

Influence of extreme ultraviolet radiation on the P v ionization fraction in hot star winds

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ABSTRACT

Different diagnostics of hot star wind mass-loss rates provide results that are difficult to reconcile with each other. The widely accepted presence of clumping in hot star winds implies a significant reduction of observational mass-loss rate estimates from diagnostics that depend on the square of the density. Moreover, the ultraviolet P v resonance lines indicate a possible need for an even stronger reduction of hot star mass-loss rates, provided that P v is a dominant ionization stage of phosphorus, at least in some hot stars. The latter assumption is challenged by the possible presence of extreme ultraviolet (XUV) radiation.

Here, we study the influence of XUV radiation on the P v ionization fraction in hot star winds. Using a detailed solution of the hydrodynamical radiative transfer and statistical equilibrium equations, we confirm that a sufficiently strong XUV radiation source might decrease the P v ionization fraction, possibly depreciating the P v lines as a reliable mass-loss rate indicator. However, the XUV radiation also influences the ionization fraction of heavier ions that drive the wind, leading to a decrease of the wind terminal velocity. Consequently, we conclude that XUV radiation alone cannot bring theory and observations into agreement.

We fit our predicted wind mass-loss rates using a suitable formula and we compare the results with the observational mass-loss rate diagnostics. We show that for supergiants and giants the theoretical predictions do not contradict the mass-loss rate estimates based on X-ray line profiles or density-squared diagnostics. However, for main-sequence stars, the predicted mass-loss rates are still significantly higher than those inferred from P v or X-ray lines. This indicates that the ‘weak wind problem’ recently detected in low-luminosity main-sequence stars might also occur, to some extent, for stars with higher luminosity.

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

1 INTRODUCTION

Mass loss plays an important role in the evolution of massive stars. Most of the mass of massive stars is lost during their evolution from zero-age main sequence to the final remnant. Different processes contribute to the mass loss in individual evolutionary phases. These processes include line-driven winds during hot evolutionary stages (Puls, Vink & Najarro 2008a), decretion discs in fast-rotating stars (Lee, Osaki & Saio 1991; Okazaki 2001), luminous blue variable type explosions in hot supergiants (Smith & Owocki 2006), dust-driven winds in cool supergiants (Woitke 2006) and a final supernova explosion (Umeda & Nomoto 2008). Consequently, estimates of the amount of mass lost per unit of time (mass-loss rate)

as a function of stellar parameters are one of the most important elements of evolutionary models.

Unfortunately, the uncertainties in modern determinations of mass-loss rates significantly affect the evolutionary models of massive stars. In the case of the line-driven wind of hot stars, these uncertainties seem to be mostly connected with the occurrence of small-scale inhomogeneities (Hamann, Feldmeier & Oskinova 2008). The inhomogeneities are typically divided into three different groups (microclumping, porosity and vorosity), according to their influence on the spectral features, although they might be caused by the same structure being observed in different wavelengths. Microclumping (also frequently referred to as clumping) accounts for the enhanced density in the optically thin inhomogeneities, and it can be most easily incorporated in the wind models (e.g. Hamann & Gräfener 2004; Puls et al. 2006; Krtička et al. 2008). Microclumping affects the ionization equilibrium via enhanced recombination,

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and consequently it influences the radiative transfer only indirectly (Abbott, Biegging & Churchwell 1981). Porosity (also referred to as macroclumping) accounts for the non-negligible optical depth of inhomogeneities (which can become optically thick) and this directly influences the radiative transfer (Oskinova, Hamann & Feldmeier 2007; Sundqvist et al. 2011; Šurlan et al. 2012a). Porosity affects the line profiles, and it is connected with the different Doppler shifts of individual inhomogeneities (Owocki 2008). From the point of view of predictions for the mass-loss rate, the inhomogeneities might affect the ionization fractions of the wind that drives ions (Krtićka et al. 2008; Muijres et al. 2011), or they might lead to a decrease of the wind mass-loss rate as a result of the base turbulence (Lucy 2007; Krtićka & Kubát 2010).

There could be a simple observational solution to the problem of determining the mass-loss rate, that is, to find an observational characteristic that is not affected by the wind inhomogeneities. There are two potential candidates for such convenient observables: X-ray radiation (either line profiles or the continuum flux distribution; MacFarlane et al. 1991; Owocki & Cohen 2001; Ignace & Gayley 2002; Cohen et al. 2011a) and unsaturated resonance line profiles. The latter case is fulfilled for trace elements, and the P v ion is especially interesting (Crowther et al. 2002; Massa et al. 2003; Fullerton, Massa & Prinja 2006). However, even these characteristics face some problems. The opacity in the X-ray domain scales mostly linearly with the density, and consequently it should be possible, in principle, to model its effect on the X-ray diagnostics in a straightforward way. Indeed, the observations of mostly symmetric X-ray line profiles, which are not strongly affected by absorption, indicate low wind mass-loss rates (Waldron & Cassinelli 2001; Cohen et al. 2010; Gagné et al. 2011). However, these results are challenged by the effect that the porosity might possibly have on the X-ray opacity (Feldmeier, Oskinova & Hamann 2003; Oskinova, Feldmeier & Hamann 2006). Note that there is no general consensus on this problem (Oskinova et al. 2012; Owocki et al. 2012).

