NLTE models of line-driven stellar winds – II. O stars in the Small Magellanic Cloud

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ABSTRACT
We calculate non-local thermodynamic equilibrium (NLTE) line-driven wind models of selected O stars in the spectral range of O4 to O9 in the Small Magellanic Cloud (SMC). We compare predicted basic wind properties, i.e. the terminal velocity and the mass-loss rate with values derived from observation. We found relatively good agreement between theoretical and observed terminal velocities. On the other hand, predicted mass-loss rates and mass-loss rates derived from observation are in a good agreement only for higher mass-loss rates. Theoretical mass-loss rates lower than approximately $10^{-7}$ $M_\odot$ yr$^{-1}$ are significantly higher than those derived from observation. These results confirm the previously reported problem of weak winds, since our calculated mass-loss rates are in fair agreement with predictions of Vink et al. We study multicomponent models for these winds. For this purpose we develop a more detailed description of wind decoupling. We show that the instability connected with the decoupling of individual wind elements may occur for low-density winds. In the case of winds with very low observed mass-loss rates the multicomponent effects are important for the wind structure, however this is not able to explain consistently the difference between the predicted mass-loss rate and the mass-loss rate derived from observation for these stars. Similar to previous studies, we found the level of dependence of the wind parameters on the metallicity. We conclude that the wind mass-loss rate significantly increases with metallicity as $M \sim Z^{0.67}$, whereas the terminal velocity of wind on average depends on metallicity only slightly, namely $v_\infty \sim Z^{0.06}$ (for studied stars).

Key words: instabilities – hydrodynamics – stars: early-type – stars: mass-loss – stars: winds, outflows – Magellanic Clouds.

1 INTRODUCTION
In recent years, 8-m class telescopes became routinely available for stellar research. This enabled the detailed study of many stars in the Local Group. Clearly, many astrophysically important types of stars can be studied from another perspective. This is especially true for stars from the Small Magellanic Cloud (SMC). Their lower metallicity compared to the solar value (the average metallicity of individual elements is $Z/Z_\odot = 0.2$, e.g. Venn 1999; Bouret et al. 2003) enables one to study the stellar properties and evolution with respect to metallicity.

One of the most important properties of hot stars, which can influence both the observed spectrum and the stellar evolution, is the presence of the stellar wind. The existence of significant dependence of the basic wind properties (i.e. the amount of mass expelled from the star per unit of time, the mass-loss rate and the wind velocity at large distances from the star, and the terminal velocity) on the metallicity has been anticipated already, at the very beginning of the theoretical study of hot star winds (Abbott 1982; Kudritzki, Pauldrach & Puls 1987). Although the most abundant elements in the observed Universe, hydrogen and helium, mostly contribute to the wind density, their contribution to the radiative acceleration is very small (e.g. Abbott 1982). Heavier elements like carbon, nitrogen, oxygen or iron are much more important for the wind acceleration of present hot stars. This is because heavier elements have, effectively, many more lines that are available to absorb the stellar radiation and to accelerate the stellar wind. Clearly, in most cases the radiative force shall be higher for higher metallicity. Consequently, the basic wind properties shall depend on the metallicity.

Although relatively simple expressions for the dependence of the mass-loss rate and the terminal velocity on the metallicity can be obtained even on the basis of the standard Castor, Abbott & Klein (1975) (CAK) theory (e.g. Pulsa, Springmann & Owocki 1998), the detailed dependence is probably more complicated (Puls, Springmann & Owocki 1998; Vink, de Koter & Lamers 2001). It is clear that more precise (non-local thermodynamic equilibrium,
NLTE models of line-driven stellar winds – II

2 MODEL DESCRIPTIONS

The models applied in this paper were in described detail by KK1. Here we only summarize the basic model properties; we refer the interested reader to that other paper.

