X-RAY PHOTOIONIZED BUBBLE IN THE WIND OF VELA X-1 PULSAR SUPERGIANT COMPANION

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ABSTRACT

Vela X-1 is the archetype of high-mass X-ray binaries (HMXBs), composed of a neutron star and a massive B supergiant. The supergiant is a source of a strong radiatively driven stellar wind. The neutron star sweeps up this wind and creates a huge amount of X-rays as a result of energy release during the process of wind accretion. Here, we provide detailed NLTE models of the Vela X-1 envelope. We study how the X-rays photoionize the wind and destroy the ions responsible for the wind acceleration. The resulting decrease of the radiative force explains the observed reduction of the wind terminal velocity in a direction to the neutron star. The X-rays create a distinct photoionized region around the neutron star filled with a stagnating flow. The existence of such photoionized bubbles is a general property of HMXBs. We unveil a new principle governing these complex objects, according to which there is an upper limit to the X-ray luminosity the compact star can have without suspending the wind due to inefficient line driving.

Key words: hydrodynamics – radiative transfer – stars: early-type – stars: mass-loss – stars: winds, outflows

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1. INTRODUCTION

A high-mass X-ray binary (HMXB) is a binary star system consisting of a massive luminous hot star (frequently OB supergiant) and a compact object, either a neutron star or a black hole (Remillard & McClintock 2006). A fraction of the stellar wind of the luminous hot star is trapped in the gravitational well of the compact object and is accreted onto its surface (Davidson & Ostriker 1973; Lamers et al. 1976). Part of the released potential energy of accreting material is transformed into X-rays, resulting in one of the most powerful stellar X-ray sources. Such systems of stars in interaction are some of the most valuable astrophysical laboratories. The binary nature of the object enables us to determine stellar parameters precisely, which subsequently serve as a firm base for further study.

Vela X-1 (HD 77581, GP Vel) is the archetype of HMXBs, consisting of a neutron star and a massive B supergiant (Chodil et al. 1967; Brucato & Kristian 1972; Barziv et al. 2001; Tomsick et al. 2010). The neutron star is a source of pulsed X-ray and γ-ray emission with a period of 283 s (McCointock et al. 1976; North et al. 1987), modulated both by the orbital motion and stochastic variations (Bildsten et al. 1997). The X-rays propagating through the hot star wind probe the wind structure, yielding information about the mass-loss rate and the velocity field (Watanabe et al. 2006). The perpetual X-ray variation (flaring) reveals the existence of some structure in the wind—clumping (Ducci et al. 2009; Fürst et al. 2010). On the other hand, X-rays also significantly influence the stellar wind, resulting in X-ray photoionization of its material (MacGregor & Vitello 1982; Watanabe et al. 2006). Because the stellar wind of hot stars is mostly driven by the light absorption in the lines of heavier elements, the X-ray photoionization may influence the wind acceleration. Particularly, the appearance of highly charged ions, which absorb the light less effectively than low-charged ions, causes the decrease of the radiative force. Since this force is responsible for driving the wind, the wind flow may subsequently stagnate.

Numerical studies of stellar winds in HMXBs concentrate mainly on the multidimensional simulation of wind accretion (Blondin et al. 1990; Blondin & Woo 1995; Feldmeier et al. 1996; Hadrava & Čechura 2012), while the wind driving is simplified using force multipliers that take the X-ray irradiation into account in an approximative way (Stevens & Kallman 1990; Stevens 1991). This is a significant shortcoming, because the X-ray photoionization affects the radiative force, and consequently the amount and velocity of wind material accreted on the compact companion. Detailed modeling of ionization and excitation balance in the wind is crucial for the understanding of the influence of X-ray photoionization on the wind dynamics. The ionization and excitation balance should be properly derived using equations of statistical equilibrium.3 To remedy the situation, we provide wind models that include the influence of X-ray irradiation using up-to-date NLTE models.

2. VELA X-1 PRIMARY WIND MODEL

The applied models of the Vela X-1 primary wind are based on the NLTE code with comoving frame (CMF) line force (Krtička & Kubáš 2010). Our models enable us to self-consistently predict wind structure just from the stellar parameters (the effective temperature, mass, radius, and chemical composition). Here, we assume that the stellar wind of the supergiant component is symmetric with respect to the binary axis (connecting centers of both components) and that the stellar wind in the direction given by the inclination φ from the binary axis can be locally described by a spherically symmetric wind model. The influence of the neutron star is taken into account by its inclusion as the source of external X-ray irradiation of the wind.