Here, we concentrate mostly on the other promising observational characteristic, that is, on the P v resonance lines. The weakness of the observed P v lines also indicates low mass-loss rates of hot star winds (Fullerton et al. 2006). However, the ionization fraction of P v might be modified by the effect of clumping (Puls, Markova & Scuderi 2008b; Krtićka et al. 2008). Additional changes of the P v ionization fraction might be caused by the influence of X-rays. Although our previous calculations have indicated that the P v ionization fraction is not strongly affected by X-rays (Krtićka & Kubát 2009), Waldron & Cassinelli (2010) have argued that the extreme ultraviolet (XUV) radiation might affect P v ionization fractions. Because the work of Waldron & Cassinelli (2010) was based on rather simplified ionization estimates and because the calculations presented in Krtićka & Kubát (2009) were carried out without enhanced XUV radiation, we have decided to fill this gap. We apply our non-local thermodynamic equilibrium (NLTE) wind models to study the influence of the XUV radiation (parametrized in a convenient way) on the P v ionization fraction. The XUV region is defined here as the energy from interval 54.4 eV (He II edge) to 124 eV.

2 WIND MODELS

For our calculations, we use NLTE wind models of Krtićka & Kubát (2010) with a comoving frame (CMF) line force. Our models assume stationary and spherically symmetric wind flow. They enable us to self-consistently predict wind structure from just the stellar parameters (i.e. the effective temperature, mass, radius and chemi-

cal composition). The line radiative force is calculated directly by summing the contribution from individual atomic transitions (i.e. we do not use the CAK line force parameters).

The ionization and excitation state of the considered elements is derived from the statistical equilibrium (NLTE) equations. Ionic models are either adopted from the TLUSTY grid of model stellar atmospheres (Lanz & Hubeny 2003, 2007) or we create them using the data from the Opacity and Iron Projects (Seaton et al. 1992; Hummer et al. 1993). For phosphorus, we have employed data described by Pauldrach, Hoffmann & Lennon (2001). Auger photoionization cross-sections from individual inner-shells have been taken from Verner & Yakovlev (1995) – see also Verner et al. (1993) – and Auger yields have been taken from Kaastra & Mewe (1993). The emergent surface flux is taken from the H–He spherically symmetric NLTE model stellar atmospheres of Kubát (2003, and references therein). For our wind calculations, we assume a solar chemical composition following Asplund et al. (2009).

The radiative force is calculated using the solution of the spherically symmetric CMF radiative transfer equation (Mihalas, Kunasz & Hummer 1975). The corresponding line data were extracted in 2002 from the VALD data base (Piskunov et al. 1995; Kupka et al. 1999). The radiative cooling and heating terms are derived using the electron thermal balance method (Kubát, Puls & Pauldrach 1999). For the calculation of the radiative force and the radiative cooling and heating terms, we use occupation numbers derived from the statistical equilibrium equations. The hydrodynamical equations (i.e. the continuity equation, the equation of motion with the CMF line force and the energy equation with radiative heating and cooling included) are solved iteratively to obtain the wind density, velocity and temperature structure. The wind mass-loss rate is derived from the critical condition (Castor, Abbott & Klein 1975) generalized for the case with the CMF line force. The derived mass-loss rate corresponds to the maximum rate for which a smooth transonic solution can be obtained (Poe, Owocki & Castor 1991).

For our study, we have selected an O star model grid with effective temperatures in the range 30 000–42 500 K. The parameters for the stars with given effective temperatures were obtained using relations derived by Martins, Schaerer & Hillier (2005a) for main-sequence stars, giants and supergiants (see Table 1).

Table 1. Stellar parameters of the model grid.

