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X-RAY FORMATION MECHANISMS IN MASSIVE BINARY SYSTEMS

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Abstract. Massive, hot, luminous stars of types O, early B and WR have strong supersonic radiatively driven winds. Both single and binary early-type stars are known X-ray emitters. According to current understanding of X-ray formation mechanisms in the winds of single and binary early-type massive stars, binaries should be harder and more luminous X-ray sources than single stars. However, recent observational studies with the X-ray satellites XMM-Newton and Chandra show that, *on average*, X-ray properties of single and binary early-type massive stars are not very different. I review the mechanisms of X-ray production in early- type stars with emphasis on binary systems and discuss a possible explanation to this discrepancy.

1. INTRODUCTION

Stars of spectral types O, early B, and Wolf-Rayet (WR) are usually referred to as early-type stars. These objects are massive ($\geq 10\,\mathrm{M}_\odot$) and hot ($T_{\rm eff} \simeq 30000 - -90000\,\mathrm{K}$). WR stars are believed to be the evolved stage of the evolution of massive O stars, their spectra show the presence of the products of nuclear burning of hydrogen (in the case of WN subclass) or helium (WC subclass). A very characteristic feature of early-type stars is the presence of strong supersonic winds (terminal flow velocities $v_\infty \sim 1000 - 3000\,\mathrm{km\,s^{-1}}$, mass loss rates $\dot{M} \sim 10^{-6} - 10^{-4}\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$). The winds are driven by the strong radiation field of central stars. The driving force is created by line absorption as was first proposed by Lucy and Solomon (1970) and further refined by Castor et al. (1975), Abbott and Lucy (1985) and others.

Early-type stars are also known X-ray emitters. Most of them show relatively soft thermal X-ray spectra. In several cases, however, the spectra are hard, and in a few cases non-thermal hard spectral tails above 10 keV are observed. X-ray luminosity of O stars scales with their bolometric luminosity as $L_{\rm X}/L_{\rm bol} \approx 10^{-7}$. WR stars do not show such a clear correlation. First X-ray surveys of early-type stars showed that O + O binary stars are systematically brighter that single O stars (see, e.g., Chlebowski & Garmany, 1991). However, recent observational studies with the X-ray satellites XMM-Newton and Chandra show that, *on average*, X-ray properties of single and binary early-type massive stars are not very different (see, e.g., Sana et al. 2006, Antokhin et al., 2008).

In the present paper, I discuss various mechanisms proposed to explain X-ray formation in early-type stars, with the emphasis on binary systems.

2. THERMAL AND NON-THERMAL EMISSION

Whether the X-ray emission from hot plasma is thermal or non-thermal, depends on the energy distribution of the electrons involved in the photon production. If the energy distribution is Maxwellian, the resulting spectrum is thermal. To produce a non-thermal X-ray spectrum, relativistic electrons distributed according to the power law are needed. In case such electrons are present, there are several mechanisms which are able to produce non-thermal emission. The first one is synchrotron radiation of relativistic electrons travelling in a magnetic field. This mechanism is unlikely to produce significant X-ray flux in the case of early-type stars as the magnetic fields in their winds are not strong enough for the moderately fast electrons to produce high energy photons. The second mechanism which probably provides most of the non-thermal flux of early-type stars is inverse Compton scattering. When an ultraviolet photon is scattered by a relativistic electron, part of the electron's energy may be transferred to the photon, thus "shifting" the photon from the UV to the X-ray domain. For more details on non-thermal processes in the winds of early-type stars see De Becker (2007).

Thus the central questions to the X-ray formation in the winds of early-type stars are (i) how very hot plasma (with temperatures of $\sim 10^6 - 10^7$ K) is formed, and (ii) how some electrons gain energy and reach relativistic velocities.

