Influence of X-ray radiation on the hot star wind ionization state and on the radiative force

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Abstract
Hot stars emit large amounts of X-rays, which are assumed to originate in the supersonic stellar wind. Part of the emitted X-rays is subsequently absorbed in the wind and influences its ionization state. Because hot star winds are driven radiatively, the modified ionization equilibrium affects the radiative force. We review the recent progress in modelling the influence of X-rays on the radiative equilibrium and on the radiative force. We focus particularly on single stars with X-rays produced in wind shocks and on binaries with massive components, which belong to the most luminous objects in X-rays.

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

1. Introduction
The idea of influence of X-rays on the ionization structure of hot star winds dates back to the beginning of modern hot star wind studies. The observations with the Copernicus satellite revealed the problem of "super-ionization" connected with the presence of strong P Cygni line profiles of surprisingly high ionization species (such as N v or O vi) in the spectra of early-type stars (Rogerson & Lamers, 1975; Lamers & Morton, 1976; Snow and Morton, 1976). The existence of these ions in the wind was subsequently proposed to be a result of radiative ionization due to the UV flux (Castor, 1979) and X-ray photoionization (Olson, 1978; Cassinelli & Olson, 1979).

Since then the problem of the influence of X-rays on the wind ionization structure has been addressed also by the solution of kinetic equilibrium (NLTE) equations. Pauldrach (1987) showed that the ionization fraction of N v derived from observation can be reproduced using NLTE models, but the models with only atmospheric irradiation can not fully explain the ionization fraction of O vi. Ionization equilibrium calculations that included also the X-ray irradiation (albeit in a simplified form, MacFarlane et al., 1994; Pauldrach et al., 1994) predicted O vi ionization fractions and wind line profiles that agree with observations much better. Their calculations also show that the ionization fraction of dominant ionization states is not affected by X-ray irradiation. Consequently, the radiative driving may proceed nearly unaffected in the presence of X-ray irradiation.

The numerical simulations of instabilities connected with radiative driving (Feldmeier et al., 1997) provided more reliable predictions for the X-ray irradiation, especially for the spectral energy distribution of emitted X-rays. More realistic prescriptions for the X-ray irradiation are used in recent NLTE wind models (e.g., Pauldrach et al., 2001; Krčička et al., 2009), although empirically-based formulae for the X-ray irradiation also give ionization fractions and spectra that agree with observations (e.g., Hillier et al., 1993; Bouret et al., 2012).

Because the X-ray radiation affects the wind ionization state, it is able to destroy ions responsible for the wind acceleration if the X-ray source is sufficiently strong. This happens in high-mass X-ray binaries, where the X-rays originate in the accretion of matter on the compact component. From earlier models (Pringle, 1973; Hatchett & McCray, 1977) of the stellar wind ionization structure in high-mass X-ray binaries Fransson & Fabian (1980) realized that the X-ray ionization affects also the radiative force and provided a general picture of the structure of circumstellar environment in such objects. Numerical simulations (Blondin et al., 1990; Feldmeier et al., 1996) revealed a complex structure of the flow influenced by the gravity of the compact object (accretion wake) and X-rays (photoionization wake).

The line force in X-ray irradiated stellar winds has to be obtained from the solution of the 3D radiative transfer equation assuming NLTE. Because this requires formidable effort, the realistic calculations of the line force concen-
trated on the 1D problem (Kallman & McCray, 1982). While Stevens & Kallman (1990) provide modification for usual force multipliers (originally introduced by Castor et al., 1975, and Abbott 1982) in the presence of a strong X-ray field, Krtiˇcka & Kubát (2009) showed by detailed calculation without using force multipliers that the X-rays produced in wind shocks do not affect the line force significantly. On the other hand, in X-ray binaries with large X-ray luminosities the influence of the X-ray emission may lead to the decrease of the radiative force and the inhibition of the stellar wind (e.g., Krtiˇcka et al., 2015).

Some attention was also given to the importance of XUV/EUV radiation for the wind ionization balance following the work of Pauldrach et al. (1994). The XUV/EUV radiation was studied in connection with the ultraviolet resonance doublet of P v, which is too weak in comparison with the theory (Fullerton et al., 2006). Waldron & Cassinelli (2010) proposed that XUV radiation, which cannot be directly observed, may explain the observations of P v lines. However, subsequent calculations (Bouret et al., 2012; Krtiˇcka & Kubát, 2012) showed that this explanation is unlikely, because the XUV/EUV radiation in an amount that explains the weak observed P v lines destroys ions responsible for the wind acceleration.

