NLTE models of line-driven stellar winds – III. Influence of X-ray radiation on wind structure of O stars

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ABSTRACT

We study the influence of X-rays on the wind structure of selected O stars. For this purpose we use our non-local thermodynamic equilibrium (NLTE) wind code with inclusion of additional artificial source of X-rays, assumed to originate in the wind shocks.

We show that the influence of shock X-ray emission on wind mass-loss rate is relatively small. Wind terminal velocity may be slightly influenced by the presence of strong X-ray sources, especially for stars cooler than $T_{\text{eff}} \lesssim 35 000 \, \text{K}$.

We discuss the origin of the $L_X/L \sim 10^{-7}$ relation. For stars with thick wind this relation can be explained assuming that the cooling time depends on wind density. Stars with optically thin winds exhibiting the ‘weak wind problem’ display enhanced X-ray emission which may be connected with large shock cooling length. We propose that this effect can explain the ‘weak wind problem’.

Inclusion of X-rays leads to a better agreement of the model ionization structure with observations. However, we do not find any significant influence of X-rays on P V ionization fraction implying that the presence of X-rays cannot explain the P V problem.

We study the implications of modified ionization equilibrium due to shock emission on the line transfer in the X-ray region. We conclude that the X-ray line profiles of helium-like ions may be affected by the line absorption within the cool wind.

Key words: hydrodynamics – stars: early-type – stars: mass-loss – stars: winds, outflows – X-rays: stars.

1 INTRODUCTION

The evolution of hot stars seems to be strongly influenced by the loss of a substantial part of their mass via winds. Consequently, a proper knowledge of the amount of material expelled from the stellar surface per unit of time (mass-loss rate) is necessary for the stellar evolution calculations.

There exist some serious problems with mass-loss rate predictions for hot stars. The situation is not satisfactory even in the O star domain, where several different theoretical models are available (e.g. Vink, de Koter & Lamers 2000; Pauldrach, Hoffmann & Lennon 2001; Puls et al. 2003; Krtička & Kubát 2004, hereafter Paper I). A good agreement between these theoretical models and observations may be just an illusory effect of the possible manifestation of local wind inhomogeneities (clumping) in the observed spectra (e.g. Bouret et al. 2003; Martins et al. 2005; Puls et al. 2006). The problem is that the spectrum of a clumped wind with small mass-loss rate may mimic the spectrum of a smooth wind with large mass-loss rate. Consequently, the mass-loss rates derived from observations with account of clumping may be significantly lower than those derived without taking into account the influence of clumping. Lower mass-loss rates are indicated also by weak P V wind lines (Fullerton, Massa & Prinja 2006), and by the study of X-ray line profiles (Owocki & Cohen 2006). If the mass-loss rates derived from observations are really much lower due to the influence of clumping on the observed spectra, then there exists a significant discrepancy between theory and observation (Puls, Markova & Scuderi 2008).

Moreover, some O stars with low luminosities exhibit the so-called ‘weak wind problem’ (Bouret et al. 2003; Martins et al. 2004, 2005; Krtička 2006). Theoretically predicted mass-loss rates of these stars are much higher than the mass-loss rates inferred from observations (even without taking into account the clumping). The origin of this discrepancy is unclear.

One of the reasons that may cause these mentioned differences between observation and theory of hot star winds is the neglect of X-ray radiation. The X-ray radiation of hot stars is likely generated by the wind shocks that exist in the wind either due to the instability caused by the radiative driving (Owocki, Castor & Rybicki 1988, ⋆E-mail: krticka@physics.muni.cz (JKr); kubat@sunstel.asu.cas.cz (JKu)
Feldmeier, Puls & Pauldrach 1997b) or due to the collisions of wind streams channelled by the magnetic field (Babel & Montmerle 1997; ud-Doula & Owocki 2002). The X-rays may be generated also due to decoupling of wind components accompanied by frictional heating (Kubát, Krtička & Pustynik 2004). In the case of binaries the X-rays may also originate in wind collisions (Prilutskii & Usov 1976; Antokhin, Owocki & Brown 2004).

X-ray radiation, above all, influences trace ionization states in most of hot O stars (MacFarlane, Cohen & Wang 1994) and the inclusion of X-ray sources is necessary especially for the correct prediction of hot star spectra (Pauldrach et al. 2001). On the other hand, for cooler stars the wind ionization balance may be dominated by the influence of X-ray radiation (MacFarlane et al. 1994).

Recently Fullerton et al. (2006) showed that the mass-loss rate determined from the Pν lines is much lower than that derived from the Hζ line or radio emission. This implies also that hot star wind mass-loss rates determined from Pν lines are significantly lower than the theoretical ones. However, this conclusion is sensitive to the ionization state of phosphorus. If Pν is not a dominant ion at any effective temperature studied by Fullerton et al. (2006, e.g. due to the presence of X-rays), then the discrepancy between theory and observation of OB star winds may not be so significant. Hence, the inclusion of X-ray ionization may also be important from this perspective.

Thus, we present here a study of the influence of X-ray radiation on the wind properties of O stars.

2 NLTE WIND MODELS

The process of calculation of models used in this paper was described in Paper I, thus here we only summarize its basic features and describe improvements.

2.1 Basic model description

Our models assume spherically symmetric stationary stellar wind. Excitation and ionization state of elements important for the radiative driving and for the correct calculation of the radiative field is derived from the statistical equilibrium [non-local thermodynamic equilibrium (NLTE)] equations.

The radiative transfer equation is artificially split (as in Paper I) into two parts, namely the radiative transfer in continuum and the radiative transfer in lines. The solution of the radiative transfer in continuum is based on the Feautrier method in spherical coordinates (Mihalas & Hummer 1974; Kubát 1993) with inclusion of all free–free and bound–free transitions of model ions, however neglecting line transitions. The radiative transfer in lines is solved in the Sobolev approximation (e.g. Castor 1974) neglecting continuum opacity and line overlaps.

The radiative force [calculated in the Sobolev approximation after (1.25)]¹ using data extracted in 2002 from the VALD data base (Piskunov et al. 1995; Kupka et al. 1999)] and the radiative cooling/heating term (we use the electron thermal balance method; Kubát, Puls & Pauldrach 1999) are calculated using occupation numbers derived from statistical equilibrium equations. Finally, the continuity equation, equation of motion and energy equation are solved and consistent wind velocity, density and temperature structure are obtained using iteration procedure. For our calculations we use Asplund, Grevesse & Sauval (2005) solar abundance determinations.

The lowest wavelength considered in the models is 7.5 Å and the largest X-ray wavelength is defined as 100 Å.

2.2 Inclusion of shock X-ray radiation

The consistent inclusion of X-ray generation into NLTE wind models (using hydrodynamical simulations that are able to predict the shock properties, Feldmeier et al. 1997b) is likely beyond the possibilities of the present-day computers. To make the problem more tractable, and since we are interested in the effect of already generated X-rays on the wind, not in the process of X-ray generation itself, we use a simpler approach after Pauldrach et al. (1994), i.e. we include X-rays into our stationary models in an artificial way using two free parameters introduced below.

We assume that a part of the wind material is heated to a very high temperature $T_X$ due to the shock. The shock temperature is given by the Rankine–Hugoniot shock condition

$$T_X = \frac{3m_H}{2k} \left( \frac{u_X^2 + 14}{5} \frac{a_H}{14} \left( 1 - \frac{3}{14} \frac{a_H^2}{u_X^2} \right) \right),$$

where $k$ is the Boltzmann constant, $m_H$ is the hydrogen mass, $a_H$ is the sound speed calculated assuming a completely ionized hydrogen plasma,

$$a_H = \sqrt{\frac{10kT_H}{3m_H}},$$

where $T_H$ is the hydrogen temperature taken from stationary wind models, and $u_X$ is the upstream shock velocity,

$$u_X = u_{rel}v_{rel},$$

where $v_{rel}$ is the radial velocity in the stellar rest frame and $u_{rel}$ is a dimensionless free parameter influencing the hardness of X-rays. Instead of the linear dependence of $u_X$ on the wind velocity it would be possible to employ different assumptions, e.g. constant $u_X$. However, the observed X-rays originate at larger radii where the wind velocity approaches the terminal one; consequently such dependence would not result in a very different result. Moreover, in the case of constant $u_X$ it would be necessary to introduce additional free parameter corresponding to the radius at which X-rays start to be emitted. Without it we would obtain unrealistically strong X-ray source at the wind base as the wind density is the largest there.