Historically, the first attempt to explain X-ray emission from early-type single stars involved a hot corona at the base of the stellar wind (e.g. Waldron, 1984). In this case one would expect a substantial absorption of the soft emission below 1 keV, due to large optical depth of stellar winds in this spectral range. However, observed spectra do not show such absorption. The currently standard model for X-ray emission is based on the phenomenological model proposed by Lucy & White (1980) and further elaborated by Lucy (1982). According to this model, hydrodynamic shocks are generated throughout a radiation driven stellar wind as the consequence of the intrinsic instabilities of radiative driving. The velocity jumps in such shocks heat the post-shock plasma to temperatures of a few million degrees. These shocks are distributed throughout the wind so that soft X-rays can escape the wind without substantial absorption. The energy distribution of most electrons in the post-shock plasma follows a Maxwell-Boltzmann law and the resulting spectra are thermal. For recent theoretical studies of such instabilities see, e.g. Owocki & Cohen (1999), and Dessart & Owocki (2005). High resolution spectra obtained with the X-ray observatories XMM-Newton and Chandra have confirmed the thermal origin of the bulk of the X-ray emission from early-type stars (e.g., Kahn et al., 2001).

In early-type binaries, the collision of the two stellar winds is expected to generate a strong X-ray-bright shock between the stars (see e.g. Stevens et al., 1992) and thus the X-ray luminosity of such binaries is expected to be significantly higher than that of single stars. Moreover, since the relative velocities of colliding winds can be much higher than the shock velocity jumps in winds of single stars, the post-shock plasma can be heated to very high temperatures. As a result, X-ray spectra of colliding wind early type binaries can be quite hard. In fact the hardness of the observed spectra of some early-type stars has been suggested as an indication of possible binarity. An

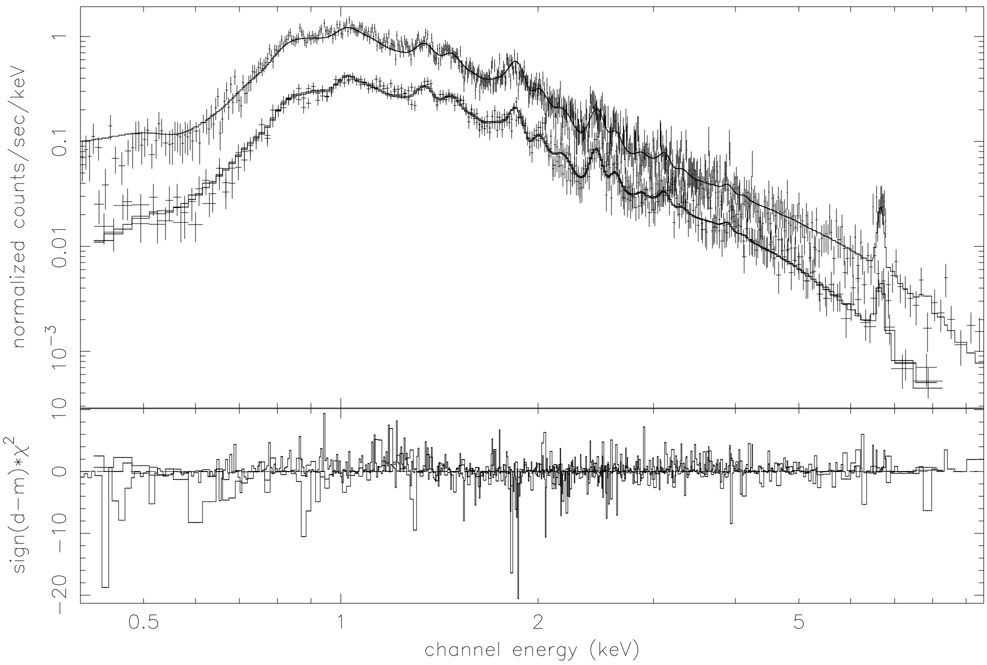

Figure 1: The XMM-Newton EPIC spectra of WR 25. Upper spectrum on the top plot is EPIC PN, bottom spectra are MOS1 and MOS2. Solid lines represent the best two-temperature thermal plasma model fit to the observed spectra. Note the presence of the Fe XXV–XXVI lines at ~ 6.7 keV indicative of high plasma temperature. The bottom plot shows the contribution of individual energy bins to the χ^2 of the fit.

