Wolf-Rayet Stars
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X-ray emission from single WR stars

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In this review I briefly summarize our knowledge of the X-ray emission from single WN, WC, and WO stars. These stars have relatively modest X-ray luminosities, typically not exceeding $1\,L_\odot$. The analysis of X-ray spectra usually reveals thermal plasma with temperatures reaching a few $\times 10$ MK. X-ray variability is detected in some WN stars. At present we don't fully understand how X-ray radiation in produced in WR stars, albeit there are some promising research avenues, such as the presence of CIRs in the winds of some stars. To fully understand WR stars we need to unravel mechanisms of X-ray production in their winds.

1 X-rays from WR stars: history

The discovery of X-ray emission from WR-stars was among the first results achieved by the *Einstein* X-ray observatory (Seward et al. 1979). This confirmed the theoretical prediction that WR stars, specifically WR binaries, are X-ray sources (Cherepashchuk 1976). Pollock (1987b) summarized the *Einstein* observations of WR stars and outlined their key X-ray properties. From the analysis of the observations it was concluded that (*i*) the X-ray brightest WR stars are often massive binaries; (*ii*) single WR stars are usually faint; (*iii*) the WN stars are on average more X-ray bright than WC stars. These conclusions remains valid today.

The *Rosat* X-ray telescope performed an all sky survey. Besides increasing the number of detected WR stars, it also obtained X-ray spectra and light curves for some key targets (e.g. Willis & Stevens 1996). A preliminary X-ray catalog of WR stars was presented by Pollock et al. (1995). For single WR stars no correlation between X-ray luminosity and their bolometric luminosity or wind momentum was found (Wessolowski 1996). This result was later on confirmed by the detailed studies (Ignace & Oskinova 1999; Ignace et al. 2000).

The ASCA X-ray telescope observed four WR stars in great details, yielding X-ray spectra and light-curves. Monitoring of massive binaries revealed the unambiguous evidence that the X-rays are produced in the wind-wind collision zone (e.g. Stevens et al. 1996). Other X-ray observatories, such as EXOSAT, also contributed to the studies of X-rays from WR-type stars (e.g. Williams et al. 1987).

Today, a fleet of X-ray telescopes operating in space routinely observes WR stars. Modern X-ray telescopes have broad pass-bands and significantly improved sensitivity, spectral and spatial resolution. Among these telescopes, *Chandra* and *XMM-Newton* have unprecedented capabilities allowing in depth studies of the formation and propagation of X-rays in WR stars. The future also looks bright in X-rays with new missions such as Spektrum-Röntgen-Gamma (SRG), Astro-H, and Athena being under development.

2 General properties of X-rays from WR stars

Luminosity. The lack of correlation between X-ray and bolometric luminosity of WR stars is in a strong contrast to O-type stars. The X-ray luminosities of the latter are $L_\mathrm{X} \approx 10^{-7} L_\mathrm{bol}$ (Pallavicini et al. 1981). This correlation holds for single as well as for binary O stars (Oskinova 2005; Nazé 2009). The origin of this correlation in O stars is not yet understood and might be related to the properties of shocks or to magnetic effects (Oskinova et al. 2011; Owocki et al. 2013). As can be seen in Fig. 1, the X-ray luminosities of WN-type stars are diverse. While WN binaries seem to show a trend similar to the O+OB binaries, the putatively single WN stars have X-ray luminosities that differ by orders of magnitude. Overall, the X-ray luminosities of WN stars do not significantly exceed $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$ with binaries being on average more X-ray bright.

Variability. The X-ray monitoring of WR stars revealed that single as well as binary stars are X-ray variable. The X-ray variability of binaries is on the orbital period time scale and is well documented, studied, and understood (among most recent papers, e.g. Pandey et al. 2014; Lomax et al. 2015; Zhekov & Skinner 2015). The sample of single WR stars that were monitored in X-rays is significantly smaller. Data of high fidelity exist so far only for WR6 (Ignace et al. 2013). This WN4 star shows X-ray variability on the level of 20% and with a characteristic period similar to the 3.766 day period well known from the optical (e.g. Morel et al. 1997), but is not in phase. This is quite similar to the X-ray variability observed in single O-type stars (e.g. Oskinova et al. 2001; Nazé et al. 2013). The origin of the X-ray variability is likely related to the presence of corotating interaction regions (CIRs) in the stellar winds (Chené et al. 2011; Massa et al. 2014).