We add the X-ray emissivity

$$\eta_X(v) = f_X(\xi\rho\xi)\Lambda_{\gamma}(T_X)/4\pi$$

into the emission coefficient, where $f_X$ is the second free parameter determining the amount of X-rays (also called the filling factor), $\Lambda_{\gamma}(T_X)$ is calculated using the Raymond–Smith X-ray spectral code (Raymond & Smith 1977; Raymond 1988), and $\xi$ relates the wind density $\rho$ and the electron number density

$$\xi = \frac{1 + 2y}{m_H 1 + 4y},$$

where $y$ is the helium number density relative to the hydrogen one (here we assume a fully ionized gas).

We used different values of $f_X$ in our calculations. The free parameter $u_{rel} = 0.3$ in all presented calculations. This roughly gives the same X-ray temperature compared to the results of numerical simulations (e.g. Oswcki et al. 1988; Feldmeier et al. 1997b; Runacres & Oswcki 2002) and observations (e.g. Berghöfer et al. 1997; Miller et al. 2002; Sana et al. 2006).

1 The equations from Paper I are denoted as Lx, where x is the equation number there.
2.3 Joint calculation of wind model

In our previous work we split the calculation of wind model to parts below and above the critical point, at which the mass-loss rate of our stationary wind models is determined (Castor, Abbott & Klein 1975) (hereafter CAK). This effectively means that we neglected the influence of the region above the critical point on to the region below this point. This was justifiable in our previous models with negligible contribution of X-ray radiation, because the wind close to the critical point is optically thick in the ultraviolet (UV) region and optically thin for other wavelengths (except lines). The splitting of wind solution may not be legitimate in the case where additional sources of X-rays are present, because the X-rays that predominantly originate in the wind above the critical point may penetrate downwards and, consequently, influence the solution below this point.

Here we calculate the joint wind model below and above the critical point during the procedure of mass-loss rate determination. To do so, we first calculate several global iteration steps (during which we search for the base density corresponding to the solution which smoothly passes through the critical point, see Paper I) for models in which we account only for the wind close to the stellar surface. As soon as the appropriate base density is roughly known (with a precision of about 30 per cent), we add the solution above the critical point and perform several additional global iteration steps until the base density is known with sufficiently high precision of 1 per cent. This approach enables us to properly take into account the influence of X-rays on the mass-loss rate.

2.4 Statistical equilibrium equations

The statistical equilibrium equation for level \( i \) of a given atom (ion) has the form [Mihalas 1978, also (1.1)]

\[
\sum_{j \neq i} N_j P_{ji} - N_i \sum_{j \neq i} P_{ij} = 0, \tag{6}
\]

where \( N_i, N_j \) are relative occupation numbers of studied levels \( (N_i = n_i / n_{atom}) \), where \( n_i \) is the number density of atoms in the given excitation and ionization state \( i \) and \( n_{atom} \) is the total number density of given atoms; similarly for level \( j \). \( P_{ij} \) are rates of all the processes by which an atom can change its state (see e.g. Mihalas 1978). Note that for simplicity we do not explicitly write the radial dependence of all the variables in equation (6).

2.4.1 Modification of atomic data

Model atoms are based on the set of TLUSTY files (Hubeny 1988; Hubeny & Lanz 1992, 1995; Lanz & Hubeny 2003). The original set described in Paper I was extended to allow for consistent inclusion of X-rays (see Table 1). Our model atoms are based on the data derived from the Opacity Project (Fernley, Taylor & Seaton 1987; Seaton 1987; Luo & Pradhan 1989; Sawey & Berrington 1992; Seaton, Zeippen & Tully 1992; Butler, Mendoza & Zeippen 1993; Nahar & Pradhan 1993) and Iron Project (Hummer et al. 1993; Bautista 1996; Nahar & Pradhan 1996; Zhang 1996; Bautista & Pradhan 1997; Zhang & Pradhan 1997; Chen & Pradhan 1999). For phosphorus we employed data described by Pauldrach et al. (2001).

2.4.2 Auger ionization

In addition to the direct ionization (of a valence electron), the Auger ionization can significantly alter the ionization state of a stellar wind in the presence of X-rays (see Cassinelli & Olson 1979; Olson & Castor 1981; MacFarlane et al. 1994; Pauldrach et al. 1994).

To include the Auger ionization we inserted Auger photoionization terms into statistical equilibrium equation (6),

\[
\sum_{j \neq i} N_j P_{ji} - N_i \sum_{j \neq i} P_{ij} - N_i \sum_{j \neq i} R_{ij}^{Auger} = 0, \tag{7}
\]

where \( R_{ij}^{Auger} \) is the Auger photoionization rate with \( j \) corresponding to the ground level of higher ions. Introducing the notation ion \( i \), which means the ionization state, to which the level \( i \) belongs, the Auger photoionization rate is given as a product

\[
R_{ij}^{Auger} = a_{(ion)}^{(ion)} R_{j}^{Auger}, \tag{8}
\]

where \( a_{(ion)}^{(ion)} \) is the Auger yield, i.e. the probability that ion \( j \) — ion \( i \) electrons are expelled due to the Auger ionization of ionic state \( i \), i.e. that ionization state ion \( j \) is created during the process of Auger ionization, and \( R_{j}^{Auger} \) is the total inner shell photoionization rate of ion \( j \). The total inner shell photoionization rate is given as a sum of partial inner shell photoionization rates from all the closed inner shells. Auger rates for transitions ending in the ionization states which are not included in statistical equilibrium equations are assumed to contribute to the closest lower ionization state considered. The term corresponding to the Auger ionization is also included in the absorption coefficient in the continuum part of the radiative transfer equation.

The influence of Auger ionization on the temperature and the photon emission due to Auger ionization are neglected.

Photoionization cross-sections from individual inner shells were taken from Verner & Yakovlev (1995, see also Verner et al. 1993) and Auger yields were taken from Kaastra & Mewe (1993).

2.4.3 Accelerated lambda iterations

Iterative solution of the radiative transfer equation together with the statistical equilibrium equations may in some cases cause numerical problems with convergence (see Hubeny 2003 for a

| Ion | Levels | Ion | Levels | Ion | Levels | Ion | Levels |
|-----|--------|-----|--------|-----|--------|-----|--------|
| H   | 9      | O   | 50     | Al  | 16     | Ar  | 25     |
| He  | 1      | He  | 14     | O   | 39     | Ar  | 16     |
| He  | 14     | O   | 14     | Al  | 16     | Ar  | 11     |
| He  | 1      | O   | 20     | Al  | 1       | Ar  | 16     |
| Ca  | 14     | O   | 1      | Si  | 12     | Ca  | 16     |
| Ca  | 23     | Ne  | 15     | Si  | 12     | Ca  | 14     |
| Ca  | 25     | Ne  | 14     | Si  | 13     | Ca  | 20     |
| Ca  | 11     | Ne  | 12     | Si  | 15     | Ca  | 22     |
| Ca  | 1      | Ne  | 17     | Si  | 1      | Ca  | 1      |
| Ca  | 14     | Ne  | 11     | Pi  | 16     | Fe  | 29     |
| Ca  | 32     | Ne  | 11     | Pi  | 17     | Fe  | 32     |
| Ca  | 23     | Na  | 13     | Pi  | 21     | Fe  | 30     |
| Ca  | 13     | Na  | 14     | Pi  | 14     | Fe  | 27     |
| Ca  | 15     | Na  | 18     | Pi  | 1     | Fe  | 1      |
| Ca  | 1      | Na  | 16     | Si  | 14     | Ni  | 36     |
| Ca  | 1      | Si  | 10     | Ni  | 38     |
| Mg  | 14     | S   | 14     | Ni  | 48     |
| Mg  | 14     | S   | 14     | Ni  | 1      |
| Mg  | 13     | S   | 16     |
| Mg  | 1      | S   | 1      |