example of such spectrum is shown in Fig.1. The star WR 25 (WN6ha) is a bright X-ray source. A fit of the XMM-Newton EPIC spectrum with the thermal plasma model (Raassen et al, 2003) revealed two components at 0.6 and 2.8 keV. A clear indication of the high plasma temperature is the presence in the spectrum of the Fe XXV–XXVI lines at ~ 6.7 keV. Still, for a long time, no traces of a companion were found in the optical data. Finally, inspired by the X-ray data, Gamen et al. (2006) collected an extensive set of optical spectroscopic data and showed that WR 25 is indeed a long period spectroscopic binary at an eccentric orbit.

One more way to produce high-temperature plasma in the wind of a single early-type star is through the so-called magnetic channeling. In this scenario, developed and elaborated in recent years (Owocki et al., 2005, Ud-Doula et al., 2008a, Ud-Doula et al., 2008b), the stellar wind outflowing from the northern and southern hemispheres of a star is channeled by a strong magnetic field of the star and the two flows collide at rather high relative velocity near the magnetic equator, forming a shock. This model was used to explain the hard X-ray emission of magnetic hot stars like Θ^1 Ori C.

In all mechanisms considered above hot plasma is produced in the post-shock layers of hydrodynamic shocks. It turnes out that production of relativistic electrons is also intimately related to the shocks in the winds of early-type stars. The scenario of electron acceleration was first proposed by Fermi (1949) and later developed and

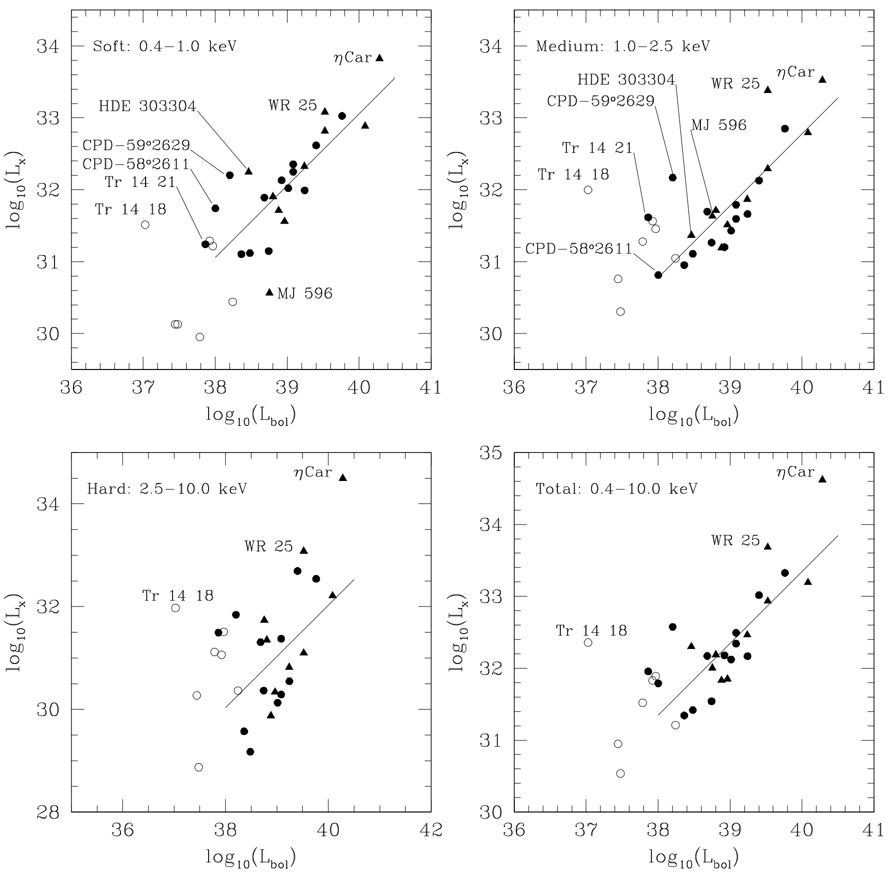

Figure 2: L_X versus L_bol for early-type stars in the Carina Nebula in different energy bands. Open circles – B-type stars; Filled circles - single O-type stars; Filled triangles – binary O-type stars. B-type stars, WR 25, and η Car are excluded from the least-square fits. From Antokhin et al. (2008).