Temperature. Already *Einstein* and *Rosat* observations revealed that X-ray spectra of WR stars can be described as thermal. In binaries, the ionization balance could be out of equilibrium and shocks could be collisionless (Pollock et al. 2005; Zhekov 2007). In single stars, the X-ray spectra were, so far, well reproduced by multi-temperature thermal plasmas in collisional equilibrium. Temperatures between 1 MK up to 50 MK are found from spectral analyses, with the emission measures of cooler plasma components being larger than that of hotter ones (the differential emission measure declines with temperature) (Skinner et al. 2002a,b, 2010; Ignace et al. 2003; Oskinova et al. 2012).

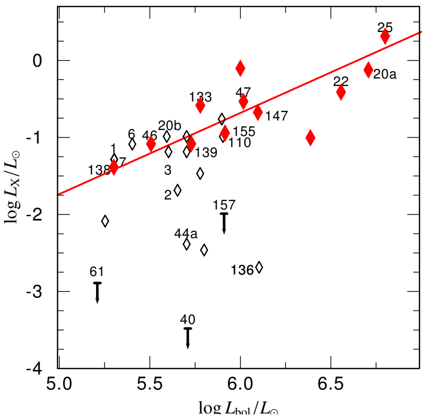

Fig. 1: L_X vs. L_{bol} for WN stars. Black empty diamonds denote single stars, while red filled diamonds denote binaries (Oskinova 2005; Gosset et al. 2005; Skinner et al. 2012; Zhekov 2012). The straight line shows the correlation for O-star binaries (Oskinova 2005).

3 X-ray production in WR stars

The present day sophisticated models are capable to describe and explain the X-ray emission from WR binaries (e.g. Stevens et al. 1992; Pittard & Dougherty 2006; Zhekov 2012; Parkin & Sim 2013; Rauw & Naze 2015). Albeit the exact physics is not yet fully understood, it is beyond reasonable doubt that the bulk of X-rays in the majority of WR binaries is produced in the wind-wind collisions zone.

The situation is very different for single WR stars. There are neither theories nor quantitative models explaining the production of X-rays in the winds of these stars, albeit there is no shortage of scenarios. Among them:

(i) X-ray emission in some "normal" WR stars could be due to the wind accretion on a compact object (White & Long 1986). Modern observations do not support this scenario. The observed X-ray properties of WR stars differ significantly from the X-ray emission of high-mass X-ray binaries. Only a few WR stars with relativistic companions are known, and their X-ray properties do not resemble those of single WR stars (Barnard et al. 2008).

(ii) The binarity idea was further examined by Skinner et al. (2002a) who suggested that a WR wind shocking onto a otherwise unseen close stellar companion could be responsible for the X-ray emission in at least some apparently single WR stars. There are a number of arguments questioning this scenario. For instance, new deep X-ray observations show no spectral signatures characteristic for low-mass stars. The X-ray variability patterns also do not support this scenario (Oskinova et al. 2012; Ignace et al. 2013).

(iii) Particle acceleration in shocks. According to this scenario, a population of relativistic electrons accelerated in the wind shocks is responsible for the generation of X- and γ-rays via inverse Compton scattering (e.g. Pollock 1987a). It seems that this mechanism may indeed operate in colliding wind binaries, however no observational evidence in its support was so far found in single WR stars.