Table 1. Atoms and ions included in the NLTE calculations. Here ‘Level’ means either an individual level or a set of levels merged into a superlevel.
To avoid these problems, we included accelerated lambda iterations into our models. Their inclusion is based on the method proposed by Rybicki & Hummer (1992). The linearity of the derived equations is based on Newton–Raphson iterations. Thus, our method resembles approximate Newton–Raphson method of Hempe & Schönberg (1986). The statistical equilibrium equation (6) have for each \( i \) the form of

\[
\sum_{j<i} 4\pi N_j \int_{\nu}^{\nu_i} \frac{\alpha_i \nu}{h \nu} J_j \, d\nu + \sum_{j>i} 4\pi N_j \left( \frac{N_i}{N_j} \right)^* \int_{\nu}^{\nu_i} \frac{\alpha_i \nu}{h \nu} \left( \frac{2h\nu^3}{c^2} + J_j \right) \exp \left( -\frac{h\nu}{kT_e} \right) \, d\nu - \sum_{j<i} 4\pi N_i \int_{\nu}^{\nu_j} \frac{\alpha_j \nu}{h \nu} J_i \, d\nu + \sum_{j\neq i} N_j P_{ji} - \sum_{j\neq i} P_{ij} = 0,
\]

where we explicitly write rates of direct radiative ionization (I.7a) and recombination (I.7b), \( \alpha_i \nu \) is the photoionization cross-section from level \( i \) with threshold frequency \( \nu_i \) (similarly for \( \alpha_j \), \( J_j \) is the mean continuum intensity, \( T_e \) is the electron temperature, asterisk denotes an LTE value and \( P_{ij} \) are rates of all remaining transitions [collisional ionization, recombination, excitation and de-excitation (I.8) and radiative bound–bound transitions, equations (I.3), (I.5), (I.14), and the Auger ionization (8)].

Introducing the quantity \( U_{ji} \) as

\[
U_{ji} = n_{H2}z_{atom} \left( \frac{N_i}{N_j} \right)^* \alpha_i \nu \left( \frac{2h\nu^3}{c^2} \right) \exp \left( -\frac{h\nu}{kT_e} \right),
\]

the free–bound emissivity has the form of

\[
\eta_v = \sum_{i, j \neq i} N_j U_{ji},
\]

where \( n_{H2} \) is the hydrogen number density and \( z_{atom} \) is abundance (number density ratio) of a given atom relative to hydrogen. During the process of the solution of the radiative transfer equation we derive the mean intensity \( J_i \) from emissivity (11) as follows. Using vector quantities \( \mathbf{J} = (J_1, J_2, \ldots, J_N)^T \) and \( \mathbf{\eta} = (\eta_1, \eta_2, \ldots, \eta_N)^T \), where \( \mathbf{R} \) is considered the number of depth points, the radiative transfer equation for a given frequency can be expressed in a symbolic form as

\[
\mathbf{J}_\nu = \mathbf{\Psi}_\nu \mathbf{[\eta]},
\]

where the matrix operator \( \mathbf{\Psi}_\nu \) represents solution of the radiative transfer equation. However, the actual process of solution is different, we do not apply the operator \( \mathbf{\Psi}_\nu \) on \( \mathbf{\eta} \), but the mean intensity \( \mathbf{J}_\nu \) is derived as the solution of linear set of equations:

\[
\mathbf{\eta} = \mathbf{\Psi}_\nu^{-1} \mathbf{J}_\nu,
\]

which is in fact the formal solution of the radiative transfer equation. Hence, while solving the radiative transfer equation (13) we do not know an explicit form of \( \mathbf{\Psi}_\nu \), but we know its inversion \( \mathbf{\Psi}_\nu^{-1} \). Since for the acceleration of convergence of statistical equilibrium equation (6) together with the continuum radiative transfer equation (13) we need to know derivatives \( \partial J_i / \partial N_j \); we consequently need to know the explicit form of \( \mathbf{\Psi}_\nu \). However, because for the solution of equations of statistical equilibrium we use only derivatives of mean intensity with respect to \( N_j \) at a given depth point, we need to know only the diagonal part of the operator \( \mathbf{\Psi}_\nu \) (see equation 11). This significantly reduces the necessary computer power. Note that because we use LAPACK package (http://www.cs.colorado.edu/~lapack; Anderson et al. 1999) for the solution of radiative transfer equation (13), which is based on LU decomposition, we can easily calculate diagonal elements of \( \mathbf{\Psi}_\nu \) (see Appendix A). Finally, derivatives of mean intensities inserted into the statistical equilibrium equations have at the depth point \( IR \) the approximate form of

\[
\frac{\partial J_v}{\partial N_i} \approx \Psi_{v,IR,IR} U_{ij},
\]

where \( \Psi_{v,IR,IR} \) is the corresponding diagonal element of \( \mathbf{\Psi}_\nu \) at a depth point \( IR \) and \( U_{ij} \) was defined in equation (10).

During the iterative solution of statistical equilibrium equations we solve for the corrections \( \delta N_i \) to the actual relative occupation numbers \( N_i \). These corrections are calculated using equation (I.22). Here we also add corrections due to the dependence of the mean intensity on \( N_i \) (equation 14). Hence, instead of equations (I.22) we solve (compare with equation 9)

\[
\sum_{j<i} 4\pi N_j \int_{\nu}^{\nu_i} \frac{\alpha_i \nu}{h \nu} \Psi_{v,IR,IR} U_{ij} \delta N_j \, d\nu + \sum_{j\neq i} \Psi_{v,IR,IR} U_{ij} \delta N_j \, \frac{\partial P_{ji}}{\partial N_i} \delta N_i + \frac{\partial P_{ji}}{\partial N_j} \delta N_j = 0,
\]

where the first four sums represent the term of accelerated lambda iterations and the meaning of the other terms is the same as in Paper I.

Finally, for the calculation of continuum mean intensities \( J_i \) (see equation 13) we use the formal solution (i.e. for given opacity and emissivity) of the momentum form of the radiative transfer equation with inclusion of sphericity factors (Auer 1971).

To accelerate the convergence even more, we have also included the Ng acceleration (Ng 1974, see also Auer 1987; Hubeny 2003).

### 3 STUDIED STARS

This paper studies the influence of X-rays on the basic parameters of radiatively driven stellar winds. However, to avoid using of ad hoc stellar parameters, we rather decided to choose a set of parameters corresponding to real stars with basic parameters already known to some degree of accuracy.

#### 3.1 Stellar parameters

This paper is based on O stars with effective temperatures \( T_{eff} \lesssim 40000 \text{ K} \), which were detected by ROSAT satellite as X-ray sources (Berghöfer, Schmitt & Cassinelli 1996, hereafter BSC). They were selected out of stars studied by Repolust, Puls & Herrero (2004, hereafter R04), Markova et al. (2004, hereafter M04) and Paper I. To enlarge our data set we also included such stars from Martins et al. (2005, hereafter M05) sample, for which the measured X-ray fluxes are available in the literature. All but one of the latter...
stars exhibit the so-called ‘weak wind problem’, i.e. their theoretically predicted mass-loss rates are significantly higher than those derived from observations.

Adopted parameters of studied O stars are given in Table 2. Effective temperatures and radii are taken from RO4, MO4, MO5 and Lamers, Snow & Lindahl (1995, hereafter LSL). Parameters derived by RO4, MO4 and MO5 were obtained using blanketed model atmospheres, i.e. they are more reliable than the older ones. Stellar masses were obtained using evolutionary tracks either by us (using tracks calculated by Schaller et al. 1992) or by LSL or MO5. The use of the evolutionary masses instead of the spectroscopic ones may cause a systematic shift due to the well-known discrepancy between these masses (e.g. Herrero et al. 1992). However, for many stars from our sample these masses are nearly the same.

3.2 Wind parameters derived from observations

Wind parameters of the studied stars (both derived from observations and the predicted ones) are given in Table 3.