refined by Blandford and Ostriker (1978) and Bell (1978a, 1978b). In the current version of this scenario, called "the first order Fermi mechanism", electrons crossing the shock front always experience head on collisions and thus always gain energy, in whatever direction they cross the shock. This is, however, not sufficient to make electrons relativistic. For that purpose, electrons must cross the shock several times, each time gaining small amount of energy. In other words, there must be some scattering mechanism which changes the electron trajectories in the upstream and downstream regions. Behind the shock, a mechanism which is likely at work is turbulent motions of the flow. On the other side of the shock, electrons may be scattered by magneto-hydrodynamic (Alfvén) waves. As a result, velocity distribution of electrons on both sides of the shock becomes isotropic which allows multiple crossing of the shock. The energy spectrum of the resulting relativistic electrons is the power low $N(E)\,\mathrm{d}E \propto E^{-2}\,\mathrm{d}E$.

This discussion shows the central role of hydrodynamic shocks in producing X-rays in early-type stars. One would expect that binary early-type stars would be systematically more luminous in X-rays (this should be true for both thermal and non-thermal components of their spectra), and that their spectra would be harder than those of single stars. However, recent studies of large samples of O stars with the latest generation of X-rays telescopes show that this is not the case. In Fig. 2, the results of such study for the Carina OB1 association with XMM-Newton from Antokhin et al. (2008) are shown.

The figure shows the intrinsic X-ray luminosity $L_{\rm X}$ versus $L_{\rm bol}$ for 25 early-type stars, in three energy bands as well as in the total XMM-Newton energy range. It is known from the literature (e.g. Sana et al. 2006) that O- and B-type stars show a different behaviour. For this reason they are marked with different symbols. Presumably single O-type stars are marked with solid circles, binary stars are plotted as solid triangles. B-type stars are marked with open circles. The demarkation line between two types of stars is located at about $10^{38}\,{\rm erg\,s^{-1}}$. Some stars in the sample have pecularities not related to their binary status, their names are shown in the plot. For more details, see Antokhin et al. (2008).

The X-ray and bolometric luminosities of O-type stars are clearly correlated in the soft and medium bands. In the hard band the scatter of the data is large and the correlation is doubtful, which is consistent with the results of Sana et al. (2006). The solid lines in Fig. 2 represent the least-square fits of the observed distributions of O-type stars (both binary and single). As seen from Fig. 2, there is no clear distinction between binary and single O-type stars in the $L_{\rm X}-L_{\rm bol}$ plane. The same result is obtained in Sana et al. (2006) for a sample of O stars in the young open cluster NGC 6231. Apart from two known binaries with large X-ray excess, all other O-type stars follow the same rather tight $L_{\rm X}-L_{\rm bol}$ relation.

These results show that, while some early-type binaries do show large X-ray luminosity excess and have hard spectra, many of them are neither particularly bright nor hard X-ray sources. What could be the reasons for this? One simple explanation could be that all those X-ray-weak binaries are close so the winds of the components do not reach their terminal velocities before entering the shocks, thus reducing both X-ray luminosity and the hardness. However, to properly address this question, quantitative models of wind-wind collision in such binaries are needed.