In this review we focus on understanding how the high energy (X-ray and EUV) radiation affects the ionization equilibrium and the radiative force. For concreteness we will focus on NLTE models with comoving-frame line force of Krtiˇcka & Kubát (2012), which use X-ray irradiation based on model of Feldmeier et al. (1997) or assume a power-law external irradiation. However, corresponding results for ionization structure can be derived also with other codes.

2. N v ionization fraction and no need for additional ionizing radiation sources

Historically, the observations of lines of ions with higher degree of ionization (e.g., C V, N v) were used as an argument for the existence of an additional source of ionizing radiation. However, this argument is based just on an oversimplification of kinetic (NLTE) equations, which can be avoided only by a detailed numerical analysis.

We demonstrate this on the ionization ratio of N iv and N v. Let us assume that the populations of the ground levels dominate for these ions, i.e. populations of excited states can be neglected. Let us also assume that the collisional rates can be neglected. Both these assumptions are justified in stellar winds. In such case the ionization balance between the N iv and N v ions follows from the kinetic equilibrium equations (Hubeny & Mihalas, 2014) as

$$N_4 R_{45} - N_5 R_{54} = 0,$$  (1)

where $N_4$ and $N_5$ are number densities of N iv and N v ions, respectively,

$$R_{45} = 4\pi \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} J(\nu) \, d\nu$$  (2)

is the radiative ionization rate, and

$$R_{54} = 4\pi \left( \frac{N_4}{N_5} \right)^* \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} \left[ \frac{2h\nu^3}{c^2} + J(\nu) \right] e^{\nu_4/\nu} \, d\nu$$  (3)

is the radiative recombination rate (an asterisk denotes the LTE value). In these expressions, $\alpha_4(\nu)$ is the photoionization cross-section with the photoionization edge at the frequency $\nu_4$, and $J(\nu)$ is the mean intensity of radiation. Approximating the integrals in Eqs. (2) and (3) by values of the integrands at $\nu_4$ and taking into account that for this frequency (high radiation energy) holds $2h\nu^3/c^2 \gg J(\nu)$, we derive from Eq. (1)

$$\frac{N_5}{N_4} = \frac{J(\nu_4)c^2}{2h\nu_4^3} \left( \frac{N_5}{N_4} \right)^* e^{\nu_4/\nu}.$$  (4)

The fraction $(N_5/N_4)^*$ can be evaluated using the Saha equation $(N_5/N_4)^* = 2 \left( 2\pi m_e kT/h^2 \right)^{3/2}/N_4 \exp \left( \frac{\nu_4}{kT} \right)$, yielding

$$\frac{N_5}{N_4} = \frac{c^2}{h\nu_4^3} \left( 2\pi m_e kT/h^2 \right)^{3/2} J(\nu_4)/N_4,$$  (5)

where we assumed unity ionic partition functions and $N_4$ is the free electron number density. From this equation it seems that the ionization ratio is directly proportional to the mean radiation intensity $J$ at a given ionization frequency $\nu_4$. Using values appropriate for the model supergiant with $T_{\text{eff}} = 40,000$ K (with stellar mass $M_*$ and radius $R_*$ from Martins et al., 2005a) at the radius of roughly 1.1 $R_*$, namely $\nu_4 = 1.9 \times 10^{16}$ Hz, $T = 33,000$ K, $N_4 = 2 \times 10^{11}$ cm$^{-2}$, and $J(\nu_4) = 5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ we obtain in absence of additional sources of ionizing radiation from Eq. (5) the ionization ratio $N_5/N_4 \approx 7 \times 10^{-3}$. This indicates low N iv ionization fraction and a need for higher ionizing radiation to enhance the N v abundance to values inferred from observations. However, from our full NLTE models calculated using our code (Krtiˇcka and Kubát, 2010), which consider reliable model ions (from Lanz & Hubeny, 2003) with a sufficient number of energy levels, we obtain for the same wind location $N_5/N_4 \approx 0.14$.

The reason for the difference is that the kinetic equilibrium equations are quite complex and their oversimplification may lead to incorrect results. In the particular case of N v ionization fraction, the most important ionization process is not that from the ground level, but those from excited levels. Although upper levels are less populated, they are closely coupled with the ground level by strong bound-bound transitions. Moreover, their ionization energies are lower and they fall within frequencies with higher radiation flux.