Table 2. Stellar parameters of selected O stars. Stars exhibiting the ‘weak wind problem’ appear in the bottom part below the blank line. Spectral types are taken from the SIMBAD database.

| Star | HD number | Spectral type | $R_e$ (R☉) | $M$ (M☉) | $T_{eff}$ (K) | Source |
|------|-----------|-------------|------------|----------|-------------|--------|
| ξ Per | 24912 | O7.5IIIe | 14.0 | 36 | 35000 | R04 |
| α Cam | 30614 | O9.5Iae | 27.6 | 43 | 30900 | LSL |
| λ Ori A | 36861 | O8 III | 12.3 | 30 | 36000 | LSL |
| ♂ Oph | 54662 | O7III | 11.9 | 38 | 38600 | MO4 |
| λ Oph | 93204 | O5V | 11.9 | 41 | 40000 | MO5 |
| η Ori | 149757 | O9V | 8.9 | 21 | 32000 | R04 |
| 63 Oph | 162978 | O8III | 16.0 | 40 | 37100 | LSL |
| 68 Cyg | 203064 | O8e | 15.7 | 38 | 34500 | R04 |
| 19 Cep | 209975 | O9Ib | 22.9 | 47 | 32000 | R04 |
| λ Cep | 218039 | O6Iab | 19.6 | 51 | 38200 | LSL |
| AE Aur | 34078 | O9.5Ve | 7.5 | 20 | 33000 | MO5 |
| μ Col | 38666 | O9.5V | 6.6 | 19 | 33000 | MO5 |
| 42088 | 60.3V | 9.6 | 31 | 38000 | LSL |
| 46202 | 09V | 8.4 | 21 | 33000 | MO5 |

Table 3. Wind and X-ray parameters of studied O stars. Wind parameters derived from observation are described in Section 3.2. Predicted wind parameters were derived using our NLTE models with different properties of X-ray sources (models with $f_X = 0, f_X = 0.02$ and $u_{in} = 0.3$).

| HD number | $\log L_X$ (CGS) | $v_{\infty}$ (kms$^{-1}$) | $M$ (M☉ yr$^{-1}$) | $v_{\infty}$ (kms$^{-1}$) | $M$ (M☉ yr$^{-1}$) | $L_X$ (CGS$^2$) | $M$ (M☉ yr$^{-1}$) | $v_{\infty}$ (kms$^{-1}$) |
|-----------|------------------|-------------------------|------------------|-------------------------|------------------|----------------|------------------|------------------|
| 24912     | 31.91            | 1.2 × 10$^{-6}$         | 2450             | 4.4 × 10$^{-7}$         | 2270             | 31.71          | 4.4 × 10$^{-7}$ | 2750             |
| 30614     | 32.24            | 1.5 × 10$^{-6}$         | 1500             | 1.5 × 10$^{-6}$         | 1950             | 32.27          | 1.4 × 10$^{-6}$ | 2290             |
| 36861     | 32.59            | 4 × 10$^{-7}$           | 2200             | 4.8 × 10$^{-7}$         | 2150             | 31.80          | 4.8 × 10$^{-7}$ | 2500             |
| 54662     | 32.34            | 5.6 × 10$^{-7}$         | 2450             | 7.9 × 10$^{-7}$         | 2290             | 32.40          | 1.3 × 10$^{-6}$ | 2400             |
| 93204     | 32.07            | 5.6 × 10$^{-7}$         | 2900             | 1.3 × 10$^{-6}$         | 2290             | 32.40          | 1.3 × 10$^{-6}$ | 2400             |
| 149757    | 31.14            | 3.9 × 10$^{-8}$         | 1550             | 4.7 × 10$^{-8}$         | 2040             | 30.23          | 4.7 × 10$^{-8}$ | 2280             |
| 162978    | 32.95            | 2.0 × 10$^{-6}$         | 2200             | 2.0 × 10$^{-6}$         | 2040             | 32.50          | 1.9 × 10$^{-6}$ | 2190             |
| 203064    | 31.76            | 1.1 × 10$^{-6}$         | 2550             | 5.7 × 10$^{-7}$         | 2080             | 31.87          | 5.8 × 10$^{-7}$ | 2590             |
| 209975    | 32.47            | 1.2 × 10$^{-6}$         | 2050             | 8.4 × 10$^{-7}$         | 2430             | 31.99          | 8.4 × 10$^{-7}$ | 2900             |
| 210839    | 32.12            | 3.0 × 10$^{-6}$         | 2200             | 6.1 × 10$^{-6}$         | 1990             | 32.95          | 6.0 × 10$^{-6}$ | 1910             |
| 34078     | 31.32            | 3.2 × 10$^{-10}$        | 800              | 1.4 × 10$^{-8}$         | 2950             | 29.34          | 1.4 × 10$^{-8}$ | 3490             |
| 38666     | 31.80            | 3.2 × 10$^{-10}$        | 1200             | 7.9 × 10$^{-9}$         | 4380             | 28.78          | 8.0 × 10$^{-9}$ | 4480             |
| 42088     | 32.38            | 1 × 10$^{-8}$           | 1900             | 3.1 × 10$^{-7}$         | 2180             | 31.63          | 3.2 × 10$^{-7}$ | 2680             |
| 46202     | 32.40            | 1.3 × 10$^{-9}$         | 1200             | 2.3 × 10$^{-8}$         | 1900             | 29.76          | 2.4 × 10$^{-8}$ | 2890             |

X-ray luminosities, which are assumed to originate in the wind, were taken from BSC with an exception of stars HD 42088, HD 46202 and HD 93204, for which the X-ray luminosities were taken from Chlebowski & Garmany (1991) and Evans et al. (2003).

Because there is still no broad consensus about the influence of clumping on mass-loss rates derived from observations, we used mass-loss estimations from Puls et al. (2006, hereafter PO6), which were regarded as upper limits with respect to clumping, supplemented by results of MO5. Although MO5 derived mass-loss rates of some stars with inclusion of clumping, for most stars selected by us from this sample the clumping factor was set by them to 1, because these stars exhibit the ‘weak wind problem’. The only exception is the star HD 93204, for which MO5 provide mass-loss rate with clumping taken into the account. However, to keep our sample more compact, we used mass-loss rate uncorrected for clumping (calculated as $M/\sqrt{T_{\infty}}$, where $T_{\infty}$ is the clumping factor in the outer wind derived by MO5). Because PO6 concluded that mass-loss rates derived from radio data are less influenced by clumping, for the star HD 149757 we adopted such rates derived by Lamers & Leitherer (1993).

Terminal wind velocities were taken from LSL, Puls et al. (1996), and MO4 (the uncertainties were either taken from LSL or calculated assuming 10 per cent errors as suggested by Puls et al. 1996). For stars that exhibit the ‘weak wind problem’ the terminal velocities derived from observations may be just lower limits, similarly as in Martins et al. (2004). Consequently, we did not consider the terminal velocities of these stars in the following analysis.

4 THE EMERGENT X-RAYS

4.1 The $L_X/L$ relation

From the analytic considerations Owocki & Cohen (1999, hereafter OC) showed that the optically thin X-ray luminosity depends on the square of the mass-loss rate $L_X \sim (M/v_\infty)^2$, whereas the X-ray luminosity of the optically thick wind scales linearly with the mass-loss rate $L_X \sim M/v_\infty$. A slightly different form of these relations can be expected due to the assumed dependence of the shock temperature $T_X$ on the wind terminal velocity. Consequently, in the following we use simpler relations $L_X \sim M^2$ for the optically thin case and $L_X \sim M$ for the optically thick case.
thin wind in the X-ray region and \( L_X \sim M \) for the optically thick wind. From the relation \( M \sim L^{1/\alpha'} \) (Kudritzki & Puls 2000), where \( \alpha' = \alpha - \delta \) and \( \alpha \) and \( \delta \) are usual CAK force multipliers, the X-ray luminosity of optically thick wind is predicted to be proportional to \( L_X \sim L^{1/\alpha'} \) (\( \alpha' \approx 0.5 \)).

However, from the observations a slightly different trend emerges, because the observed X-ray luminosity \( L_X \) is roughly linearly proportional to the total luminosity \( L \) (e.g. Chlebowski, Harnden & Sciortino 1989; BSC, Sana et al. 2006). The origin of the difference is not clear. OC suggested that the observed relation can be reproduced assuming that \( f_X \) decreases with radius.