	Model	T_{eff} (K)	R_* (R_{\odot})	M (M_{\odot})	\dot{M} ($M_{\odot} \text{ yr}^{-1}$)
Main sequence	300-5	30 000	6.6	12.9	9.5×10^{-9}
	325-5	32 500	7.4	16.4	9.8×10^{-9}
	350-5	35 000	8.3	20.9	4.6×10^{-8}
	375-5	37 500	9.4	26.8	1.8×10^{-7}
	400-5	40 000	10.7	34.6	6.4×10^{-7}
	425-5	42 500	12.2	45.0	1.2×10^{-6}
Giants	300-3	30 000	13.1	19.3	8.7×10^{-8}
	325-3	32 500	13.4	22.8	1.8×10^{-7}
	350-3	35 000	13.9	27.2	4.5×10^{-7}
	375-3	37 500	14.4	32.5	1.0×10^{-6}
	400-3	40 000	15.0	39.2	1.8×10^{-6}
	425-3	42 500	15.6	47.4	2.9×10^{-6}
Supergiants	300-1	30 000	22.4	28.8	4.7×10^{-7}
	325-1	32 500	21.4	34.0	7.7×10^{-7}
	350-1	35 000	20.5	40.4	1.3×10^{-6}
	375-1	37 500	19.8	48.3	2.3×10^{-6}
	400-1	40 000	19.1	58.1	3.0×10^{-6}
	425-1	42 500	18.5	70.3	3.7×10^{-6}

Our new models predict slightly lower mass-loss rates than our older models (Krtička et al. 2009), because of the inclusion of line overlaps via the solution of the CMF radiative transfer equation (Krtička & Kubát 2010). The mass-loss rate predictions for all models are also listed in Table 1. We have fitted these mass-loss rate predictions as

$$\log\left(\frac{\dot{M}}{10^{-6} M_{\odot} \text{ yr}^{-1}}\right) = (a + a_1 l) \log\left(\frac{L}{10^6 L_{\odot}}\right) + b + b_1 l, \quad (1)$$

where l is the luminosity class (i.e. 1 for supergiants, 3 for giants and 5 for main-sequence stars) and

$$\begin{aligned} a &= 2.040, & a_1 &= -0.018, \\ b &= 0.552, & b_1 &= 0.068. \end{aligned} \quad (2)$$

We have compared equation (1) with the mass-loss rate predictions of Vink, de Koter & Lamers (2001) calculated for the mass fraction of heavier elements $Z = 0.0134$; note that the solar mass fraction of heavier elements assumed by Vink et al. (2001) is different, $Z = 0.0194$ (Anders & Grevesse 1989). On average, our models predict slightly lower mass-loss rates by a factor of about 1.7. Equation (1) shows an excellent agreement with the Pauldrach, Vanbeveren & Hoffmann (2012) models A^+/A^- of ζ Pup, while the predictions of our equation are a factor of about 1.6 lower than the mass-loss rate of models D^+/D^- .

3 ADDITIONAL X-RAY/XUV RADIATION SOURCE

We include an additional source of X-ray/XUV radiation in our wind models. For this purpose, we use the X-ray emissivity $\eta_X(r, \nu)$ (Krtička et al. 2009, equation 11), which was derived using the numerical simulations of wind instability (Feldmeier, Puls & Pauldrach 1997). This additional high-energy emission starts at the radius $2R_*$ and integrates the emission from the gas with different shock temperatures, as derived from hydrodynamical simulations. In our approach, the X-ray emission lines, which mostly contribute to the high-energy emission in hot stars, are not treated individually, but they are summed over selected wavelengths. This approach is fully satisfactory because most of these lines are optically thin in the cold wind. Consequently, the X-ray emission lines influence the wind ionization equilibrium via Auger and direct photoionization only (e.g. MacFarlane et al. 1991).

The original expression for the X-ray emissivity $\eta_X(r, \nu)$ is modified to test the influence of the XUV radiation on the wind ionization. We introduce a non-dimensional free parameter β_{XUV} that scales the original X-ray emissivity $\eta_X(r, \nu)$ in the XUV region. This region includes frequencies $\nu_{XUV}^{\min} \leq \nu \leq \nu_{XUV}^{\max}$, where ν_{XUV}^{\min} is the He II ionization threshold (54.4 eV). We have selected $\nu_{XUV}^{\max} = 3 \times 10^{16} \text{ s}^{-1}$, which corresponds to 124 eV. Thus, the modified X-ray emissivity included in our models is given by

$$\tilde{\eta}_X(r, \nu) = \begin{cases} 0, & \nu < \nu_{XUV}^{\min}, \\ \beta_{XUV} \eta_X(r, \nu), & \nu_{XUV}^{\min} < \nu < \nu_{XUV}^{\max}, \\ \eta_X(r, \nu), & \nu > \nu_{XUV}^{\max}. \end{cases} \quad (3)$$

For $\beta_{XUV} = 0$, the additional XUV emission is not considered at all and only the additional X-ray ionization source is included, whereas $\beta_{XUV} > 1$ corresponds to the enhanced source of the XUV emission.

4 C v IONIZATION FRACTION AND ADDITIONAL IONIZATION SOURCES

The presence of lines of ions with a higher degree of ionization (e.g. C v) is often used (e.g. by Waldron & Cassinelli 2010) as an argument for the existence of an additional XUV or X-ray ionization source. Although it is generally true that an additional ionization source shifts the degree of ionization, because of the complexity of the processes involved we cannot claim that the presence of a particular ion is caused exclusively by radiation at a chosen frequency.