3. WIND – WIND COLLISION MODELS

One of the first theoretical studies of wind-wind collision in massive early-type binaries was done by Usov (1992). With semi-analytical approach he made theoretical predictions about the hardness and X-ray luminosity of colliding binaries in the limit of adiabatic shocks and constant wind velocities. Two-dimensional and, lately, three-dimensional dynamical simulations of colliding winds followed shortly after, see, e.g., Stevens et al. (1992), Zhekov & Skinner (2000), Pittard et al. (2002), Parkin & Pittard (2008). They have been quite successful for the *adiabatic* shocks characteristic of the relatively low densities at interaction fronts of wide binary systems. However, these numerical simulations encounter severe difficulties in resolving the extensive structure of unstable *radiative* shocks (e.g., Langer et al. 1981, Chevalier & Imamura 1982, Myasnikov et al. 1998, Walder & Folini 2000) that occur at the higher interaction densities of close binaries.

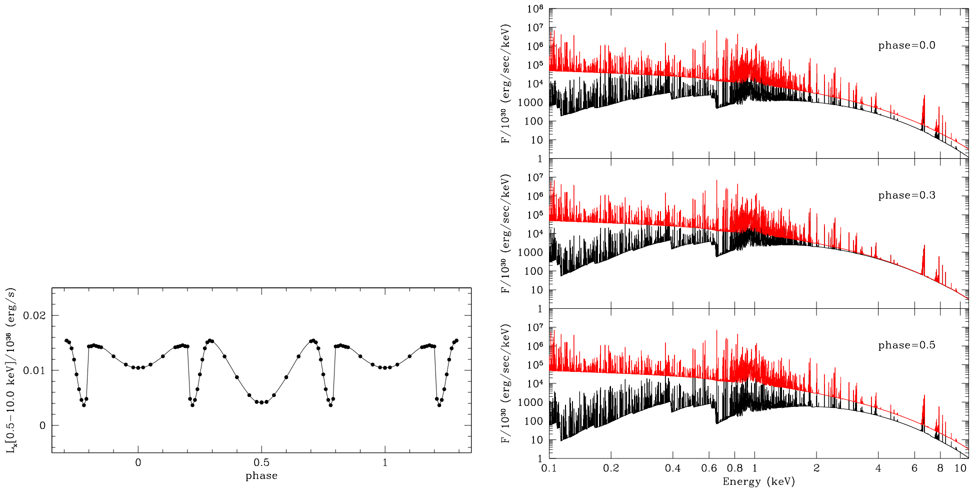

Figure 3: X-ray light curve (left) and the corresponding X-ray spectra (right) of a sample moderately close binary system. For the stellar and orbital parameters, see the text. Spectra at three characteristic orbital phases are shown. In every spectral panel, the intrinsic spectra of the collision zone (upper plot) and the output spectra which account for the absorption in the cooling layers and the winds (bottom plot) are shown. Note the presence of the Fe XXV–XXVI lines at 6.7 keV. From Antokhin et al. (2004).

These difficulties prompted Antokhin et al. (2004) to develop a steady-state numerical model of wind-wind collision. In this model, the extensive structure and numerical mixing of hydrodynamical simulations are totally ignored. The model also neglects an unknown level of *physical* mixing between hot and cool material that should soften the X-ray emission from such structured, radiative shocks. As long as the shock remains fully radiative, the mixing does not affect the level of overall emission, but it can shift it into the UV and EUV, and so reduce what is detected in the bandpass of X-ray telescopes. The model implements detailed planar shock emission calculations within simplified, steady-state geometry of the wind interaction front. It also accounts for the absorption of the emission by the cooling post-shock layers and the winds of the binary components. As a result, X-ray emission spectra for close binary systems can be produced. The spectra derived in such a way actually define *upper limits* to the level and hardness of expected X-ray emission.

In either hydrodynamical numerical models or in the above steady-state one it is assumed that the kinematics of both winds outside the collision zone is identical to the kinematics of single stars. The flow velocity follows the usual "β"-law $v(r) = v_\infty \left(1 - \frac{r_*}{r}\right)^\beta$.