To understand the origin of \( L_X/L \) relation we calculated wind models with a fixed filling factor. To be specific, we chose \( f_X = 0.02 \). In agreement with the calculations of OC, the X-ray luminosity of individual stars depends mostly on the wind mass-loss rate (see Fig. 1). Stars with large mass-loss rates \( M \gtrsim 10^{-7} M_\odot \) yr\(^{-1} \) have an optically thick wind in the X-ray domain (between the outermost model point and the region where most of the X-rays are generated) and the X-ray luminosity of theoretical models calculated with a fixed \( f_X \) depends on \( M \) linearly. On the other hand, stars with low mass-loss rates \( M \lesssim 10^{-7} M_\odot \) yr\(^{-1} \) have optically thin wind and their theoretical X-ray luminosity depends on \( M^2 \).

The \( L_X/M \) relation plotted using wind parameters derived from observations (Fig. 1) is different. The correlation between the observed mass-loss rate and X-ray luminosity is less apparent. Moreover, the observed X-ray luminosities for stars with low mass-loss rates \( M \lesssim 10^{-7} M_\odot \) yr\(^{-1} \) lie considerably above the theoretical expectations. These stars have nearly the same \( L_X \) as stars with high mass-loss rates.

The predicted dependence of \( L_X \) on \( M \) displayed in Fig. 2 reflects the dependence of \( L_X \) on \( M \). For stars with dense winds, i.e. for stars with large luminosities (\( L \gtrsim 5 \times 10^{38} \) erg s\(^{-1} \)) the X-ray luminosity scales as \( M \), and due to the dependence of \( M \) on \( L_X \) depends mostly on the stellar luminosity as \( L_X \sim L^{1/\gamma} \). This is in agreement with scaling \( L_X \sim L^{1/\alpha'} \) where \( \alpha' \approx 0.6 \). For stars with thin winds these models roughly recover the observed \( L_X/L \) relation. Remaining difference between predicted slope of \( L_X/L \) relation and the observed one may be either due to the radial dependence of the filling factor (as proposed by OC), or due to the dependence of the filling factor on wind density (Section 8.1). Higher scatter of the observed X-ray luminosities may be partly caused by poorly known distances (cf. with the results of Sana et al. 2006).

For stars with lower luminosities, \( L \lesssim 5 \times 10^{38} \) erg s\(^{-1} \), there is an abrupt change in \( L_X/L \) relation derived from our models with fixed \( f_X \). These stars have optically thin wind, and their X-ray luminosities scale as \( L_X \sim M^2 \). Because the mass-loss rate depends mainly on the stellar luminosity, the \( L_X/L \) relationship derived from theoretical models consequently steepens. However, the observed X-ray luminosities are much higher than the predicted ones. The observational \( L_X/L \) relation is almost the same for both groups of stars with optically thick and thin winds. Because in the case of optically thin winds we observe basically all X-rays emitted, our description of shock properties of these stars is likely oversimplified. Other possibilities, like different heating mechanism (e.g. wind frictional heating; Kubát et al. 2004) are also not ruled out.

The enhanced X-ray activity may not be limited only to the stars exhibiting the ‘weak wind problem’. From observations of Bergföhr et al. (1997) follows that also many other late O main-sequence stars show X-ray luminosity corresponding to the stars with thick winds.

### 4.2 The radial distribution of X-ray emissivity

Most of the X-rays in our models are generated close to the star, as shown in the plot of radial variations of X-ray emissivity (Fig. 3). Due to the assumed dependence of the shock temperature on wind velocity (via equations 1 and 3), the X-ray emissivity is an increasing function of radius close to the star. On the other hand, we assume that the X-ray emissivity depends on the square of the wind density (see equation 4); consequently the emissivity decreases in the outer regions.

For stars with optically thick wind only a very small part of the generated X-rays finally escapes the wind and may reach a distant observer, as can be seen from the difference between the radii at which \( 4\pi r^2 n_X \) has maximum and at which the monochromatic luminosities approach the terminal value in Fig. 3. Due to the continuum X-ray absorption the X-ray luminosity of optically thick wind is predicted to be proportional to the total luminosity \( L \) (e.g. Chlebowski, Harnden & Sciortino 1989; BSC, Sana et al. 2006), observed values for studied stars, and the linear fit to the theoretical expectations (only for stars with thick winds). Grey symbols denote values for stars exhibiting ‘weak wind problem’.

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**Figure 1.** The relation between \( L_X \) and \( M \) plotted using wind parameters derived from observations and from theoretical models (\( f_X = 0.02 \)). The relations \( L_X \sim M \) for stars with optically thick winds in the outer regions (stars with large mass-loss rates) and \( L_X \sim M^2 \), valid for stars with optically thin winds (OC) are also plotted in the graph (dotted lines). Grey symbols denote values for stars exhibiting ‘weak wind problem’.

**Figure 2.** The relation between the X-ray luminosity \( L_X \) and the total luminosity \( L \) for studied stars calculated assuming \( f_X = 0.02 \). Overplotted are the average observed relations derived by Bergföhr et al. (1997), Sana et al. (2006), observed values for studied stars, and the linear fit to the theoretical expectations (only for stars with thick winds). Grey symbols denote values for stars exhibiting ‘weak wind problem’.
The relation between the radius $R_{\text{bol}}$ of the formation of fir lines of He-like ions derived from observations by Waldron & Cassinelli (2007) and the radius $R_{1/2}$ at which the monochromatic luminosity is equal to half of its terminal value (for $f_X = 0.02$). The radii derived for individual lines for giants (III) and main-sequence stars (V) are plotted using different symbols. Dashed line denotes one-to-one relation.

5 INFLUENCE OF X-RAYS ON THE IONIZATION STATE

Although not directly observable, ionization structure of the wind gives us a useful direct insight to the effect of different radiation processes in the stellar atmosphere and wind. In our models the X-rays affect wind ionization structure via direct and Auger ionization (MacFarlane et al. 1994; Pauldrach et al. 1994).

5.1 Radial variations of the ionization fractions

As an example we discuss the variations of nitrogen ionization in the case of the star $\lambda$ Cep (HD 210839). To understand the influence of individual ionization mechanisms on the wind ionization structure we also calculated models without additional X-ray sources and models which take these sources into account, but which neglect Auger processes (see Fig. 6 for the plot of the variations of nitrogen ionization fractions with the radius).
The ionization fractions of most abundant ions (\(N\) m, \(N\) iv) close to the stellar surface are not significantly influenced by the additional sources of X-rays. This region is optically thick for the X-ray radiation and only a very tiny amount of X-rays emitted in the highly supersonic wind parts may penetrate close to the stellar surface and modify the ionization fractions of minor higher ions there (in our case \(N\) vi and \(N\) vii). With increasing radius (for \(r/R_\star < 0.1\)) the wind becomes more ionized due to lower wind density, and X-rays start to play a more important role in the ionization balance. As a result of our assumptions, the Auger ionization significantly influences the ionization balance only in the outer wind regions. This is caused by the fact that more energetic X-rays emitted in the wind with sufficiently high velocity are necessary for the Auger ionization than for direct ionization.

The ionization fraction of \(N\) v is increased due to direct ionization from \(N\) iv and is influenced also by ionization to and recombination from \(N\) vi. The ionization fraction of \(N\) vi is increased by both Auger and direct ionization. \(N\) vii is generated due to the direct ionization of \(N\) vi (see Fig. 7).

The result that for \(r/R_\star < 0.1\) the ionization fraction of \(N\) vii is higher in the case of neglected Auger processes than in the model with these processes may seem paradoxical, but it has a simple explanation. In the case of neglected Auger processes the stellar wind is less opaque in the X-ray region and, consequently, the intensity of X-ray radiation is higher. Because \(N\) vii is created via direct ionization of \(N\) vi, the ionization fraction of \(N\) vii is higher.

5.2 Variations with the effective temperature

To compare the ionization equilibrium for different stars, we plot the ionization fractions of selected ions for the points where the wind velocity is equal to \(v_\infty = 0.5 v_\infty\) (Fig. 8). The model predictions are compared with the ionization fractions derived from observations by Howarth & Prinja (1989), Lamers et al. (1999) for Galactic stars, and Massa et al. (2003) for stars from the Large Magellanic Cloud (LMC). Stars from the Clouds have generally lower metallicity than the Galactic ones (e.g. Martins et al. 2004). However, because the dependence of ionization fractions on metallicity is not strong, we use also these fractions for our comparison.