Basic parameters of Vela X-1 binary system are given in Table 1. Binary parameters and the physical parameters of binary members are taken from the spectroscopic analysis (van Kerkwijk et al. 1995). The effective temperature of the supergiant is taken from the tables of Straižys & Kuriliene (1981) for the corresponding spectral type. The derived value agrees relatively well with the determination based on NLTE

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3 This approach is usually referred to as non-LTE or NLTE and it means that the assumption of thermodynamic equilibrium is not used for evaluation of the excitation and ionization balance.
model atmospheres (Fraser et al. 2010). The parameters of the X-ray source are adopted from observational analysis of Watanabe et al. (2006). For our calculations, we assume the solar chemical composition (Asplund et al. 2009).

2.1. Wind Model without X-Ray Irradiation

For supergiant parameters given in Table 1 we first calculated the NLTE wind model with CMF line force neglecting the influence of the companion star. The emergent surface flux is taken from the H–He spherically symmetric NLTE model stellar atmospheres (Kubát 2003). The predicted wind mass-loss rate $1.5 \times 10^{-6} M_\odot \text{year}^{-1}$ agrees well with its estimate derived from the observed X-ray spectrum $1.5–2 \times 10^{-6} M_\odot \text{year}^{-1}$ (Watanabe et al. 2006). The predicted terminal velocity $750 \text{ km s}^{-1}$ is lower than the observed one $1100 \text{ km s}^{-1}$ (Prinja et al. 1990). This disagreement may stem either from the model simplifications, inaccurate stellar parameters (e.g., metallicity), or from the sensitivity of the wind terminal velocity to a detailed ionization balance in the outer wind regions (Puls et al. 2000), which probably manifests itself in a significant scatter of the ratio of the terminal to the escape velocity for stars with the same effective temperatures (e.g., Crowther et al. 2006).

The velocity structure of the wind model without X-ray irradiation can be approximated by

$$
\tilde{v}(r) = \left[ v_1 \left( 1 - \frac{R_\odot}{r} \right) + v_3 \left( 1 - \frac{R_*}{r} \right)^3 \right] \times \left\{ 1 - \exp \left[ \gamma \left( \frac{r}{R_*} - 1 \right)^2 \right]\right\},
$$

(1)

where

$$
v_1 = 1042 \text{ km s}^{-1}, \quad v_3 = -297 \text{ km s}^{-1}, \quad \gamma = -1220. \quad (2)
$$

Note that the representation of the velocity law by a polynomial expansion provides better approximation than the ordinary “$\beta$-velocity law,” because these polynomials may form a functional basis (Krtička & Kubát 2011). The exponential term is included for a better fit of the velocity law close to the sonic point. The calculated X-ray opacity per unit mass averaged for radii $1.5 R_\odot$–$5 R_\odot$ may be approximated by

$$
\tilde{k}_X(\nu) = \begin{cases} a_1(\lambda - b_1)^2, & \lambda < \lambda_1, \\
& \lambda > \lambda_1,
\end{cases}
$$

(3)

where $\lambda = 10^8 c/\nu$, $a_1 = 0.704 \text{ g cm}^{-2}$, $b_1 = 1.056$, $a_2 = 4.06 \times 10^{-3} \text{ g cm}^{-2}$, $b_2 = 11.41$, and $\lambda_1 = 20.18$. We stress that $\lambda$ enters as a non-dimensional parameter here, which has for convenience the same value as the wavelength in units of Å.

2.2. Modeling of the Two-dimensional Wind Structure

The full treatment of the problem would essentially require a complex solution of three-dimensional time-dependent hydrodynamic equations (Friend & Castor 1982; Blondin et al. 1990; Feldmeier et al. 1996). However, because the typical wind flow time $R_\odot/v_\infty \approx 0.3 \text{ days}$ is roughly a factor of 30 shorter than the orbital period, we neglect the influence of the orbital motion on the wind structure. Consequently, we assume that the stellar wind of the supergiant component is axisymmetric with respect to the binary axis connecting the centers of components. Moreover, we assume that the stellar wind in the direction given by the inclination $\phi$ from the binary axis can be modeled by a spherically symmetric wind (see Figure 1). Consequently, in the orbital plane of the binary our two-dimensional wind model consists of sectors of a circle.

The wind model in each sector is calculated using our NLTE wind code. Because the radial wind velocity may be non-monotonnic in some sectors, we do not use the CMF line force for the calculation of these models directly, however the line radiative force is given by the force calculated in the Sobolev approximation (e.g., Castor 1974) multiplied by the ratio of the CMF to the Sobolev line force derived from the wind model that neglects the radiation from the companion star (Section 2.1).

