High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Wind inhibition in HMXBs: the effect of clumping and implications for X-ray luminosity

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Abstract. Winds of hot stars are driven by the radiative force due to absorption of light in the lines of heavier elements. Consequently, the mass-loss rate and the wind velocity depend on the ionization state of the wind. As a result of this, there is a feedback between the ionizing X-ray source and the stellar wind in HMXBs powered by wind accretion. We study the influence of the small-scale wind structure (clumping) on this feedback using our NLTE hydrodynamical wind models. We find that clumping weakens the effect of X-ray irradiation. Moreover, we show that the observed X-ray luminosities of HMXBs can not be explained by wind accretion scenario without introducing the X-ray feedback. Taking into account the feedback, the observed and estimated X-ray luminosities nicely agree. We identify two cases of X-ray feedback with low and high X-ray luminosities that can explain the dichotomy between SFXTs and sgXBs.

Keywords. Stars: winds, outflows, stars: mass-loss, stars: early-type, X-rays: binaries, hydrodynamics

1. Introduction

A class of high-mass X-ray binaries (HMXBs) is powered by accretion of stellar wind on a compact component – either a neutron star or a black hole (see Martínez-Núñez *et al.* 2017, for a review). Stellar winds of massive hot stars are accelerated by the absorption of radiation mainly in resonance lines of heavier elements (e.g., C, N, O, and Fe). Therefore, the radiative force is sensitive to the ionization state of the stellar wind. As a result, while the wind powers X-ray emission, there is a feedback effect, because the emitted X-rays influence the radiative force. We will study the feedback effect of X-ray irradiation using our NLTE wind models.

2. Adopted model

We study the effect of X-ray irradiation using our METUJE code (Krtička & Kubát 2017) for calculation of spherically symmetric stationary hot star wind models. The radiative force is calculated in the comoving frame using solution of statistical equilibrium equations. Wind density, velocity and temperature are derived from hydrodynamical equations. The models enable us to predict the wind velocity, density, and temperature structure including wind mass-loss rate $\dot{M}$ and terminal velocity v_∞.

The flow in accreting high mass X-ray binary has a complex 3D structure. Calculation of detailed radiative force in such complex environment is beyond the possibilities of current computers. Therefore, to simplify the problem, we solve the wind equations only

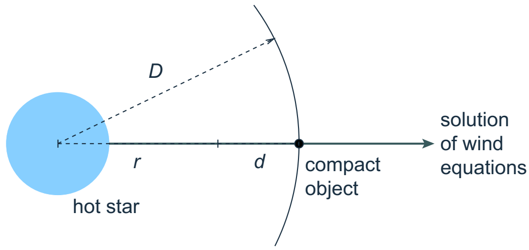

Figure 1. Assumed geometry of the solution. Here D is the binary separation, and r and d are distances of a given point from the donor and compact star, respectively.

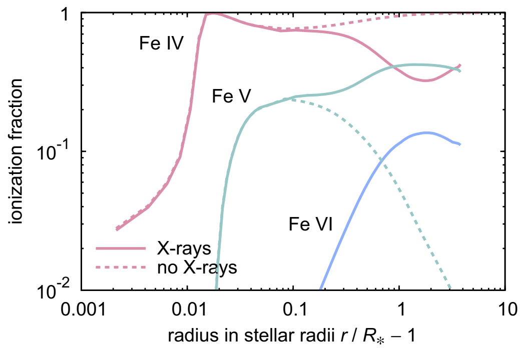

Figure 2. Radial variations of ionization equilibrium of iron in a model corresponding to Vela X-1. Dashed lines denote model without X-ray irradiation and solid lines model with X-ray irradiation.

in the direction of the X-ray source (see Fig. 1). This enables us to understand the effect of X-rays on the radiative force while keeping the whole problem tractable.

The effect of the compact companion is included only by the X-ray irradiation of the donor star due to the wind accretion on the compact star. We include an additional term to the mean intensity

$$J_\nu^{\mathrm{X}} = \frac{L_\nu^{\mathrm{X}}}{16\pi^2 d^2} \mathrm{e}^{-\tau_{\nu(r,d)}},$$

where L_ν^{X} is luminosity per unit of frequency, d is the distance from the neutron star, and the optical depth along a given ray is

$$\tau_{\nu(r,d)} = \int_0^d \kappa_\nu(z)\rho(z)\,\mathrm{d}z.$$

3. Influence of X-rays and the effect of clumping

The presence of strong X-ray radiation leads to a change of the ionization structure due to X-ray ionization (Fig. 2). Higher ionization states become more populated, while the population of lower ionization states decreases. Because the higher ions are less effective in line driving, the change of the wind ionization implies decrease of the radiative force (Hatchett & McCray 1977, Krtička *et al.* 2012, 2015, Sander *et al.* 2018). This is seen in the radial velocity plot in Fig. 3 as decrease of the wind velocity.