The ionization fractions are influenced not only by the stellar effective temperature and by local wind parameters, but also by the amount of additional ionizing X-rays. Consequently, the variations plotted in Fig. 8 are far from being monotonic. In agreement with MacFarlane et al. (1994), the ionization fractions of the dominant ions are usually not influenced by X-ray emission. X-rays, above all, modify the ionization fractions of minor higher ionization states of a particular atom due to both the direct and Auger ionization. There is a satisfactory agreement between our results and models of MacFarlane et al. (1994). Note that the influence of X-rays on the ionization balance is already very deep in the wind as both observational and theoretical results show relatively large amount of \(O\) vi close to the stellar surface for \(v_\infty = 0.5 v_\infty\) (Fig. 9). However, X-rays do not alter the ionization state of the dominant and the lower neighbouring ions there (cf. Fig. 6).

The influence of X-rays on the ionization structure is stronger for stars with less dense winds and for stars with weaker flux of the ionizing radiation, i.e. for cooler stars.

The presence of \(N\) v lines in the wind spectra is a frequently used argument for the existence of an additional source of ionization. However, as we can see from the comparison of the ionization structure derived from observations and from our models for \(v_\infty = 0.05\) and \(0.5 v_\infty\) (Figs 9 and 8), the ionization fraction of \(N\) v can be explained just by the detailed NLTE models without a contribution of X-ray radiation. This was shown already by Pauldrach (1987). Only the presence of \(N\) v in a significant amount at higher wind speeds (see Fig. 10 and also Fig. 6) is caused by the existence of a strong X-ray source.
5.3 Phosphorus

The failure of the present NLTE wind models to reproduce the ionization fractions of P\textsc{v} derived from observations is one of the main arguments for lower values of wind mass-loss rates. There is a large discrepancy between P\textsc{v} ionization fraction derived by us and those derived from observations by Fullerton et al. (2006), who concluded that either the ionization fraction of P\textsc{v} is lower than 0.1 or there is a significant disagreement between mass-loss rates derived from P\textsc{v} and He lines. Some part of this discrepancy may come from the neglected influence of inhomogeneities on the wind ionization fractions or radiative transfer (Krtička, Puls & Kubát 2007; Oskinova, Hamann & Feldmeier 2007; Puls et al. 2008). Anyway, it is worthwhile to understand whether some part of this discrepancy is not caused by the fact that P\textsc{v} is a fragile ion, which is not a dominant one for any effective temperature, and to test the influence of X-rays on P\textsc{v} ionization fraction.

Our calculations show that P\textsc{v} is a dominant ion in the inner part of the wind only for stars with $T_{\text{eff}} \lesssim 34\,000$ K (in accordance with theoretical results discussed by Fullerton et al. 2006, see lower right-hand panels of Fig. 8 for the predicted ionization fraction of P\textsc{v} and P\textsc{i}v). For hotter stars also P\textsc{vi} becomes an important ionization stage. However, the presence of shock X-ray radiation does not significantly modify the ionization fraction of P\textsc{v}. Consequently, even for hotter stars for which P\textsc{v} is not a dominant ion there is a significant discrepancy between theoretical and observational results, as can be seen from Fig. 11. Here we plot the values, which can be in fact derived from observations, i.e. the product of the ionization fraction and the mass-loss rate $\dot{M}$, and compare it with the predicted ones. For hotter stars ($T_{\text{eff}} \gtrsim 35\,000$ K), the predicted values are higher on average by a factor of 7 than those derived from observations (with an exception of the star HD 42088, which displays the ‘weak wind problem’). On the other hand, for cooler stars ($T_{\text{eff}} \lesssim 35\,000$ K) the predicted values are on average even about 100 times higher than those derived from observations.

The maximum frequency considered in our models (corresponding to 1.7 keV) is lower than P\textsc{v} inner shell ionization energy threshold 2.2 keV. To test our results, we calculated also models with higher maximum frequency considered, i.e. corresponding to 3.7 keV (see Fig. 12). However, even in these models the Auger ionization of P\textsc{v} due to low flux of high-energy X-rays does not significantly modify the ionization fraction of P\textsc{v}.

6 Influence of X-rays on Hydrodynamic Structure

To understand the influence of X-rays on wind parameters, we calculated several wind models corresponding to $\alpha$ Cam stellar parameters, however with a different value of $f_X$, i.e. with a different value of X-ray luminosity. The variations of wind parameters with X-ray luminosity are shown in Fig. 13. As a consequence of assumed
dependence of X-ray emissivity on $f_X$ via equation (4), the emergent X-ray luminosity depends linearly on $f_X$. For lower X-ray luminosities ($L_X/L \lesssim 10^{-8}$) both mass-loss rate and terminal velocity are not significantly affected by X-ray radiation, since the latter influences only the ionization state of minor ions (typically VI–VII). This picture changes for higher X-ray luminosities ($L_X/L \gtrsim 10^{-8}$). The mass-loss rate slightly decreases with increasing X-ray luminosity, whereas the terminal velocity slightly increases. Changes of wind parameters are caused by modification of ionization equilibrium due to X-rays. The X-ray radiation shifts the ionization balance to higher excited states of all elements. Because the number density of minor ionization state Fe IV, which is important for the radiative acceleration close to the star, is lowered, the radiative acceleration decreases. Consequently, the wind mass-loss rate slightly decreases in the case of α Cam.

Generally, the changes of the wind mass-loss rate due to X-rays are relatively small. The mass-loss rates for the same star calculated with $f_X$ from 0 to 0.04 differ by no more than about 5 per cent. This is connected with the fact that in our models the wind mass-loss rate is determined in the region close to the stellar surface below the critical point. Because this wind region is opaque to X-rays, the X-rays do not influence the ionization states, significantly contributing to the radiative force there and the mass-loss rates remain basically unaltered.

The change in ionization due to the presence of X-rays does not decrease the line force due to the lighter elements. The important lines stay optically thick and higher excited elements capable of contributing to the radiative force emerge (e.g. N V, O VI, O VII). Thus, it makes sense to understand that X-rays do not significantly change P V ionization fraction and that P V dominates at $r \gtrsim 2R_\ast$.
the situation in the outer wind, where the contribution of iron lines is smaller and the influence of X-rays is higher, is different. The increase of the radiative force (supported in some cases by the decrease of $M$) causes the increase of the wind terminal velocity.

For stars with stronger ionizing flux in the far-UV region the influence of X-rays on the wind structure is not so significant. More X-rays are necessary to modify the ionization fractions of wind-driving ions. Consequently, the increase of the wind terminal velocity is larger for cooler stars ($T_{\text{eff}} \lesssim 35000 \, \text{K}$, see Fig. 14) for stars with more tenuous winds.

The energy of artificially included X-rays also transforms to the thermal energy due to the X-ray absorption. Consequently, wind temperature may become higher by few thousands kelvin due to X-rays. However, this effect does not significantly influence the radiative force.

7 CONSEQUENCES FOR THE X-RAY LINE TRANSFER

Using modern X-ray spectrographs it became possible to resolve the X-ray line profiles of hot stars. The study of ‘fir’ lines of He-like ions enabled us to derive radii at which the X-ray emission is generated (e.g. Kahn et al. 2001; Miller et al. 2002; Raassen et al. 2005; Leutenegger et al. 2006). It is also possible to predict the shapes of these X-ray lines (e.g. Owocki & Cohen 2001). Most of the predictions assume that the X-ray lines originate in the hot optically thin environment surrounded by cool wind, which is optically thick in continuum. These theoretical calculations based on currently available theoretical mass-loss rates predict asymmetric X-ray line profiles due to the wind continuum absorption. However, the observed X-ray line profiles are in most cases symmetric (e.g. Miller et al. 2002; Leutenegger et al. 2007). This either indicates that the theoretical wind mass-loss rates are overestimated or leads to the discussion on the influence of wind inhomogeneities on the X-ray line transfer (Feldmeier, Oskinova & Hamann 2003; Owocki, Gayley & Shaviv 2004; Oskinova, Feldmeier & Hamann 2006a; Owocki & Cohen 2006). Here we study the influence of the modified ionization equilibrium due to hot shock emission on the line transfer in the X-ray region.