The effect is even stronger for the C v ion (Krtiˇcka & Kubát, 2012). Consequently, care has to be taken when...
making the conclusions about the existence of additional ionizing radiation source just from the observations of C\textsc{v} or N\textsc{v} lines. Pauldrach (1987) and Krtička & Kubát (2009) showed that in many cases it is possible to obtain sufficient abundance of N\textsc{v} by proper treatment of the kinetic equilibrium equations without any additional source of X-ray radiation. Although it is generally true that an additional ionization source shifts the degree of ionization, due to the complexity of the processes involved in the kinetic equilibrium equations, we can not claim that the presence of a particular ion is caused exclusively by radiation at a chosen frequency. The above example of C\textsc{v} and N\textsc{v} ionization

Figure 1: Comparison of the ionization fractions calculated with additional X-ray emission (full dots) and without X-ray emission (empty circles) at the point, where the radial velocity is half of the terminal velocity, with observations (+ symbols: Massa et al. 2003, × symbols: Howarth & Prinja 1989, ∗ symbols: Lamers et al. 1999) for CNO elements.
fractions illustrates also a potential importance of ionization by XUV radiation with frequencies larger than the He \textsc{ii} ionization edge (see also Odegard & Cassinelli, 1982; Pauldrach et al., 1994).

3. The case of single stars: influence of intrinsic X-ray radiation on the ionization state

We first discuss the influence of intrinsic X-rays created in the wind of single stars. We assume that the X-ray generation is connected with the line-driving instability (MacGregor et al., 1979; Carlberg, 1980; Abbott, 1980; Lucy & White, 1980; Owocki & Rybicki, 1984; Owocki & Puls, 1999) which steepens into highly supersonic shocks (Owocki et al., 1988; Feldmeier et al., 1997; Runacres and Owocki, 2002). We use our NLTE wind models with CMF line force, which consistently solve for the wind hydrodynamical and thermodynamical structure. Our models include all relevant processes that affect the level populations, i.e., radiative and collisional excitation and deexcitation, radiative and collisional ionization and recombination, and the Auger processes. The corresponding radiative ionization cross-sections are mostly taken from the Opacity and Iron Projects (Seaton et al., 1992; Hummer et al., 1993). These cross-sections include the auto-ionization and dielectronic recombination. In our models we include the fits (by Krťčka et al., 2009) to the X-ray emission generated from the hydrodynamical simulations of Feldmeier et al. (1997). The models and methods are described by Krťčka & Kubát (2012) in detail.

In Figs. 1 and 2 we compare the predicted ionization fractions of selected elements with observations. The comparison of the ionization fraction calculated with and without X-ray emission shows that X-rays do not significantly influence the ionization fraction of ions with low ionization energies, such as C \textsc{iv} or N \textsc{v}, except for the lowest effective temperatures and outer wind regions. Ionization fractions of ions with higher ionization energies (e.g., O \textsc{vi}) are affected by X-rays. The N \textsc{v} ionization fraction is influenced by X-rays only for cooler O stars (and only in outer wind regions).

The ionization fractions derived from fitting of observed UV spectra with theoretical ones (assuming wind mass-loss rates) in general agree with ionization fractions predicted using hydrodynamic NLTE wind models. However,
Figure 3: Variation of the nitrogen ionization fractions with radius in the wind model of a supergiant with \( T_{\text{eff}} = 37\,500 \, \text{K} \). Top panel: Ionization fractions calculated with an additional X-ray source (solid lines) and without the X-ray source (dashed lines). Bottom panel: Ionization fractions calculated with additional X-ray sources with inclusion of Auger processes (solid lines) and neglecting the Auger processes (dashed lines).

there are some exceptions, for example the ionization fraction of N\textsc{iv} derived from observations is significantly lower than the predicted ionization fraction (see Fig. 1). A high ionization fraction of O\textsc{vii} (see Fig. 1) derived from observations is a consequence of X-rays, which can be nicely reproduced by NLTE models with additional X-ray source. We also note that our smooth stationary wind models and the observational diagnostics of ionization fractions neglect inhomogeneities which are present in the wind and which may be connected for example with clumping (Sundqvist et al., 2010; Šurlan et al., 2012, 2013), or with effect of binary component (e.g., Kaper et al., 1993; van Loon et al., 2001).

A further insight into the importance of individual ionization processes can be obtained from the study of radial variations of ionization fractions. As an example we plot the radial variations of the nitrogen ionization fractions in the supergiant wind model calculated by our code for \( T_{\text{eff}} = 37\,500 \, \text{K} \) in Fig. 3. Here we compare the ionization structure of three different wind models: a model with an additional X-ray source and with Auger ionization, model with additional X-ray source but without Auger ionization, and model without any additional X-ray source.