As an example, let us study the ionization ratio of C IV and C v. Assuming that the populations of the ground levels of these ions dominate (i.e. we can neglect the population of excited states), the ionization balance between the C IV ion (N_4 is its number density) and the C v ion (number density N_5) follows from the equations of statistical equilibrium (Mihalas 1978) as

$$N_4 R_{45} - N_5 R_{54} = 0. \quad (4)$$

Here, we have taken into account only the radiative ionization and recombination (collisional transitions are neglected). The radiative ionization rate is

$$R_{45} = 4\pi \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} J(\nu) d\nu, \quad (5a)$$

and the radiative recombination rate is

$$R_{54} = 4\pi \left(\frac{N_4}{N_5}\right)^* \int_{\nu_4}^{\infty} \frac{\alpha_4(\nu)}{h\nu} \left[\frac{2h\nu^3}{c^2} + J(\nu)\right] e^{-(h\nu/kT)} d\nu, \quad (5b)$$

where an asterisk denotes LTE values and $\alpha_{4,\nu}$ is the photoionization cross-section. Replacing the integrals in equation (5) with values at the ionization frequency ν_4 and taking into account that, for a considered spectral range, $2h\nu^3/c^2 \gg J(\nu)$, we derive from equation (4)

$$\frac{N_5}{N_4} = J(\nu_4) \frac{c^2}{2h\nu_4^3} \left(\frac{N_5}{N_4}\right)^* e^{(h\nu_4/kT)}. \quad (6)$$

Using the Saha–Boltzmann equation, the fraction $(N_5/N_4)^*$ can be eliminated and the latter equation can be further simplified (assuming unity ionic partition function) to

$$\frac{N_5}{N_4} = \frac{c^2}{h^4 \nu_4^3} (2\pi m_e kT)^{3/2} \frac{J(\nu_4)}{N_e}, \quad (7)$$

where N_e is the electron 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 350-1 at roughly $2.3R_*$, without additional ionization sources, from equation (7) we obtain the ionization ratio $N_5/N_4 \approx 7 \times 10^{-4}$ for $\nu_4 = 1.6 \times 10^{16} \text{ Hz}$, $T = 22\,000 \text{ K}$, $N_e = 3 \times 10^9 \text{ cm}^{-3}$ and $J(\nu_4) = 8 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}$. This indicates a low ionization fraction of C v there. However, from our full NLTE models, which consider reliable model ions, for the same location we obtain $N_5/N_4 \approx 0.2$.

The reason for this is that statistical equilibrium equations are complex in hot star winds and their oversimplification, using convenient equations such as equation (7), can lead to incorrect results. In the particular case of the C v ionization fraction, the most important ionization process is not that from the ground level, but that from the less populated upper levels, which are closely coupled with the ground level by a strong bound–bound transition. This information can be obtained only by solving the equations of statistical equilibrium.

Consequently, care has to be taken when making conclusions about the existence of an additional ionization source just from the

observations of C v lines. The same comment is also valid for N v lines (Pauldrach 1987; Krtićka & Kubát 2009).

5 INFLUENCE OF XUV RADIATION ON P v IONIZATION FRACTION AND WIND MODELS

Let us now turn our attention to P v. Without additional XUV sources, for $\beta_{\text{XUV}} = 0$, our models agree with the conclusions of Krtićka & Kubát (2009), according to which the X-rays do not significantly influence the ionization fraction of P v. Only the ionization fraction of P vii (and P vi in cooler stars) is significantly influenced by the X-rays, while P v remains one of the dominant ionization stages.

The inclusion of XUV radiation (with $\beta_{\text{XUV}} = 1$; see Fig. 1) leads to a slight reduction of the P v ionization fraction to roughly 60 per cent of its value when calculated without XUV radiation ($\beta_{\text{XUV}} = 0$). This indicates that a stronger XUV source might lead to a significant reduction of the P v ionization fraction. Indeed, the P v ionization fraction is significantly reduced in the models with $\beta_{\text{XUV}} = \sqrt{10}$, as shown in Fig. 2, where we plot the product of the P v ionization fraction and the wind mass-loss rate $q(\text{Pv})\dot{M}$ averaged over radii $2 \leq r/R_* \leq \min(5, x_{\text{max}})$. Here, x_{max} is the radius of the outer model boundary (in units of R_*).