The influence of the neutron star is taken into account only by inclusion of its X-ray radiation due to the wind accretion on the neutron star. This radiation irradiates the supergiant and interacts with its wind. To describe this effect, we add an additional term $J_X(v, r, d)$ to the specific intensity $J(v, r, d)$ in the form

$$
J_X(v, r, d) = \frac{L_X(v)}{16\pi^2 d^2} e^{-\tau(v, r, d)},
$$

(4)

where the optical depth along the given ray is ($z$ measures the distance along this ray)

$$
\tau(v, r, d) = \int_0^d k(v, z)\rho(z) dz,
$$

(5)

Table 1

| Parameter       | Value    | Reference               |
|-----------------|----------|-------------------------|
| Separation $D$  | $53.4 R_\odot$ | van Kerkwijk et al. (1995) |
| Period $P$      | 8.96 day | van Kerkwijk et al. (1995) |
| Spectral type   | B0.5Iae |                        |
| Radius $R_*$    | $30 R_\odot$ | van Kerkwijk et al. (1995) |
| Mass $M$        | $23.5 M_\odot$ | van Kerkwijk et al. (1995) |
| Effective $T_{\text{eff}}$ | 27,000 K |                      |
| Wind mass-loss rate $M$ | $1.5 \times 10^{-6} M_\odot \text{year}^{-1}$ | This work |
| Wind terminal velocity $v_\infty$ | 750 km s$^{-1}$ | This work |
| Mass $M_\odot$  | 1.88 $M_\odot$ | van Kerkwijk et al. (1995) |
| X-ray luminosity $L_X$ | $3.5 \times 10^{36} \text{ erg s}^{-1}$ | Watanabe et al. (2006) |
$L^X(v)$ is the X-ray luminosity per unit of frequency, $d$ is the distance from the given point in the supergiant wind region to the surface of the neutron star, $\kappa(v, z)$ is the absorption coefficient per unit of mass, and $\rho(z)$ is the wind density. The distribution of emergent X-rays $L^X(v)$ is approximated by the power law (Watanabe et al. 2006). Energies higher than 3 keV, which are well above the ionization energies of all included ions, were not considered in the model. The absorption coefficient and the density in Equation (5) can be derived from models for individual sectors. However, to simplify our approach, for the calculation of $J^X(v)$ we use fits following from Equations (1) and (3):

$$\rho(z) = \frac{M}{4\pi r^2 v(z)},$$

$$v(z) = \min(\tilde{v}(r), \tilde{v}(\phi)),$$

$$\kappa(v, z) = \kappa^X(v),$$

where the relation between the distance along the ray $z$ and the radius $r$ is derived from the geometry of the problem, and $\tilde{v}(\phi)$ is an average velocity in the velocity plateau which occurs due to X-rays (see Figure 3).

The models describing the wind in different sectors with inclination $\phi$ with respect to the binary axis are calculated for a sequence in $\phi$ with a step of 10$^\circ$.

### 3. WIND STRUCTURE IN TWO DIMENSIONS

The X-ray source located on the surface of the neutron star influences the ionization state of the supergiant wind. The influence is stronger if the X-ray optical depth between a given point in the wind and the neutron star surface is lower. To illustrate this, in Figure 1 we plot the optical depth (Equation (5)) in a plane containing the binary axis. Due to the assumed symmetry of the problem, the optical depth is axisymmetric with respect to the binary axis. The X-rays strongly penetrate the wind that directly faces the neutron star. On the other hand, due to geometrical reasons, the radial wind streams that are significantly inclined with respect to the neutron star are affected by X-ray radiation at larger distances from the primary.

As a result of the X-ray photoionization of the wind, lower ionic states are effectively destroyed and higher ionic states appear in a nonnegligible amount. This can be seen from Figure 2, where we compare the ionization fraction of selected ions in the model with and without X-ray irradiation. The X-rays influence the wind ionization state in the region where the X-ray optical depth between a given point and the neutron star is low, $\tau \ll 1$, i.e., to a distance comparable to an orbital separation $D$. X-rays are not able to penetrate the wind close to the supergiant star (since $\tau \gg 1$ if we aim to approach the supergiant surface), consequently the ionization state of material there is not affected by X-rays.