In Fig. 3 an example X-ray light curve and the corresponding spectra at three characteristic orbital phases are shown, for a moderately close binary with the following parameters: the distance between the stars is $60\,R_\odot$, the radii of the stars $R_1 = R_2 = 10\,R_\odot$, orbital inclination $i = 90°$, mass loss rates $\dot{M}_1 = 10^{-6}\,M_\odot\,\mathrm{year}^{-1}$,

$\dot{M}_2 = 0.5 \cdot 10^{-6}\,M_\odot\,\mathrm{year}^{-1}$, the velocity law parameters $\beta_1 = \beta_2 = 1.0$, the terminal velocities of the winds $v_{\infty,1} = v_{\infty,2} = 2000\,\mathrm{km/s}$, the orbit is circular.

The spectra in Fig. 3 look differently from the observed spectrum shown in Fig. 1. This is because (i) interstellar absorption is not accounted for in the model spectra, and (ii) the observed spectra are a convolution of the intrinsic (absorbed) spectrum of an object with the response function of an X-ray telescope.

The variations in the X-ray luminosity and spectra with the orbital phase are due to the varying optical depth of the winds in the direction of an observer and also due to geometrical eclipses of the collision zone by the star bodies. The key point here is that even in this relatively close system and with rather conservative value of the β parameter[1] (the canonical value following from the theory of line-driven winds is 0.5, see Lamers and Cassinelli, 1999), the spectra of the binary are still quite hard at all orbital phases. This is clearly demonstrated by the presence of the Fe XXV–XXVI lines at 6.7 keV. The steady-state model was used for the analysis of X-ray spectra obtained with XMM-Newton for the O+O binary HD 159176 (De Becker et al., 2004). It turned out that the model overestimated the observed X-ray luminosity of the binary by a factor of 4.

The above results show that even for close binary systems, the current wind collision models still predict excessively high X-ray luminosities and hard spectra, which contradicts observations. A possible solution to this problem is accounting for the so-called radiative inhibition or braking. The idea behind these mechanisms is very simple: radiative forces of a component of a binary system accelerate the wind of that component but may reduce or inhibit the acceleration of its companion stellar wind, as these forces act againts the radiative forces of the latter. This idea was first brought forward by Stevens & Pollock (1994). Later on, Owocki and Gayley (1995) showed that in a case when two winds are unequal, the stonger wind may be suddenly decelerated by the radiation of the other star as it approaches the surface of that star. They called this effect “radiative braking”. The importance of radiative inhibition and radiative braking was further demonstrated by Owocki (2005). It was shown that at certain conditions the flow velocity immediately before the material enters the shock can be reduced by a hundred per cent or even more. As the temperature immediately behind the shock depends on the square of the flow velocity component normal to the shock surface, this decrease may significantly reduce the strength and the X-ray emission of the collision zone.

4. CONCLUSIONS

Thanks to the observational and theoretical progress in the last two decades there is a growing understanding of how X-ray emission is formed in single and binary early-type stars. It seems that the key factor to the X-ray production are hydrodynamic shocks in the winds of these stars created by either internal instability of a single star wind or by wind-wind collision in a binary system.

Current models of X-ray production experience some difficulties in quantitative description of observational data. In binary stars, these models still predict too high X-ray luminosity and too hard spectra even for close binaries. Problems also exist in the case of single early-type stars. The current paradigm of X-ray formation

[1] The larger the value of β, the slower the wind acceleration.

experiences difficulties with explaining the shapes of X-ray emission lines of some stars. E.g., according to recent *XMM-Newton* high resolution observations of ζ Orionis, all emission lines have the same velocity profile which contrast with the paradigm of wind shocks, in which line profiles should be dependent of the global kinematic structure of the wind. This contradiction prompted Pollock and Raassen (2006) to bring forward a new idea about the origin of X-ray from single O stars. For the details, see their paper.

Returning to binary early-type stars, there are some ideas which can hopefully address problems encountered by the current wind-wind collision models. However, these ideas need to be integrated into the existing models at a quantitative level to allow for their confrontation with observational data.

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