In Fig. 2, the comparison of predicted P v ionization fractions and those derived from observations by Fullerton et al. (2006) supports the suggestion of Waldron & Cassinelli (2010) that an enhanced source of XUV radiation leads to a reduction of the P v ionization fraction. There is good agreement between the product $q(\text{Pv})\dot{M}$ for the parameter $\beta_{\text{XUV}} = \sqrt{10}$ and the one determined by Fullerton et al. (2006) from observations for supergiants and giants. However, the results for main-sequence stars are ambiguous. While there is good agreement with observations for main-sequence stars with a detected P v line, even without an additional X-ray/XUV source, for stars with only an upper limit of $q(\text{Pv})\dot{M}$ available, even a very strong X-ray/XUV source does not bring the predictions and observations into agreement. Such disagreement could be the sign of a weak wind problem (e.g. Bouret et al. 2003; Martins et al. 2005b).

Waldron & Cassinelli (2010) have argued that because of a unique distribution of XUV radiation, where the strongest XUV emission lines have energies lower than the S v edge (72.7 eV), the XUV radiation affects the ionization fraction of P v and not that of S v. This effect might not be fully included in our models, where the XUV

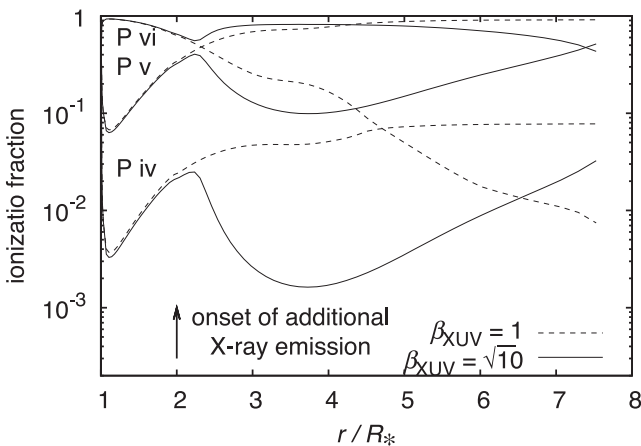


Figure 1. Ionization fraction of individual phosphorus ions in the model 400-1 with different XUV sources.

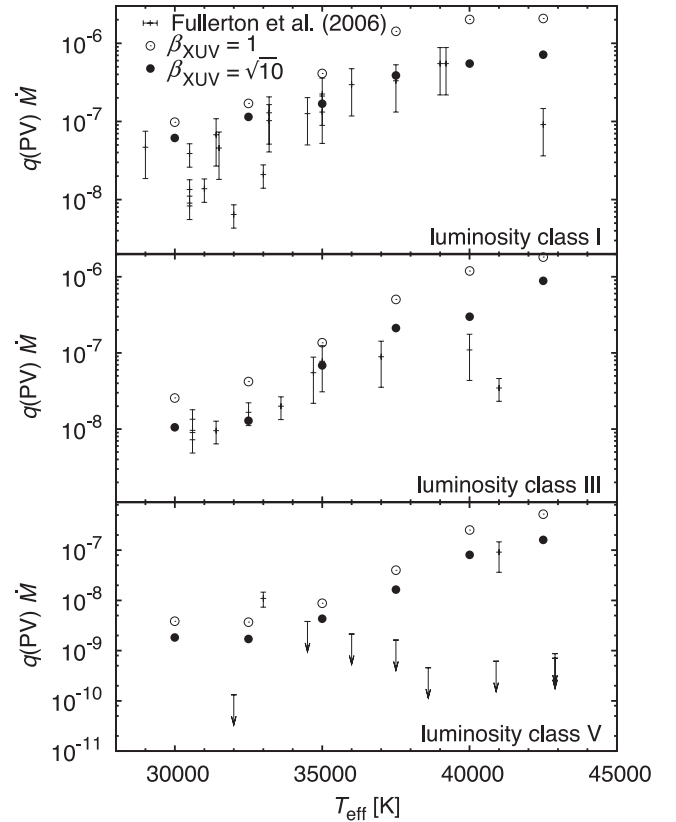


Figure 2. Comparison of the predicted product of the averaged P v ionization fraction and the wind mass-loss rate $q(\text{Pv})\dot{M}$ calculated with $\beta_{\text{XUV}} = 1$ (empty circles) and $\beta_{\text{XUV}} = \sqrt{10}$ (full circles) with the results derived from observations (Fullerton et al. 2006, error bars and upper limits) as a function of stellar effective temperature. The results for different luminosity classes are separated into individual graphs.

emission lines are summed over a corresponding wavelength region. This ensures that the total line emissivity is properly taken into account, but some subtle effects of line distribution might be missing. To test the effect of the XUV line distribution, we have calculated additional models with XUV emission present only for energies lower than 72 eV. These models confirm that, with a convenient distribution of XUV emission, the influence of XUV radiation on the P v ionization fraction is more significant than on S v (roughly by a factor of 2). However, even the ionization fraction of S v is affected by XUV radiation with energies lower than the ionization energy of S v because of the ionization from higher levels of S v, especially from the relatively strongly populated second level $3s3p^3P$ with an ionization energy of 62.4 eV. This is a similar situation to the C v ionization fraction discussed in Section 4.