Because the stellar wind of hot stars is accelerated by the light absorption in the lines of heavier elements, any change of the wind ionization state affects the accelerating radiative force. On average, ions with higher charge are less effective in driving the wind, basically due to the lower number of their spectral lines. For a weak X-ray irradiation the emergence of new ionization states causes a slight increase of the radiative force (cf. Krtička & Kubát 2009). On the other hand, for a strong irradiation when the degree of ionization is higher the radiative force significantly decreases (MacGregor & Vitello...
wind structure, we find that the neutron star is able to collect matter only from a narrow cone defined by the value of $\phi < 15^\circ$ (for $\phi = 15^\circ$ and the distance $D$ we have $v_{\text{wind}} = 32.0 \text{ km s}^{-1}$ and $r_{\text{HL}} = 0.17D$). We can express the relation between the accretion rate $\dot{M}_{\text{acc}}$ and the mass-loss rate $M$ from the supergiant as (Watanabe et al. 2006) $\dot{M}_{\text{acc}} = M r_{\text{HL}}/(4D^2)$. Then the X-ray luminosity $L_X = GM_X\dot{M}_{\text{acc}}/R_\star$ is $L_{X} = 8.8 \times 10^{37} \text{ erg s}^{-1}$. This value is approximately one order of magnitude higher than the observed one (Watanabe et al. 2006). The reason for this difference is the fact that only a small fraction of matter in the accretion cone gets finally accreted and the rest falls back to the surface of the primary as a consequence of the flow stagnation between the supergiant and the neutron star.

4.2. Existence of two Types of Solutions

The wind equations allow the existence of two types of solutions giving different X-ray luminosities and wind velocities. The solution presented here appears in the case of a strong X-ray source, which significantly affects the wind ionization state and consequently also the radiative force. This results in a slow wind that can be accreted by the neutron star in large amounts, producing a strong X-ray source.

Another type of solution may occur in the case of a weak X-ray source that does not significantly influence the wind ionization state. The radiation force becomes higher, similar to that without any X-ray irradiation. This results in faster outflow roughly corresponding to the “no X-rays” case in Figure 3. Due to the dependence of the accretion rate on the velocity via $\dot{M}_{\text{acc}} \sim v^{-4}$ and having roughly two times higher $v$, the X-ray luminosity is an order of magnitude lower in this case (since $L_X \sim \dot{M}_{\text{acc}}$). This agrees with the adopted assumption of a weak X-ray source. Consequently, this is also a possible solution of the wind equations.

Different types of solutions may appear in different systems, or even an external perturbation may cause switching between these two wind solutions in a particular binary system, possibly contributing to the variability of X-ray luminosity. This variability might be accompanied by the variability of the distribution of emitted X-rays, if the accretion regime changes with accretion rate (Shakura et al. 2012).

4.3. Implication for Other HMXBs

For a slightly lower mass-loss rate or for a slightly higher X-ray luminosity than assumed here the X-rays could penetrate deeply into the stellar wind and significantly influence the ionization state at the wind base, resulting in the decrease of the radiative force. This could lead to the disruption of the stellar wind and a significant decrease of X-ray luminosity, possibly providing another contribution to the overall X-ray variability observed in Vela X-1 (Kreykenbohm et al. 2008).

This means that there exists a maximum X-ray luminosity the compact star can have for a given geometry of the system and wind mass-loss rate. Assuming that the Vela X-1 luminosity is the maximum one, the maximum allowed X-ray luminosities for other HMXBs $L_X^{\text{max}}$ can be derived using the optical depth (compare with the ionization parameter $\xi$; Tarter et al. 1969)

$$\tau_X = \int_{R_\star}^{D} \kappa \rho dr \sim \frac{\dot{M}(D - R_\star)}{(v_\infty D R_\star)}$$

and corresponding parameters of Vela X-1 as

$$L_X^{\text{max}} e^{-\tau_X} = L_X(\text{Vela X-1}) e^{-\tau_X(\text{Vela X-1})},$$

(9)
or, in scaled quantities

$$\log(L_X^{\text{max}}/\text{erg}) = 32.6 + 3.9 \left( \frac{M}{1.5 \times 10^{-6} \, M_\odot \, \text{year}^{-1}} \right) \times \left( \frac{v_\infty}{750 \, \text{km s}^{-1}} \right)^{-1} \left( \frac{(D-R_\odot)/(D-R_*)}{68.5 \, R_\odot} \right)^{-1}. \quad (10)$$

Here $\dot{M}, v_\infty, R_*,$ and $D$ are the wind mass-loss rate, the terminal velocity, the radius of the luminous component, and the binary separation for individual HMXBs.

The results of observations for other HMXBs collected in Figure 4 clearly support the picture that there exists a maximum allowed X-ray luminosity, which depends on the wind and geometry parameters. Some systems lie close to the boundary of the forbidden area, whereas others have typically higher wind mass-loss rate $M > 5 \times 10^{-6} \, M_\odot \, \text{year}^{-1}$ that keeps them away from the boundary. The position of individual stars in this diagram may vary with time due to the existence of two possible solutions of the wind equations (as discussed in Section 4.2).