(iv) If a strong dipolar magnetic field is present, it may confine stellar winds and lead to strong shocks at the magnetic equator (Babel & Montmerle 1997). Albeit this mechanism is sometimes considered in the literature to explain the X-ray emission from WR stars, no strong magnetic fields capable to confine powerful WR-winds were detected so far (de la Chevrotière et al. 2014, Hubrig et al. 2016, in press). Nevertheless, even if the wind confinement model does not explain X-rays from WR stars, the role of magnetism for the X-ray generation cannot be ruled out. E.g. a strong magnetic field was suspected in a few peculiar WR stars, such as WR2 (Shenar et al. 2014), but their X-ray properties are not outstanding (Oskinova 2005; Skinner et al. 2010).

(v) Shock heating due to line-driven wind instabilities (LDI) is often invoked to explain X-ray emission from OB-type stars (Feldmeier et al. 1997). Gayley & Owocki (1995) showed that multiple scattering in dense WR winds reduces this instability. However, the residual instability may still lead to clumping of WR winds. These authors did not address X-ray emission from WR stars, i.e. they did not show that the instability in WR winds is sufficient to drive strong shocks where the plasma can be heated to a few MK. Yet, it is tempting to draw parallels between WR and OB supergiant X-ray production mechanisms (Gayley 2016, submitted).

(vi) Gayley (2012) hypothesized that the fast wind may ram into the slow moving clumps, whose signatures are observed as moving bumps on top of lines observed in optical WR spectra (Lépine & Moffat 1999). Plasma could be heated in the resulting shocks. This is an interesting scenario that shall be tested by detailed modeling and observations.

(vii) Observations confirm that corotating interaction regions (CIRs) are present in WR winds (Chené & St-Louis 2011). Their origin is not fully understood but may be related to the presence of surface magnetic fields (Michaux et al. 2014). Mullan (1984); Chené et al. (2011) and Ignace et al. (2013) invoked CIRs to explain the X-ray generation in WR winds. The detailed hydrodynamic models of the CIRs in OB winds (Cranmer & Owocki 1996; Lobel

& Blomme 2008) are so far isothermal, so it remains to be seen whether CIRs can be the origin of X-rays from OB star winds. For the WR winds, to our knowledge, no hydrodynamic modeling of CIRs was performed so far. Yet it seems that the CIR scenario is the most promising one to explain the X-ray emission it least in some rotating single WR stars.

4 Propagation of X-rays

The combination of large column densities and high metal abundance makes WR winds very opaque for X-rays (e.g. Ignace & Oskinova 1999). Figure 2 demonstrates that WR winds may remain optically thick for X-rays up to a few $\times 1000\, R_*$. Wind clumping allows X-rays to emerge from somewhat deeper wind layers due to the porosity effects (Shaviv 2000; Feldmeier et al. 2003; Oskinova et al. 2004).

The X-ray field can be included in non-LTE stellar atmosphere models, such a PoWR (Baum et al. 1992) allowing to consistently solve the X-ray transfer in WR winds. This has important implications for applying X-ray spectral diagnostics, such as the widely used ratios of forbidden to intercombination lines in the X-ray spectra of He-like ions (Leutenegger et al. 2006; Waldron & Cassinelli 2007, Huenemoerder et al. 2016, in press).

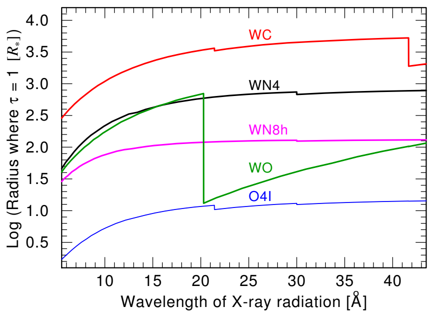

Fig. 2: Radius where the continuum optical depth reaches unity, as predicted by PoWR models for the "cool" wind component in different WR stars and an O-supergiant, in dependence on wavelength.