The models assume spherically symmetric and stationary stellar wind. The occupation numbers of selected atoms and ions (see Table 1) are obtained by the solution of statistical equilibrium (NLTE) equations together with the radiative transfer equation. The radiative transfer equation for lines is solved in the Sobolev approximation (Sobolev 1947; Castor 1974), whereas the continuum radiative transfer equation is solved by the Feautrier method for the spherical coordinates (see Mihalas & Hummer 1974 or Kubát 1993). Derived occupation numbers are used to calculate the radiative force (in the Sobolev approximation) and the radiative cooling/heating term (using the thermal balance of electrons method, Kubát, Puls & Pauldrach 1999). This enables one to solve the hydrodynamic equations. These procedures are iterated to obtain a consistent model structure. Finally, the wind mass-loss rates and terminal velocities of studied stars can be obtained from our models and compared with observations.

Although our models involve some simplifying assumptions, especially the simplified treatment of the radiative transfer (splitting of the radiative transfer in continuum and in the lines, neglect of line overlaps), compared to the more advanced models of e.g. Pauldrach et al. (2001), VKL or Gräfener & Hamann (2005), they were able to correctly predict the basic wind parameters of late O stars (see KK1) and of an A supergiant (see Krtička & Kubát 2004). Moreover, our models have some advantages compared to some other models available in the literature, for example the direct calculation of the radiative force without using force multipliers or multicomponent treatment of model equations (see Krtička & Kubát 2001, hereafter KKII).

Table 1. Atoms and ions included in the NLTE calculations. In this table, ‘Level’ means either an individual level or a set of levels merged into a superlevel.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Levels</th>
<th>Ion</th>
<th>Levels</th>
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<td>10 Ni VI</td>
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</table>
The boundary radiative flux is taken from grid of line-blanketed plane-parallel model atmospheres OSTAR2002 (Lanz & Hubeny 2003) instead of from the H–He spherically symmetric models of Kubát (2003). Because line-blanketed fluxes have generally lower flux in the UV region (where there are many lines important for radiative driving), the obtained mass-loss rates are slightly lower (roughly $1.4 \times$ lower) than the rates derived using H–He fluxes. However, this difference is lower than the dispersion of mass-loss rates for Galactic O stars (see KK1) and does not significantly influence predicted wind terminal velocities (the difference between the terminal velocities is about 100 km s$^{-1}$).

### Table 2. Stellar and wind parameters of selected SMC stars.

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp.</th>
<th>Stellar parameters</th>
<th>Mass-loss rates</th>
<th>Terminal velocities $v_{\infty}$</th>
<th>Source</th>
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<td>$M_\odot$</td>
<td>$T_{\text{eff}}$</td>
<td>$Z/Z_\odot$</td>
<td>$\dot{M}$ $M_\odot$ yr$^{-1}$</td>
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</tr>
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<td>41 500</td>
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3 CALCULATED WIND MODELS

3.1 Parameters of studied SMC stars

Because our main intention for future studies is to investigate the weak winds of B stars, for the present study we selected only the cooler (i.e. with effective temperatures $T_{\text{eff}} < 42,000$ K) O SMC stars, for which at least reliable estimates of their mass-loss rate is available in the literature. We tried to omit stars for which the wind parameters are uncertain and which are binaries. Moreover, we also aim to base the list on broader surveys with larger number of individual stars studied. The stellar and wind parameters of these stars are given in Table 2. The stellar effective temperatures and radii are taken from Puls et al. (1996, hereafter P96), Bouret et al. (2003, hereafter B03), Massey et al. (2004, hereafter M04). Whereas parameters given by P96 were obtained by models without wind-blanketing, parameters given by B03 and M04 were derived using models with wind-blanketing. To study the thin-wind problem in detail, we also added stars from the Martins et al. (2004, hereafter Mr04) sample. These stars are suspected Vz stars, i.e. stars close to the ZAMS. They exhibit a much lower wind spectral signature than that predicted by standard theory. On the other hand, only the upper limits of their observed mass-loss rates and lower limits of their observed terminal velocities are available.