4.4. Mass-loss Rate Determination

Our results support the mass-loss rate predictions based on up-to-date wind models in two ways. First, our mass-loss rate prediction of HD 77581, $1.5 \times 10^{-6} \, M_\odot \, \text{year}^{-1}$, agrees with the value estimated from X-ray spectroscopy, $1.5-2 \times 10^{-6} \, M_\odot \, \text{year}^{-1}$ (Watanabe et al. 2006). Moreover the wind mass-loss rate cannot be lower than this value, because a decrease of the wind mass-loss rate would lead to lower X-ray opacity, stronger wind X-ray photoionization close to the star, and even more significant reduction of the radiative force. This would finally cause a disruption of the wind and a disappearance of X-ray emission. This imposes a strong lower limit on the observational wind mass-loss rate estimates, which is in agreement with current mass-loss rate predictions (Vink et al. 2001; Krtička & Kubát 2010).

4.5. Limitations of the Present Models

The consistent inclusion of the X-ray irradiation, which is an advantage of our models, also determines their shortcomings. The coupled solution of NLTE and radiative transfer equations is significantly time-consuming even in one dimension. Its inclusion in multidimensional time-dependent simulations is likely beyond the possibilities of current computers. Consequently, while one part of the problem solution is treated in detail, the second one is simplified. The correct picture of the flow in the HMXBs should take into account the results of both approaches: the stagnation of the flow in the direction toward the neutron star, which is studied in this paper, and a complex two-dimensional picture of the wind accretion on the neutron star (Blondin et al. 1990; Blondin & Woo 1995; Feldmeier et al. 1996).

On the other hand, there are effects that are not described by any of the available models. It is well established that the hot star wind is inhomogeneous on small scales (clumped; see Hamann et al. 2008). In the case of HMXBs, clumping (which favors recombination) may affect the region in which the photoionized bubble is formed (Oskinova et al. 2012). However, the hydrodynamical simulations (Feldmeier et al. 1997; Runacres & Owocki 2002) predict that clumping starts above the critical point of the wind solution; consequently, it does not affect wind mass-loss rates and terminal velocities. Thus, we expect that clumping does not significantly influence the results of our models.

The wind inhomogeneities likely cause the high variability of the X-ray source (Fürst et al. 2010; Oskinova et al. 2012). The calculation of the wind ionization should in fact account for such time-dependent X-ray photoionization. However, because the typical flow time of the wind is longer than the typical timescale of X-ray variability, we expect that our models are able to reproduce the mean effect of the X-ray photoionization. On the other hand, the variable X-ray ionization source causes temporal changes of the radiative acceleration, providing external perturbation which may contribute to the natural wind clumping. As a result, the primary wind may be more clumpy than the wind of a similar single supergiant.

5. CONCLUSIONS

We provide detailed numerical models of the influence of X-rays on the supergiant wind in the Vela X-1 binary system. The effect of X-ray photoionization on the radiative force and wind dynamics has never been studied using appropriate NLTE wind models. The X-rays photoionize the wind and destroy the ions responsible for the wind acceleration. This results in flow stagnation in the vicinity of the neutron star, which was identified in observations. For a sufficiently strong X-ray source the wind that directly faces the neutron star falls back on the star losing mass and never reaches the compact companion.

We have shown that there is an upper limit to the X-ray luminosity the compact star can have without disrupting the stellar wind. For a higher luminosity than the limiting one the decrease of the wind acceleration is so strong that no wind material would reach the neutron star. This theoretical picture of the maximum X-ray luminosity is supported by observation of many HMXBs.

The wind equations allow the existence of two types of solutions with different X-ray luminosities and wind velocities. The case of a strong X-ray source, which significantly affects the wind ionization, leads to accretion of slow wind in large amounts resulting in a strong X-ray source. On the other hand,
a weak X-ray source that does not significantly influence the wind ionization results in accretion of fast wind in low amounts producing a weak X-ray source. Different types of solution may appear in different binary systems, or perturbations may cause switching between these two types of wind solutions contributing to the X-ray variability.

The predicted mass-loss rate agrees with the value estimated from X-ray spectroscopy. Moreover, the wind mass-loss rate cannot be lower than this value, because a decrease of the wind mass-loss rate would lead to the disruption of the wind and disappearance of the X-ray emission. This supports the reliability of current mass-loss rate predictions.

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