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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 modeling 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 "superionization" connected with the presence of strong P Cygni line profiles of surprisingly high ionization species (such us N V or O VI) in the spectra of early-type stars (Rogerson and Lamers, 1975; Lamers and 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 and 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) and 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) and Krtička et al. (2009)), although

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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 and McCray, 1977) of the stellar wind ionization structure in high-mass X-ray binaries (Fransson and 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 concentrated on the 1D problem (Kallman and McCray, 1982). While Stevens and Kallman (1990) provide modification for usual force multipliers (originally introduced by Abbott (1982) and Castor et al. (1975)) in the presence of a strong X-ray field, Krtička and 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., Krtička 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 and 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; Krtička and 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 Krtička and 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 and Mihalas, 2014) as

$$N_4 R_{45} - N_5 R_{54} = 0, \tag{1}$$

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

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

is the radiative ionization rate, and

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

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 ν_4, and $J(\nu)$ is the mean intensity of radiation. Approximating the integrals in Eqs. (2) and (3) by values of the integrands at ν_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)

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

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

$$\frac{N_5}{N_4} = \frac{c^2}{h^4 \nu_4^3} (2\pi m_e kT)^{3/2} \frac{J(\nu_4)}{N_e}, \tag{5}$$

where we assumed unity ionic partition functions and N_e 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 ν_4. Using values appropriate for the model supergiant with $T_{\mathrm{eff}} = 40{,}000$ 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, $N_e = 2 \times 10^{11}$ cm^{-3}, and $J(\nu_4) = 5 \times 10^{-12}$ erg cm^{-2} s^{-1} Hz^{-1} we obtain in absence of addi-