SMC stars are in some sense more suitable for the test of theoretical models than stars from our Galaxy. Since the distance to SMC is known with relatively high precision, the stellar radius and mass-loss rate may also be derived more reliably.

For our study we adopted evolutionary stellar masses either derived by B03 or by us using evolutionary tracks of stars with initial metallicity $Z/Z_\odot = 0.2$ calculated by Charbonnel et al. (1993). The use of the evolutionary masses is a relatively important
assumption that can significantly influence the results derived, due to the discrepancy between stellar masses of hot stars derived from evolutionary tracks and those derived from spectroscopy (Herrero et al. 1992). As KK1 used evolutionary masses in their analysis, we also use evolutionary masses here, but in fact these masses are nearly equal for many stars from the KK1 sample. Our SMC sample is not homogeneous in that sense; for some stars these masses are equal, but for a significant fraction of stars the evolutionary mass is roughly 1.5 times higher than the spectroscopic one. The use of spectroscopic masses instead of the evolutionary ones would help to obtain a better agreement between observation and theory for some stars, but it would cause differences for some others.

When available, the abundances of individual elements were taken from the literature, but in other cases we assumed an average value $Z/Z_\odot = 0.2$ derived for SMC stars (e.g. Venn 1999, M04). We use a Galactic level of helium abundance.

There are indications that stellar winds of O stars are clumped (e.g. B03). From the observational point of view, the possible wind clumping decreases the wind mass-loss rate inferred from the observation because the line profiles of clumped wind mimic those with higher mass-loss rate. According to the numerical simulations of wind instability (e.g. Feldmeier, Puls & Pauldrach 1997; Runacres & Owocki 2002), the theoretical mean mass-loss rate is nearly the same for smooth and structured winds. Thus, if the observations really show signatures of clumping in all the spectral regions where the stellar wind is observed, then, according to our present knowledge, the theoretically predicted values of mass-loss rates should basically correspond to the values derived from observations with an account of clumping. For our study we adopted the values derived from observations assuming ‘smooth’ winds, partly because these values were for a larger SMC sample (to our knowledge) derived only by B03 and partly because the models of wind-clumping are still schematic.

Wind parameters adopted for the comparison with theoretical values will be discussed individually for those stars for which it is necessary. Note that in the text we will term the mass-loss rate estimated from observation as ‘observed mass-loss rate’, although one should keep in mind that this quantity cannot be directly derived from spectra and that it is model-dependent.

### 3.1.1 NGC 346 WB 1

This is a multiple system (Heydari-Malayeri & Hutsemékers 1991). The terminal velocity derived for this system by P96 $v_\infty = 2650 \text{ km s}^{-1}$ is marked as uncertain due to the complexity of the absorption profile. P96 note that another possible value of the terminal velocity is $v_\infty = 2250 \text{ km s}^{-1}$. Prinja & Crowther (1998) obtained a value of the edge velocity (velocity at which the line profile meets the continuum level) of $v_{\text{edge}} = 2830 \text{ km s}^{-1}$ for N v lines. Using their derived approximate relation $v_\infty = 0.8v_{\text{edge}}$, we obtain a terminal velocity $v_\infty = 2260 \text{ km s}^{-1}$. Thus, we adopted $v_\infty = 2250 \text{ km s}^{-1}$ as a value of the terminal velocity.

### 3.1.2 NGC 346 WB 4

The terminal velocity observed by P96, $v_\infty = 1550 \text{ km s}^{-1}$, is quoted as uncertain. The typical terminal velocity for stars of similar spectral type is higher, and the terminal velocity, calculated as twice the escape velocity (roughly suitable for SMC stars; B03), is $1900 \text{ km s}^{-1}$. Using the approximate relation $v_\infty = 0.8v_{\text{edge}}$, and the measurement of the edge velocity of the C iv lines from Prinja & Crowther (1998), we obtain $v_\infty = 1950 \text{ km s}^{-1}$. Hence, we adopt this value as the terminal velocity.