5 X-rays from WNE stars

Hydrogen free early-type WN stars (WNEs) occupy a distinct region in the HRD and have rather similar stellar parameters (Hamann et al. 2006). It appears that the X-ray properties of WNEs are also similar. The rate of X-ray detections of WNE stars is quite high – all stars that were observed so far with pointing observations were detected. Those WNE stars have similar X-ray luminosities ($L_X \approx 2 \ldots 6 \times 10^{32}\,\mathrm{erg\,s^{-1}}$). Their X-ray temperatures are also similar, with the emission measure weighted average temperature of $\langle T \rangle \approx 5\,\mathrm{MK}$. The parameter R_t (see its definition and discussion in Hamann et al. 2006, or in these Proceedings) is used to characterize the emission measure of WR winds. Figure 3 shows an interesting trend between the X-ray luminosity of WNE stars and their R_t. The presence of such trend implies that the generations of X-rays is an intrinsic property of stellar winds.

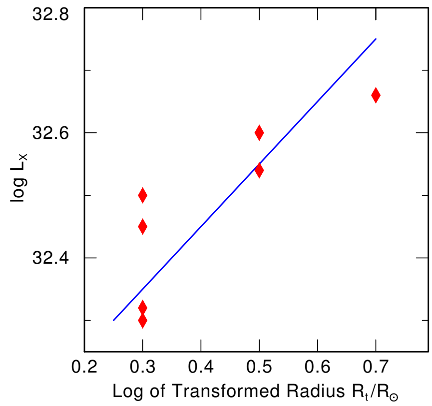

Fig. 3: X-ray luminosity versus transformed radius R_t for a sample of WNE stars (red diamonds). The values are from Skinner et al. (2002a,b, 2010); Ignace et al. (2003); Oskinova (2005); Hamann et al. (2006). The straight blue line shows a linear regression fit.

A high-resolution X-ray spectrum is available, so far, for only one single WR star, WR6 (WN4) (see also D. Huenemoerder, these proceedings). Its spectra were obtained by both *XMM-Newton* (Oskinova et al. 2012) and *Chandra* (Huenemoerder et al. 2016, submitted). The abundances in X-ray emitting plasma are consistent with WNE abundances, e.g. no oxygen lines are detectable. This provides a strong argument against a non-degenerate binary component scenario. The X-ray lines are broad, blue-shifted, and have a characteristic shape as expected when the radiation forms in outer wind and suffers strong continuum absorption (Macfarlane et al. 1991; Ignace 2001). The analysis of line ratios in He-like ions confirms that the radiation is formed far out in the wind. Even the hottest plasma is formed at more than tens stellar radii. The spectral analysis reveals that X-ray emitting gas must be present even at $> 1000\, R_*$. Such very extended spatial distribution is very difficult to reconcile with the predictions of the LDI models developed for O stars. Interestingly, there are indications that the fluorescent Fe Kα line is present in the X-ray spectrum. This indicates that dense and cool matter coexists with the hot plasma.

6 X-rays from WNL stars

Late type WN stars (WNLs) have on average higher bolometric luminosities and slower winds than WNE stars (e.g. Sanders et al. 1985). Some WNLs may be descendants of more massive progenitors than WNEs, while others may be on earlier evolutionary stage (Crowther et al. 1995; Hamann et al. 2006). Gosset et al. (2005) obtained deep *XMM-Newton* observations of WR40 (WN8h) and its nebula, but neither was detected in X-rays. The wind of WR40 is more transparent for X-rays than the wind of WR1 (WN4) (see corresponding curves in Fig. 2), yet the later is > 100 times more X-ray luminous than the former. On the other hand, the WN9h star WR79a was detected with $L_\mathrm{X} \approx 10^{32}\,\mathrm{erg\,s^{-1}}$ (Oskinova 2005). Its low resolution X-ray spectrum bears similarities with spectra of WNEs, i.e. a relatively high-temperature component ($T \sim 30\,\mathrm{MK}$) is present (Skinner et al. 2012). Other WNLs well observed in X-rays are WR78 (WR7h) ($L_\mathrm{X} \approx 10^{31}\,\mathrm{erg\,s^{-1}}$ Pollock et al. 1995; Wessolowski 1996; Oskinova 2005, note that Skinner et al. (2012) report an order of magnitude higher luminosity for this object) and WR136 (WN6(h)) ($L_\mathrm{X} \approx 10^{31}\,\mathrm{erg\,s^{-1}}$, Wrigge et al. 1994; Pollock et al. 1995; Ignace et al. 2000). Thus, while some WNLs are not detected in X-rays, others appear to be relatively X-ray luminous.