However, despite the promising results derived for P v in giants and supergiants, a detailed inspection of our models (which consistently include all possible driving ions) shows that there is one additional (and natural) effect of the XUV radiation. Phosphorus is a trace element, and changes to its ionization balance have only negligible effects on the radiation force. However, many ionization states of non-trace elements, which are the wind drivers, are also depopulated by XUV radiation. These ions include C iv (ionization energy $E_{\text{ion}} = 64.5$ eV), N iv ($E_{\text{ion}} = 77.5$ eV), O iii ($E_{\text{ion}} = 54.9$ eV), O iv ($E_{\text{ion}} = 77.4$ eV) and Si iv ($E_{\text{ion}} = 45.1$ eV). This causes drastic changes in the line force accelerating the whole wind. Consequently, the wind becomes overionized and the radiation

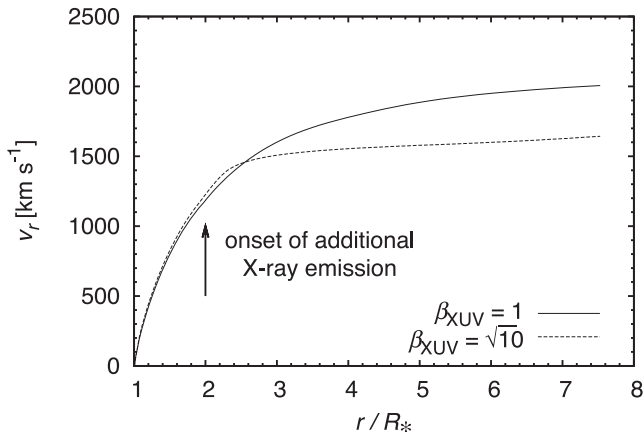


Figure 3. Influence of XUV radiation on the wind radial velocity in the model 400-1.

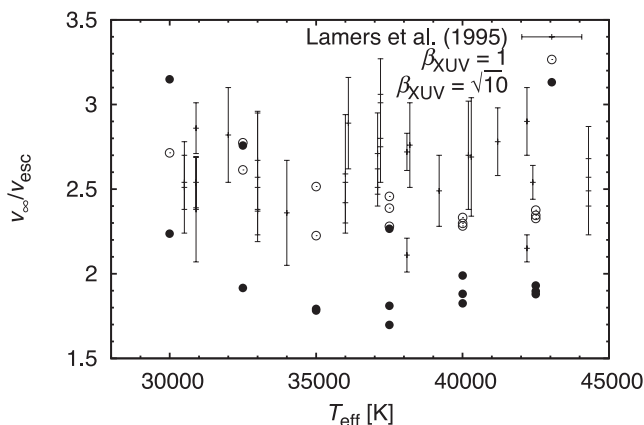


Figure 4. Comparison of the predicted ratio of the wind terminal velocity and escape velocity calculated with $\beta_{\text{XUV}} = 1$ (empty circles) and $\beta_{\text{XUV}} = \sqrt{10}$ (full circles) with the results derived from observed v_{∞} (Lamers, Snow & Lindholm 1995).

driving by higher ionization states becomes inefficient because of their insufficient line opacity. This causes a significant lowering of the radiative force. Consequently, the wind overionization leads to wind stagnation that starts roughly at the radius where the XUV radiation is switched on in our models (i.e. at $r = 2R_*$; see Fig. 3). In our calculations, models of giants and supergiants of all spectral types and main-sequence stars with $T_{\text{eff}} \gtrsim 35000$ K are subject to this effect.

Such stagnation would be observationally manifested by a decrease of the wind terminal velocity. In Fig. 4, we plot the ratio of the wind terminal velocity to the escape velocity $v_{\infty}/v_{\text{esc}}$ from our models, compared with observational results. For a weak additional XUV source $\beta_{\text{XUV}} = 1$, the predicted $v_{\infty}/v_{\text{esc}}$ nicely reproduces the observed results (Krtićka & Kubát 2009). However, for a stronger XUV source $\beta_{\text{XUV}} = \sqrt{10}$, which reproduces the observed P v ionization fractions, the predicted $v_{\infty}/v_{\text{esc}}$ is significantly lower than that based on observational results. This disagreement could, in principle, be partially compensated for in models with an onset of additional XUV emission farther from the stellar surface. However, this is not supported by either models (Feldmeier et al. 1997) or observations (e.g. Waldron & Cassinelli 2001; Leutenegger et al. 2006; Cohen et al. 2011a). In contrast, the onset of XUV emission closer to the star, suggested by observations, leads to an even lower wind terminal velocity, which does not agree with observations.