For a too high X-ray luminosity or too low binary separation, the X-rays penetrate deeply the wind base. This can lead to the wind disruption. Consequently, there is a

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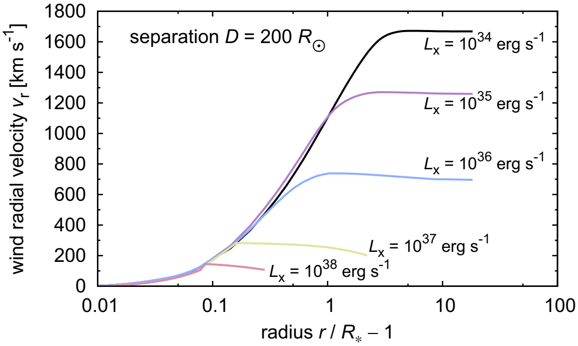

Figure 3. Radial variations of wind velocity of different X-ray luminosities.

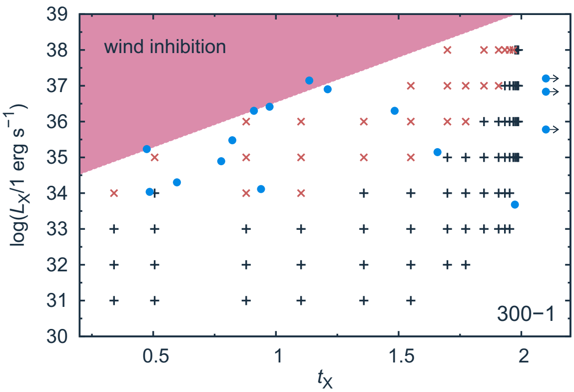

Figure 4. Models and massive binaries in $L_{\mathrm{X}} - t_{\mathrm{X}}$ diagram. Black plus symbols denote models where the X-ray irradiation does not significantly affect the radiative force. Red crosses denote models where the X-ray irradiation leads to decrease of the radiative force. The filled red area corresponds to a region where the X-ray irradiation is so strong that it leads to wind disruption. Real systems (blue circles) lie mostly outside the area of wind inhibition.

limiting X-ray irradiation given mostly by the wind optical depth (D is the binary separation)

$$\tau_{\mathrm{X}} = \int_{R_*}^{D} \kappa_\nu \rho \,\mathrm{d}r \sim \frac{\kappa_\nu \dot{M}}{4\pi v_\infty} \left(\frac{1}{R_*} - \frac{1}{D} \right). \tag{3.1}$$

Thus the effect of wind disruption can be described by the optical depth parameter

$$t_{\mathrm{X}} = \frac{\dot{M}}{v_\infty} \left(\frac{1}{R_*} - \frac{1}{D} \right) \left(\frac{10^3\,\mathrm{km\,s^{-1}}\; 1\,R_\odot}{10^{-8}\,M_\odot\,\mathrm{yr^{-1}}} \right). \tag{3.2}$$

These effects can be manifested in the $L_{\mathrm{X}} - t_{\mathrm{X}}$ diagram (see Fig. 4 and Krtička *et al.* 2015). Here models with negligible influence of X-ray irradiation (black plus symbols) appear either for high optical depth parameters or for low X-ray luminosities. With lower optical depths or higher X-ray luminosities, the influence of X-rays becomes stronger decreasing with terminal velocity (red crosses). Winds are inhibited in filled red region. Real systems (blue dots) appear mostly outside the region of wind inhibition.

A good agreement between the position of real systems and the location of region of wind inhibition in Fig. 4 was achieved by inclusion of clumping (small scale wind inhomogeneities). Clumping increases the local wind density; therefore, it favours recombination

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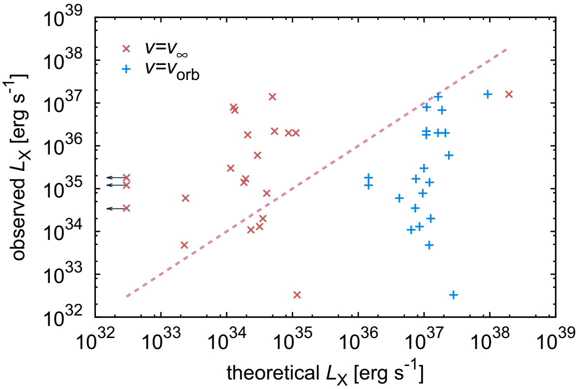

Figure 5. Predicted X-ray luminosity for sample of X-ray binaries powered by wind accretion. Derived using Eq. (4.1) assuming two limiting values of v.