7 X-rays from WC and WO stars

Rauw et al. (2015) discovered X-rays from the WC4 star WR144, making it the first single WC star detected in X-rays. Its low X-ray luminosity ($L_\mathrm{X} \approx 10^{30}\,\mathrm{erg\,s^{-1}}$) corroborates Oskinova et al. (2003)'s conclusion that WC stars are intrinsically X-ray faint, likely because of the high opacity of their stellar winds (see Fig. 2). On the other hand, known WC binaries are bright X-ray sources (e.g. Schild et al. 2004; Pollock et al. 2005; Zhekov et al. 2011). Hence, X-rays provide a convenient indication of binarity: X-ray bright WC stars should be colliding wind binaries. This makes X-rays observations a very useful diagnostic tool to search for binaries among WC populations (Clark et al. 2008; Oskinova & Hamann 2008; Hyodo et al. 2008; Mauerhan et al. 2011; Nebot Gómez-Morán et al. 2015).

WO stars represent a very advanced evolutionary stage of massive stars shortly before their supernova explosion. The WO winds are the fastest among all non-degenerate stars (Sander et al. 2012; Tramper et al. 2015). Their wind opacity for X-rays is less than that in WC stars (see Fig. 2), therefore X-rays may reach an observer. Oskinova et al. (2009) reported the first discovery of X-ray emission from this important type of objects. They detected the WO2 star WR142 using *XMM-Newton*. This X-ray source identification was confirmed with *Chandra*'s superb angular resolution (Sokal et al. 2010). The X-ray luminosity of WR142 is not very high ($L_\mathrm{X} \approx 10^{31}\,\mathrm{erg\,s^{-1}}$), while its X-ray spectrum is quite hard (with $T_\mathrm{X} > 100\,\mathrm{MK}$). WO stars are basically bare stellar cores and might expose magnetic fields (Fuller et al. 2015). This and other scenarios were considered in Oskinova et al. (2009), while Sokal et al. (2010) suggested the possibility of inverse Compton scattering or a binary companion.

8 Summary

All types of single WR stars emit X-rays. Their X-ray luminosities are orders of magnitude lower than in persistent high-mass X-ray binaries. The X-ray spectra appear to be thermal, with very hot plasma of a few$\times$10 MK being present along with cooler components. The mechanisms responsible for X-ray generation are not yet understood. Promising scenarios include an LDI-like mechanisms, interactions of wind streams with blobs, and CIRs. New observations and modeling shall uncover how X-rays are generated in winds of single WR stars.

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Tomer Shenar: Is it possible to observe indirect "products" of X-rays (e.g. O VI lines in O-star spectra) even if the X-ray emission itself cannot be observed (because it is fully absorbed in the wind)?

Lidia Oskinova: I would think that the answer is "yes". Perhaps we shall search in more detail the spectra of single WC stars for the signatures of 'over-ionization' that can be attributed to the X-rays that are produced but fully absorbed in the winds.

Andy Pollock: Does the conclusion that X-rays can be produced in situ far from the wind acceleration zone suggest that the same might happen in O stars?

Lidia Oskinova: Good question. From high-resolution X-ray spectroscopy of O-stars we have evidence that the bulk of X-ray emitting gas in these stars is produced very close to the stellar surface. Therefore, I would say, it looks quite likely that the mechanisms that produce X-rays in O and WR stars may be different.

Kenji Hamaguchi: Do X-ray light curves of WRs tend to show stochastic variations (such as flares) or cyclic (to the binary orbit)?

Lidia Oskinova: To my knowledge, single WR stars do not show stochastic X-ray variability on the observable level. But these stars show some X-ray variability on time-scale of days. It might be cyclic, but more data are needed to confirm it. WR-stars that are members of binary systems typically show cyclic X-ray variability associated with orbital motion.