6 DISCUSSION: WIND MASS-LOSS RATES – THEORY MEETS OBSERVATIONS?

The question of the correct determination of mass-loss rates is the most important of any wind theory and observation. Despite significant progress in line-driven wind theory and, especially, in our understanding of the radiative transfer in structured winds in recent years (Sundqvist et al. 2011; Šurlan et al. 2012a), the answer to this question has not been unambiguously solved. Concerning the P v ionization fractions studied here, a reduction of mass-loss rate predictions by a factor of about 3 is necessary to bring the observation of giants and supergiants and theory into agreement (assuming $\beta_{\text{XUV}} = 1$, in order not to violate the observed terminal velocities).

6.1 P v ionization fractions with XUV emission and clumping

Puls et al. (2008b) have proposed that the problem of weak P v lines is caused by microclumping (see also Crowther et al. 2002; Krtićka et al. 2008). The high density inside the clumps favours recombination, leading to a decrease of the P v ionization fraction. We have tested whether the combination of microclumping and an additional XUV source can bring observations and theory into agreement. For this purpose, we calculated other models, in which we allowed for additional XUV emission and we also took into account the influence of a higher wind density in the clumps on the NLTE equations (as in Krtićka et al. 2008). Within this microclumping approach, the inhomogeneities directly affect the ionization equilibrium only and they do not influence the radiative transfer as a result of porosity. We assume that the clumping starts above the critical point at the same radius as the additional X-ray emission (i.e. at $2R_*$). In this case, the clumping does not affect the predicted mass-loss rates (cf. Krtićka et al. 2008).

Our models show that clumping does not bring observations and theory into agreement. Clumping has an opposite effect from the additional XUV source decreasing the wind ionization. Therefore, with microclumping (and XUV emission), the phosphorus ionization fractions disagree with values derived from observations, while the higher radiative force (because of lower ionization) provides better agreement with observed terminal velocities. We have been unable to find a combination of parameters (describing additional XUV emission and microclumping) that would provide both phosphorus ionization fractions and terminal velocities in agreement with observations. However, the porosity (i.e. the effect of wind structure on the line formation; Oskinova et al. 2007; Sundqvist et al. 2011; Šurlan et al. 2012b) is more promising for the explanation of the remaining discrepancy between theoretical and observed P v line profiles.

6.2 Mass-loss rates from X-ray diagnostics

The situation is slightly different for the mass-loss rate derived from X-ray line profiles than for P v line profiles. The shape of the X-ray line profiles might also imply low mass-loss rates in hot stars (Waldron & Cassinelli 2001). In contrast to P v line profiles, the microclumping does not affect the shape of the X-ray line profiles. However, the influence of porosity is still debated (Oskinova et al. 2012; Owocki et al. 2012). Moreover, these determinations involve some simplifying approximations (e.g. the constant ionization structure of the ambient cool wind).

In Table 2, we compare the mass-loss rates calculated using equation (1) with those derived from X-ray line profiles, and from continuum X-ray absorption in the case of HD 93250. The comparison

Table 2. Wind mass-loss rates estimated for individual stars from X-ray diagnostics compared with our prediction after equation (1).

Star	Sp. type	log (L/L_{\odot})	\dot{M} ($10^{-6} M_{\odot} \text{ yr}^{-1}$)		Source (luminosities and X-ray mass-loss rates)
			X-ray diagnostics	Prediction	
HD 93129A	O2 If	6.17	6.8 ± 2.5	9.2	Cohen et al. (2011a), Repolust, Puls & Herrero (2004)
ζ Pup	O4 If	5.86	3.5 ± 0.3	2.2	Cohen et al. (2010), Puls et al. (2006)
HD 93250	O4 IIIf	5.95	1.4 ± 0.5	6.2	Gagné et al. (2011)
9 Sgr	O4V	5.67	0.34	1.8	Cohen, Wollman & Leutenegger (2011b), Martins et al. (2005a)

might be biased, because HD 93250 and 9 Sgr are binaries and they show peculiar features, including enhanced or non-thermal radio emission or colliding winds (Leitherer, Chapman & Koribalski 1995; Rauw et al. 2002, 2012; Gagné et al. 2011; Sana et al. 2011). Note also that the mass-loss rate in the case of ζ Pup was derived from observations assuming a non-solar chemical composition (Cohen et al. 2010), while our models assume a solar chemical composition.

The results shown in Table 2 show that there is good agreement between the wind mass-loss rates derived from observations and theory for the two supergiants, while for the other two non-supergiant stars, the predicted rates overestimate the observed rates by a factor of about 5. This result might reflect a similar dichotomy between supergiant and main-sequence mass-loss rates found from P v ionization fractions (see Fig. 2).