7.1 Influence of shock emission on the X-ray opacity

The theoretical prediction of the asymmetric shape of the X-ray line profiles is sensitive to the value of the opacity in the X-ray region.

Krtička & Kubát (2007) concluded that a more realistic (lower) value of adopted metallicity leads to lower continuum opacity in the X-ray region, and consequently to a better agreement between theoretical and observed X-ray line profiles. Here we test whether the ionization shift due to the presence of X-rays may affect the X-ray continuum opacity.

Our calculated opacities are in a good agreement with those presented by Oskinova et al. (2006a). Inclusion of shock X-ray emission leads to a slight decrease (on average by 8 per cent) of the calculated opacity per unit of mass due to the ionization shift of ions He ii, C v, N iv, O iv, etc., as shown in Fig. 15. This could slightly improve the agreement between predicted and observed X-ray line shapes, but the decrease is too small to explain the main part of the discrepancy.

7.2 Influence of the resonance-line scattering in the cool wind on the line transfer in the X-ray region

Ignace & Gayley (2002) proposed that X-ray emitting regions may be optically thick in lines. This effect can lead to more symmetric X-ray line profiles, which better correspond to the observed ones (see also Leutenegger et al. 2007). However, the ambient cool wind is usually assumed to absorb the X-ray radiation only in continuum and the line absorption within the cool wind is being neglected. Here we test whether this assumption is adequate.

He-like ions N vii and O vii, whose lines are observed in the X-ray spectra of hot stars, are present in a non-negligible amount also in a cool ambient wind (see Fig. 8). This is caused by the direct and Auger ionization of corresponding less ionized ions. The influence of the resonance line scattering in the cool ambient wind on the profiles of X-ray lines emitted in shocks can be estimated from the optical depth of these lines in the cool wind. Neglecting the occupation number of upper level $n_i/g_i \gg n_j/g_j$, the Sobolev optical depth in a given line is within the radial streaming approximation roughly given by (e.g. Castor 1974)

$$
\tau_s = \frac{\pi e^2}{m_e v_{ij}} n_i f_{ij} \left( \frac{dv_{ij}}{dr} \right)^{-1},
$$

where $v_{ij}$ is the line frequency, $f_{ij}$ is the oscillator strength and $n_i, n_j$ are the number densities of individual states with statistical weights $g_i, g_j$. From this equation it follows that the effect of the resonance line scattering in the cool wind is effective mainly for stars with high mass-loss rates or for stars where X-rays more significantly influence the ionization equilibrium (i.e. stars with large $f_{X}$, where higher fractions of He-like ions emerge).
For stars HD 93204, 162978, 209975 and 210839 the resonance line scattering in the cool wind is able to influence the emergent X-ray line profiles of N VII and in some cases also of O VII (see Fig. 16). This effect, discussed also by Oskinova, Hamann & Feldmeier (2006b), is sensitive to the properties of X-ray sources.

8 DISCUSSION

8.1 The dependence of $f_X$ on the cooling time

The parameter $f_X$ is an important free parameter that determines the wind X-ray luminosity. As it was used for some models, it is possible to specify $f_X$ individually for each star using observed X-ray luminosity. As with fixed $f_X$ we predict steeper $L_X$–$L$ relation than observed (Fig. 2), $f_X$ which is inversely proportional to the luminosity would lead to a $L_X$–$L$ relation that better corresponds to the observed one.

The inverse proportionality of $f_X$ on $L$ (or on the wind density) may be a more realistic one. The total X-ray emissivity is given by the amount of energy dissipated by the shocks and the fraction of X-ray emitting material (or $f_X$) may be determined by this dissipated energy and by the cooling length. In fact, $f_X$ may be lower for stars with dense winds in which the hot material is able to cool down more efficiently. To correct our results for the dependence of $f_X$ on the cooling time, we calculated wind models where $f_X$ is scaled by the value of the cooling time relatively to the hydrodynamical timescale (cf. Antokhin et al. 2004; Zhek & Palla 2007), i.e. roughly given by

$$f_X = f_0 x = f_0 \frac{a_{11} \rho}{(\xi \rho)^2} \int_0^{\infty} L(T) \, dt \, \frac{\nu_i}{r},$$

(18)

where we assume $f_0 = 0.7$. Since according to (18) $f_X \sim r$, $L_X$ now increases ad infinitum. To avoid a possible divergence of $L_X$ we limit $f_X$ in (18) by a certain value, namely $f_X \leq 0.1$ as in the outer regions shocks may become adiabatic or weaker (Feldmeier et al. 1997a,b). The derived relation between $L_X$ and $L$ in Fig. 17 shows a better agreement with observations indicating that the variable cooling time may indeed be an important property of wind shocks.

8.2 The weak wind problem

Comparison of mass-loss rates derived from observation with the predicted ones (Table 3) shows that there is a good agreement between observation and theory for stars with large mass-loss rates $\dot{M} \gtrsim 10^{-7} M_\odot \, yr^{-1}$ (provided that the observations are not significantly influenced by clumping). The situation is markedly different for stars with lower mass-loss rates $\dot{M} \lesssim 10^{-7} M_\odot \, yr^{-1}$ (except HD 149757). The predicted mass-loss rates are generally by an order of magnitude higher than those derived from observations. These stars exhibit the so-called ‘weak wind problem’, whose solution is not yet known (Bouret et al. 2003; Martins et al. 2004; M05; Krtička 2006).

The X-ray activity of these stars is higher than that of stars which do not exhibit the weak wind problem. Within our models this means that their X-ray luminosity predicted, assuming a fixed filling factor, is by two to three orders of magnitude lower than the observed one (see Fig. 2). However, the X-ray emission of these stars may still originate in the wind, because their X-ray luminosity is lower than the wind kinetic energy lost per unit of time $1/2 M v_r^2$ (M05). Note that due to low wind density of these stars the cooling length may become comparable with the hydrodynamical scale (as indicated by the plot of $\epsilon_X$ in Fig. 18). Consequently, there is a possibility that once the wind of these stars is heated by the shocks it is not able to cool down sufficiently, and remains hot and unaffected by the radiative acceleration. This can be a reasonable explanation of the ‘weak wind problem’ and high X-ray luminosity $L_X$ of these stars. A similar scenario was invoked by Cohen et al. (2008) to explain the X-ray spectrum of $\beta$ Cru.

8.3 The metallicity dependence

To discuss the influence of metallicity on $L_X$ we recalculated our models with lower value of the mass fraction of heavier elements $Z$. Because the dependence of the free parameter $f_X$ on metallicity is not known, we calculated these models with fixed $f_X$. The derived relation between $L_X$ and $L$ in Fig. 17 shows a better agreement with observations indicating that the variable cooling time may indeed be an important property of wind shocks.

Figure 16. The Sobolev optical depth (17) due to the resonance line scattering due to $\lambda_{17} = 587$ Å lines of helium-like ions N VII ($\lambda = 28.78$ Å) and O VII ($\lambda = 21.60$ Å) in the cool wind of HD 93204. The model was calculated for $f_X = 0.0094$ that fits the observed X-ray luminosity.

Figure 17. The X-ray luminosity calculated assuming the dependence of $f_X$ on the cooling time via equation (18) in comparison with observations.

Figure 18. The radial variations of $\epsilon_X$ (see equation 18) for selected stars.
The derived variations of \( L_X \) with Z given in Fig. 19 can be easily interpreted. The mass-loss rate depends on metallicity roughly as \( M \sim Z^{0.67} \) (Krtiška 2006). The X-ray emission originates mainly from lines of heavier elements, thus we can assume that the emissivity per unit of mass depends on the metallicity roughly as \( \Lambda_x(T_X) \sim Z \). Consequently, from the relations of OC (see Section 4.1) the optically thin X-ray luminosity scales with the metallicity as \( L_X \sim Z^{2.34} \).