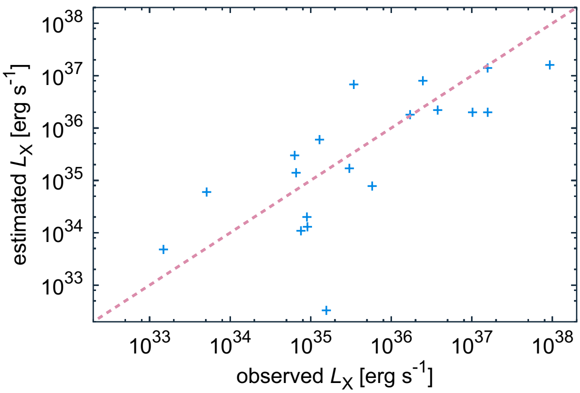

Figure 6. Predicted X-ray luminosity for sample of X-ray binaries powered by wind accretion. Derived using Eq. (4.1) assuming the dependence of v_∞ on L_X predicted by our wind models.

leading to weaker influence of X-rays (Oskinova *et al.* 2012). Furthermore, clumping increases the mass-loss rate (Muijres *et al.* 2011), causing larger X-ray optical depth and larger X-ray absorption.

4. Prediction of X-ray luminosity

The X-ray luminosity of wind accreting systems can be estimated within Bondi-Hoyle-Lyttleton model (Hoyle & Lyttleton 1941; Bondi & Hoyle 1944) as

$$L_X = \frac{G^3 M_X^3}{R_X D^2 v^4} \dot{M}, \tag{4.1}$$

where R_X is radius of the compact companion, $v^2 = v_\infty^2 + v_{\rm orb}^2$, and $v_{\rm orb}$ is the orbital velocity. Assuming $v = v_\infty$ for real wind-fed systems, Eq. 4.1 predicts too low luminosity in comparison with observations (red crosses in Fig. 5). However, inserting $v = v_{\rm orb}$ gives theoretical predictions that are always above the experimental values (blue plus symbols in Fig. 5). This demonstrates the importance of accounting for realistic wind velocity when predicting the X-ray luminosity (Ho & Arons 1987, Sander *et al.* 2018).

We used fits of the results of our models to test if the predicted X-ray luminosity is consistent with observed X-ray luminosity. Fig. 6 shows that these values nicely agree.

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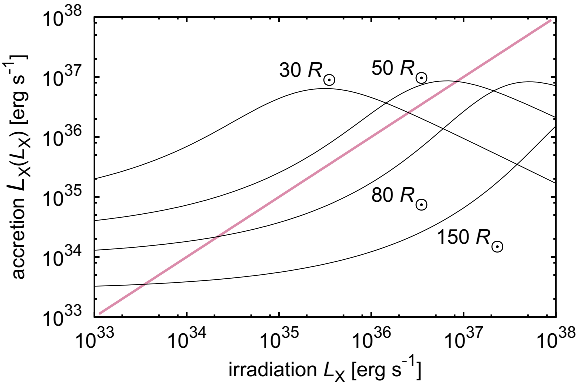

Figure 7. Predicted accretion X-ray luminosity Eq. (4.1) as a function of X-ray irradiation (black lines) for different binary separations D denoted in the plot. Red line corresponds to one-to-one relation. The intersection of the black and red lines gives solution of implicit equation Eq. (4.1) for L_X.

In a presence of X-ray irradiation, the mass-loss rate and terminal velocity in Eq. (4.1) are function of X-ray luminosity and binary separation. Therefore, for a fixed D, Eq. (4.1) is an implicit equation for L_X. The solution of this equation can be either obtained numerically or estimated from Fig. 7. Here black lines give the X-ray luminosity generated by the accretion as a function of X-ray irradiation. For a low X-ray irradiation the wind mass-loss rate and terminal velocity are not affected by X-rays and therefore the amount of accreted matter and also the X-ray luminosity are low. On the other hand, for higher X-ray irradiation the wind terminal velocity decreases, and consequently the amount of accreted mass is higher leading to higher X-ray luminosity (as predicted by Eq. (4.1)). These two states may correspond to two different types of X-ray binaries (supergiant X-ray binaries and soft X-ray transients, respectively). For even higher luminosities the mass-loss rate decreases with increasing X-ray irradiation, leading to a decrease of the accretion X-ray luminosity in Fig. 7. This shows that supergiant X-ray binaries are in self-regulated state.

5. Conclusions

We studied the effect of X-ray irradiation and small-scale wind structures (clumping) on the wind in HMXBs. As a result of X-ray irradiation, the radiative force decreases. This causes the decrease of the wind terminal velocity and also of the mass-loss rate for extreme X-ray irradiation. We found that clumping weakens the effect of X-ray irradiation. Moreover, we show that the observed X-ray luminosities of HMXBs can not be explained by wind accretion scenario without introducing the X-ray feedback. Taking into account the feedback, the observed and estimated X-ray luminosities nicely agree. We identify two cases of X-ray feedback with low and high X-ray luminosities that can explain the dichotomy between SFXTs and sgXBs.

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