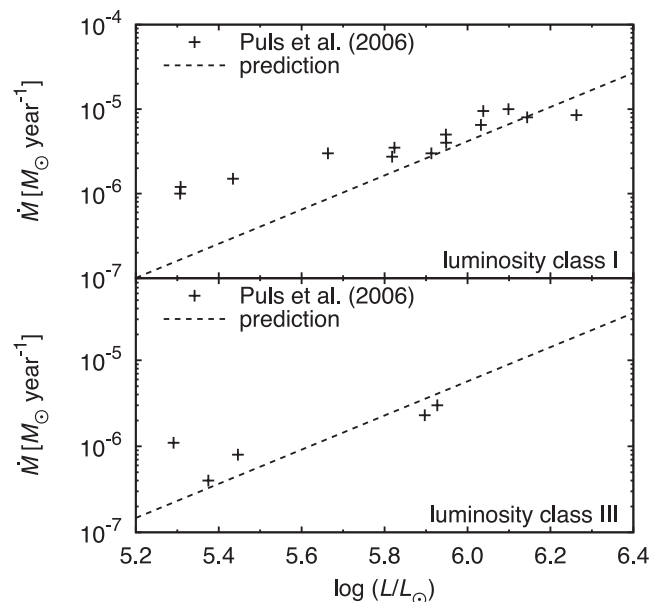
6.3 ρ^2 diagnostics as an upper limit to the mass-loss rates

The H α emission line and infrared (or radio) continua belong to traditional mass-loss rate indicators. However, the amount of H α emission or infrared excess is not directly proportional to the wind density ρ , but to its square ρ^2 (e.g. Puls et al. 2008b). The structured (clumped) wind with a lower mass-loss rate might mimic the spectral features of the homogeneous wind with a higher mass-loss rate. Consequently, the H α emission line or infrared continua might provide only upper limits to the mass-loss rate (Puls et al. 2006), because they give values that correspond to a homogeneous wind. The predicted mass-loss rates should be lower than those derived from ρ^2 diagnostics (i.e. H α emission line or infrared continua).

In Fig. 5, we plot the predicted mass-loss rates calculated using equation (1) as a function of stellar luminosity, compared with the observational upper limits derived from ρ^2 diagnostics by Puls et al. (2006). The luminosity of stars from this observational sample was derived using the stellar parameters taken from Puls et al. (2006). For supergiants with higher luminosity $\log(L/L_{\odot}) \gtrsim 5.8$ and for giants, the mass-loss rates derived from observations are, on average, only slightly higher than those predicted. This indicates that there is only a medium level of clumping in these stars. However, the mass-loss rates derived from observations are significantly higher than predictions for low-luminosity supergiants $\log(L/L_{\odot}) \lesssim 5.8$, which points to a more significant level of clumping in their winds. However, in general, the predicted mass-loss rates are no higher than those derived from the ρ^2 diagnostics. Consequently, even in this case, the predictions do not contradict the observations.

7 CONCLUSIONS

We have tested the influence of XUV radiation on the P v ionization fractions in hot star winds. Using hydrodynamical NLTE wind modelling, we have confirmed the conclusion of Waldron & Cassinelli (2010) that the XUV radiation might decrease the P v ionization fraction. As the result of various ionization and recombination


Figure 5. Comparison of upper limits to the mass-loss rates from ρ^2 diagnostics (Puls et al. 2006) with our predicted dependence of mass-loss rates equation (1) as a function of stellar luminosity.

processes, the P v ionization fraction in hot star winds does not come close to the value of 1, which implies that the role of the P v lines as mass-loss rate indicators in hot star winds is not so straightforward. However, the large amount of XUV radiation necessary to significantly lower the P v ionization fraction to the values implied by observations leads to a decrease of the wind terminal velocity because of inefficient line driving. This contradicts the observations. Moreover, the wind clumping has an opposite effect from the XUV emission that decreases the wind ionization. Consequently, it is unlikely that the effect of lowering the P v ionization fraction by XUV radiation alone can bring the theory and observations into agreement.

We also provide a useful mass-loss rate equation and we compare it with other mass-loss rate diagnostics. We show that, for supergiants and giants, this equation passes two important observational tests against mass-loss rates derived from X-ray line profiles and ρ^2 diagnostics. This supports the reliability of mass-loss rate predictions derived from modern wind codes for luminous hot stars.

For main-sequence stars, the predicted mass-loss rates are significantly higher than those inferred from the P v or X-ray lines. This could indicate that the weak wind problem recently detected in low-luminosity main-sequence stars also occurs, to some extent, for stars with higher luminosity. While there is an explanation of this weak wind problem for low-luminosity main-sequence stars – a too large cooling length (Lucy & White 1980; Martins et al. 2005b; Cohen et al. 2008; Kr̄tička & Kubát 2009; Lucy 2012) or the influence of X-rays on the mass-loss rate (Drew, Hoare & Denby

1994) – there is currently no such explanation that is valid for all main-sequence stars with any luminosity.

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