.6 $M_\odot$, respectively. If the minimum mass of the O star is scaled to the expected mass for an O3V one, the mass associated to the WN5h object could easily reach 80–100 $M_\odot$ or more. The system is oriented, compared to the observer, in roughly the same manner than WR 22; its inclination based on the minimum masses should be around 58°.8. This system has originally been detected as an X-ray source. Therefore, we decided to observe it with the *XMM-Newton* facility. Four 30 ks exposures took place at phases $\phi = 0.57$, 0.89, 0.95 and 0.97. The resulting spectra can be fitted by a two-component optically-thin thermal plasma emission with $kT = 0.8$ keV and 3.0 keV. These temperatures do not seem to vary over the orbital cycle except for a small marginal decrease while going to periastron. Concerning the X-ray lightcurve, we complemented our data with archival *Swift* and *Chandra* data (see also Sugawara et al. 2015). Fig. 1 presents the evolution of the count rates in the total band (0.4–10.0 keV) as a function of the orbital phase. From phase 0.2 to phase 0.8, the curve is not varying too much but from phase 0.8 to 0.9, an increase of the flux is clearly present. This corresponds to a behaviour in $1/D$ (where D is the binary separation). This behaviour is typical of eccentric systems where the nearing of the system is accompanied by a proportional increase of the flux if the postshock material is behaving adiabatically. This behaviour is unexpected for WR 21a. When approaching the conjunction ($\phi = 0.9935$) and periastron, the flux starts to decrease. The behaviour of the hard band is slightly different from the one of the soft band. This renders the various fits less trustable than in the case of WR 22. Apparently, a more important absorbing column density (expected near conjunction) is able to explain the decrease in the soft band, but not the entire variation in the hard band. Most probably, a disruption of the shock or a crash of it on the O surface are possible explanations. The recovery of the decrease is not so rapid and the lightcurve seems to exhibit a marked hysteresis effect. The full recovery occurs at $\phi = 0.2$ only. It is also interesting to notice that there is no particular variation around $\phi = 0.346$ that corresponds to the other conjunction. A preliminary estimation of the mass-loss rate of the WN5h star leads to a value similar to the one first adopted for WR 22.

4 Conclusion

We presented detailed studies of two very interesting binary systems. These systems are composed of a primary star of type WNLh and of an O component. The WNLh stars are particularly massive as securely determined from the binarity and keplerian laws. Such systems also harbour a collision of the wind that provides further information on them and particularly on the relative mass-loss rates. The orbital movement of these eccentric systems offers the possibility to scan the envelope of the WR component while the O star is diving in it. Such studies should help us to understand the origin and the true nature of these extreme stars and to provide constraints on their evolution.

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Götz Gräfener: Your results for WR 22 seem to agree very well with hydrodynamic models by Gräfener & Hamann (2008).

Eric Gosset: Really? I do not know this paper. I guess you are speaking of hydrodynamic models for the wind of the WNLh component alone. The agreement between our observations and your predictions indicates that we are on the verge of getting accurate values for the mass-loss rates of this kind of star