The region close to the stellar surface (for \( r/R_\star - 1 \lesssim 0.1 \)) is opaque for X-rays. Consequently, the ionization fractions of most abundant ions (N\textsc{iii}, N\textsc{iv}) are not influenced by the additional sources of X-rays close to the stellar surface and only minor higher ions (e.g., N\textsc{vi} and N\textsc{vii}) are affected by the tiny amount of X-rays deeply penetrating the wind (upper panel of Fig. 3). The wind regions with larger radius (for \( r/R_\star - 1 \gtrsim 0.1 \)) are less opaque for the transmitted X-ray photons and, consequently, they are more prone to change their ionization state as a result of the presence of X-rays.

Individual nitrogen ions are influenced in different ways by X-rays. The ionization fraction of N\textsc{v} is increased as a result of the direct ionization from N\textsc{iv}, but is also affected by ionization to and recombination from the higher ion N\textsc{vii}. The ionization fraction of N\textsc{vi} is increased by both Auger and direct ionization. N\textsc{vii} is generated due to the direct ionization of N\textsc{vi} (Krtička & Kubát, 2009).

X-rays influence mostly minor ionization states in single hot stars, consequently the wind mass-loss rate is not significantly influenced by X-rays and the terminal velocity is typically only by 10–20% percent higher, especially in stars with weaker ionizing continua (with \( T_{\text{eff}} \lesssim 35\,000 \, \text{K} \), Krtička & Kubát 2009).

4. High-mass X-ray binaries: influence of X-rays on the radiative force

The implications of X-ray irradiation may be more significant in X-ray binaries due to their larger X-ray luminosities (e.g., Watanabe et al., 2006; Thompson et al., 2007; Mereghetti et al., 2013; Zdziarski et al., 2013). The influence of a strong X-ray source, which is typical for binaries with an accreting compact companion, is shown in Fig. 4. Here we plot the radial velocity in the supergiant with \( T_{\text{eff}} = 30\,000 \, \text{K} \) for different amount of external X-ray irradiation (denoted in the graph). The irradiating source is located at \( r = 100 \, R_\odot \) (denoted by a vertical gray line).

Figure 4: Radial variations of velocity in the model of supergiant wind with \( T_{\text{eff}} = 30\,000 \, \text{K} \) for different amount of external X-ray irradiation (denoted in the graph). The irradiating source is located at \( r = 100 \, R_\odot \) (denoted by a vertical gray line).
The influence of X-rays may be also estimated using the ionization parameter
\[
\xi(r) = \frac{1}{n_d} \int L_X^X e^{-\tau_\nu(r)} d\nu. \tag{7}
\]
Here \(L_X^X\) is the X-ray luminosity per unit of frequency, \(\tau_\nu(r)\) is the optical depth between the X-ray source and a given point, and the integration in Eq. (7) goes over the whole X-ray domain. The exponential accounts for the absorption of X-rays in the wind. In the optically thin limit Eq. (7) gives the well-known ionization parameter \(\xi \sim L_X/(n_d \nu^2)\) introduced by Tarter et al. (1969, see also Hatchett & McCray 1977), where \(L_X = \int L_X^X d\nu\). Numerical analysis (Krtiˇ cká et al., 2015) shows that for ionization parameters larger than about \(\xi = 0.1 - 10\) ergs \(\cdot\) cm the X-rays strongly inhibit the radiative force. This may be modified in the presence of wind clumping, which may weaken the effect of X-ray ionization because of increased recombination inside clumps (Oskinova et al., 2012).

Salzmann et al. (2011) propose an alternative ionization parameter
\[
\eta(r) = \frac{n_\nu(r)}{n_e(r)}, \tag{8}
\]
where \(n_\nu\) is the number density of ionizing photons and \(n_e\) is the electron number density. There is a relation between \(\xi\) and \(\eta\), \(\xi = 4\pi n_\nu \hbar v\), where \(\hbar v\) is the mean photon energy. Using the ionization parameter \(\eta\) given in Eq. (8) is advantageous, because the photon number density directly enters the kinetic equations. Therefore, the photon number density is in fact the basic quantity and not the
energy density. Moreover, $\eta$ is a nondimensional parameter. Our numerical tests showed that the radiative force is inhibited by X-rays for $\eta = 10^{-4} - 10^{-3}$.