In the optically thick case we can assume that for higher frequencies \( (\nu > 1 \times 10^{17} \text{ Hz}) \) the X-ray opacity \( \kappa_x \) is mostly due to direct and inner shell ionization of heavier elements. As a result of this, \( \kappa_x \sim Z \), and in the optically thick case the relations of OC yield \( L_X \sim M \Lambda_x / \kappa_x \), i.e. \( L_X \sim Z^{0.67} \).

Relations (19) and (20) are derived assuming that \( f_X \) does not depend on the metallicity. However, lower value of \( \Lambda \) for lower metallicities could effectively mean that the cooling time of the gas in the post-shock region is longer. Consequently, \( f_X \) may become higher for lower metallicities. In such a case we can expect the dependence of \( f_X \) on the metallicity roughly as \( f_X \sim Z^{-1} \). Within this approximation the total X-ray luminosity would scale as

\[
L_X \sim Z^{1.3} \quad \text{(optically thin case),}
\]

\[
L_X \sim Z^{-0.3} \quad \text{(optically thick case).}
\]

### 8.4 Multicomponent effects

The multicomponent effects due to inefficient collisions between individual wind particle components may significantly influence structure of low-density winds (e.g. Springmann & Pauldrach 1992; Krtiška 2006). The Coulomb frictional force between wind components depends on the charge of these components, which may be influenced by the presence of X-rays. However, our tests showed that such influence is in most cases insignificant, because the X-rays typically modify the fraction of minor ionization stages only.

We tested whether the multicomponent effects are important for stars exhibiting the ‘weak wind problem’. For this purpose we treated heavier elements as individual components (as in Krtiška 2006). We concluded that phosphorus, due to its low abundance, may decouple from the wind of HD 34078 and HD 38666, and the velocity difference between phosphorus and hydrogen is high also in the wind of HD 46202. For these stars the multicomponent effects and the ionization shift induced by it may be important.

### 8.5 Model simplifications

The inclusion of additional X-ray sources into our NLTE wind models was done assuming a simplified shock picture; in reality these sources may have slightly different properties. For example, the X-ray source cannot be described just by one temperature (Feldmeier et al. 1997a). However, the main result of this paper, i.e. that the presence of X-rays does not significantly influence the wind parameters of O stars was justified for a broad range of shock parameters. On the other hand, the predicted ionization structure is much more sensitive to properties of X-ray sources.

There is a growing observational evidence that hot star’s winds are clumped (Bouret et al. 2003; Martins et al. 2004; Pö6). We will study the effect of clumping on the wind structure in a special forthcoming paper. The clumping may influence not only the comparison of ionization fractions derived from observation and from the theoretical models, but also modify the radiative force and the mass-loss rates (Krtiška et al. 2007; de Koter, Vink & Muijres 2007). On the other hand, the effect of porosity (Owocki et al. 2004; Oskinova et al. 2006a) may lead to decrease of the effective opacity in the X-ray region. This may affect the total X-ray luminosity, but as the porosity affects also the predicted wind parameters (Krtiška et al. 2007) and as its existence in the wind is a matter of discussion nowadays, we do not include it into our models. Note that the present approach of the inclusion of both clumping and porosity into wind models is based on free parameters whose values are not very well constrained observationally nor theoretically.

### 9 CONCLUSIONS

We studied an effect of additional X-ray emission on our NLTE wind models. To this end, we assumed that some part of the wind material is heated to a very high temperature (of the order of \( 10^6 \) K) and emits X-rays, and we studied their influence on wind structure.

Using our wind models we derived the same scaling of the total X-ray luminosity \( L_X \) with the mass-loss rate \( M \) as done by OC. For stars with optically thick winds most of the X-rays are absorbed in the wind, and the X-ray luminosity scales with wind mass-loss rate roughly as \( L_X \sim M \). For stars with optically thin wind in the X-ray region the X-ray luminosity scales as \( L_X \sim M^2 \).

The models with fixed filling factor \( f_X \) can roughly explain the observed \( L_X / L \) relation of stars with optically thick wind in the X-ray region. The remaining deviation between the observed slope of the \( L_X / L \) relation and that derived using fixed \( f_X \) can be the result of the dependence of the shock cooling time on wind density. The stars with optically thin wind exhibiting the ‘weak wind problem’ emit more X-rays than predicted by a simple optically thin scaling. Their enhanced X-ray emission and the ‘weak wind problem’ itself may be caused by large wind shock cooling time, comparable with the hydrodynamical time-scale.

The X-rays influence the ionization state in the whole wind. However, a significant amount of X-rays is emitted only in highly supersonic wind regions. These X-rays mostly do not penetrate close to the stellar surface; consequently the ionization changes induced by X-rays are not large enough to change the radiative force significantly. Because the mass-loss rate is determined in the region close to the stellar surface, the presence of X-rays does not significantly change its value. On the other hand, the terminal velocity is determined in the outer wind regions where the influence of X-rays is more important. Consequently, the wind terminal velocity may be slightly affected by X-rays, especially for stars with weaker ionizing continua (with \( T_{\text{eff}} \lesssim 35000 \text{ K} \)).
Although the Auger processes are important for the ionization balance in the outer wind regions, the non-negligible presence of higher ionization stages (sometimes also called ‘superions’) is a consequence of also a direct ionization.

We compared the model ionization fractions with those derived from observations. For higher ionization stages the inclusion of X-rays leads to better agreement between theory and observations. However, for many ions a significant discrepancy between theory and observations still remains. The discrepancy between the mass-loss rates derived from the Hz line or radio emission and P_v line profiles led Fullerton et al. (2006) to conclude that real wind mass-loss rates of hot stars are much lower than the ‘classical’ ones. This conclusion is sensitive to the assumed P_v ionization fraction. We have shown that for stars with $T_{\text{eff}} \gtrsim 34\,000\,K$ the P_V line becomes a dominant one, which gives a better agreement for hotter stars. But even for these hotter stars a significant disagreement between theory and observations remains. We did not find any significant influence of X-rays on P_v ionization fraction. Our calculations suggest that the effect of X-rays cannot be the reason for the low P_v mass-loss rates. This problem is especially severe for stars with $T_{\text{eff}} \lesssim 34\,000\,K$ for which we predict P_v to be the dominant ionization stage in the wind.

We studied the influence of modified ionization equilibrium due to shock emission on the X-ray line transfer. While continuum absorption by the cool wind in the X-ray domain is not significantly affected by X-ray itself, additional line opacity sources in a cool wind emerge (see also Oskinova et al. 2006b). This may affect the line profiles of more abundant elements (C, N and O) observed in wind emerge (see also Oskinova et al. 2006b). This may affect the ionization balance in the outer wind regions, the non-negligible presence of higher ionization stages (sometimes also called ‘superions’) is a consequence of also a direct ionization.

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APPENDIX A: CALCULATION OF DIAGONAL ELEMENTS OF $\Psi_\nu$

The equation of the radiative transfer (13) is solved using the LU decomposition,

$$\Psi_\nu^{-1} = LU,$$

(A1)

where $L$ is a product of permutation and lower triangular matrices with one subdiagonal, and $U$ is upper triangular matrix with two superdiagonals. In such a case the inversion matrix $\Psi_\nu$ can be easily calculated (Ralston 1965) as

$$\Psi_\nu = U^{-1}L^{-1},$$

(A2)

where $U^{-1}$ and $L^{-1}$ are upper and lower diagonal matrices. If we denote $u \equiv U^{-1}$ and

$$u_{i,j} = U_{i,j}^{-1},$$

(A3)

$$u_{i,j} = -\frac{u_{i,j+1}U_{j+1,j} + u_{i,j-1}U_{j-1,j}}{U_{j,j}},$$

(A4)

then using (A3) and (A4) and similarly for $L^{-1}$, the diagonal elements of $\Psi_\nu$ can be easily calculated.

Instead of using matrix inversion it is possible to derive (13) with respect to the occupation number $N_j$ and calculate partial derivatives $\partial f_j/\partial N_j$ as a solution of the derived system of linear equations. Although this would likely be a quick solution (remember that since we employ LU decomposition for the solution of equation 13, we can use this procedure to solve other equations with the same matrix), we would have to solve these equations for each $N_j$, and this would be very time consuming.

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