5. Implications for massive binaries with non-degenerate components

In massive binaries with non-degenerate components, the X-rays come from the wind-wind collision (e.g., Prihutskii & Usov, 1976; Cooke et al., 1978; Antokhin et al., 2004; Pittard, 2009). Consequently, the X-rays can not be so strong to inhibit any of the winds of the individual components.

This is true in most X-ray binaries with non-degenerate components, in which the parameters of individual components lie outside the forbidden area in Fig. 5. In many cases the parameters appear in the region with a strong influence of X-rays on the radiative force and therefore also on the wind velocity structure (Krtiˇcka et al., 2015). These binaries may be in a self-regulated state, but of a different type than we discussed in the case of HMXBs. In binaries with non-degenerate components, an increase in X-ray luminosity $L_X$ causes a decrease in the wind velocity and therefore a decrease in $L_X$. Similarly, the decrease in $L_X$ leads to an increase of the terminal velocity, which subsequently causes an increase in $L_X$ (Parkin & Sim, 2013). This may be one of the effects that lead to the observational finding that most non-degenerate binaries are not stronger X-ray sources than corresponding single stars (e.g., Oskinova, 2005; Sana et al., 2006; Antokhin et al., 2008).

The parameters of some secondaries of massive binaries lie in the forbidden area in Fig. 5. This indicates that their wind is inhibited by the X-ray emission. In some of them the X-ray emission may originate in the collision of the primary wind with the secondary star surface (Krtiˇcka et al., 2015).

6. X-rays and the weak wind problem

Theoretical models predict mass-loss rates that are in a fair agreement with observations for stars with large mass-loss rates $\dot{M} \gtrsim 10^{-7} M_\odot$ year$^{-1}$. However, for some stars with mass-loss rates lower than this value the predicted mass-loss rates are of order of magnitude higher than those derived from observations (Bouret et al., 2003; Martins et al., 2004, 2005b). This is the so-called “weak wind problem”.

The explanation of the “weak wind problem” may lie in the low density of the wind. As a result of the low wind density the shock cooling length may become comparable with the hydrodynamical length scale, that is, the shocks change from radiative to adiabatic (Owocki et al., 2013). Consequently, there is a possibility that once the wind of these stars is heated by the shocks it is not able to cool down radiatively, and remains hot and therefore unaffected by the radiative acceleration (Lucy & White, 1980; Martins et al., 2005b; Cohen et al., 2008; Krtiˇcka & Kubát, 2009; Lucy, 2012). Such shocks occur well above the critical point (Owocki et al., 1988; Feldmeier et al., 1997), and consequently do not influence the mass-loss rate. This means that the mass-loss rate of stars with the “weak wind problem” is roughly the same as the theory predicts. A high temperature of the winds precludes reliable determination of the mass-loss rates from UV lines. This conclusion may be supported by the observation of bow shocks around stars with weak wind (ζ Oph and AE Aur), which require significantly higher mass-loss rates than inferred from UV observations (Gvaramadze et al., 2012; Gratier et al., 2014). On the other hand, if the observed arc structures are dust waves, they may point to lower mass-loss rates (Ochsendorf et al., 2014).

There is an alternative explanation of the “weak wind problem”. The X-rays of stars with low-density winds may be so strong that they may lead to a significant decrease of the radiative force and wind mass-loss rate (Drew et al., 1994). This would mean that the mass-loss rate is indeed as low as deduced from observations. However, Krtiˇcka et al. (2015) argue that for realistic X-ray source parameters the modification of the ionization equilibrium by X-rays is not strong enough to significantly affect the mass-loss rate. This result is also supported by Oskinova et al. (2011), who using their NLTE models showed that the observed level of X-ray emission in low-luminosity stars does not lead to such a decrease of the radiative force and mass-loss rates that would explain the problem with too weak wind line profiles.

7. Conclusions

Because the radiatively driven hot star winds are highly supersonic, they can easily produce large amounts of X-rays. The X-rays influence the ionization balance in the stellar wind. We discuss the influence of X-rays on the radiative force and ionization equilibrium in hot star winds. The radiative force is not affected by X-rays in single O stars. On the other hand, the X-rays in HMXBs are so strong that they affect the radiative force, because highly ionized elements are not able to accelerate the wind efficiently. This may even lead to wind inhibition. Therefore, there is a forbidden area of the binary parameters of HMXBs, where the winds can not exist. Stellar wind of HMXBs may be in a self-regulated state, where the X-rays control the hydrodynamical structure of the wind.

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