### 3.1.3 NGC 346 WB 6

The edge velocity obtained for this star by Prinja & Crowther (1998), $v_{\text{edge}} = 1925 \text{ km s}^{-1}$, is lower than the terminal velocity $v_\infty = 2250 \text{ km s}^{-1}$ derived by P96 or that of $v_\infty = 2300 \text{ km s}^{-1}$ from B03. This difference probably illustrates the fact that the correct determination of wind velocities for SMC is difficult due to their low wind density.

This star was independently studied by P96, who obtained a slightly lower value of the effective temperature than B03 ($T_{\text{eff}} = 40000 \text{ K}$).

### 3.1.4 AzV 232

Crowther et al. (2002) applied models with wind blanketing to study the stellar parameters of this star, and they obtained a much lower value of the effective temperature than P96 ($T_{\text{eff}} = 32000 \text{ K}$). However, we calculated the wind parameters with this new determination of stellar parameters (i.e. the effective temperature, stellar mass, radius and abundances of C, N and O) and we obtained too low a value of the mass-loss rate ($M = 9 \times 10^{-7} M_\odot \text{ yr}^{-1}$), much lower than the observed value. Also, models of VKL with the new parameters predict a mass-loss rate that is about five times lower than the observed value. Probably, this may be caused by the fact that this star has a very peculiar chemical composition ($Z(C)/Z_\odot (C) = 0.07$, $Z(O)/Z_\odot (O) = 0.1$, whereas $Z(N)/Z_\odot (N) = 2.0$, Crowther et al. 2002) and abundances of other elements which are also important for driving of the stellar wind were not determined. Thus, to keep our sample more homogeneous, we used the stellar parameters derived by P96.

#### 3.2 Comparison of calculated wind parameters with observation

In Fig. 1 we compare the calculated wind terminal velocities for selected stars with observed values. While for some stars there is a very good agreement between observed and calculated terminal velocities, for some stars the agreement is worse. Before we discuss

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Comparison of calculated and observed terminal velocities. Stars for which there is no reliable estimate of their terminal velocities (in fact those stars that exhibit very weak winds) were excluded from the plot. A line denotes a one-to-one relation.
this problem in an upcoming section, let us conclude that the derived scatter between observed and calculated wind terminal velocities is slightly higher than that for Galactic stars (see KK1).

Generally, it is difficult to assess the accuracy of determination of wind parameters. P96 state that, due to the edge variability and contamination of the edges of the wind absorption lines by underlying the photospheric lines, the terminal velocities should be regarded as accurate up to ±10 per cent. Taking this as a typical error of terminal velocity determination, we conclude that, with the exception of stars NGC 346 MPG 368, AzzV 26, AzzV 232 and AzzV 238, the rest of the terminal velocity estimations lie within the mentioned uncertainty interval.

According to the predictions of stellar wind theory, the terminal velocity of wind $v_\infty$ is correlated with the surface escape velocity $v_{\text{esc}}$. For Galactic O stars the value of $v_\infty/v_{\text{esc}}$ does not depend on their effective temperature and has a mean value of about 2.5 (Lamers, Snow & Lindholm 1995). Thus, we also plot the ratio of $v_\infty/v_{\text{esc}}$ for studied stars (see Fig. 2, where we compare ratio of $v_\infty/v_{\text{esc}}$ derived using theoretical and observed values of $v_\infty$). The mean value of $v_\infty/v_{\text{esc}} \sim 2.3$ is slightly lower than that obtained by KK1 for Galactic stars. Our calculated $v_\infty/v_{\text{esc}}$ ratio is slightly lower than the recent observational finding of Evans et al. (2004), who derived the median $v_\infty/v_{\text{esc}} = 2.63$ for SMC stars with effective temperatures higher than 24 000 K. Because B03 obtained $v_\infty/v_{\text{esc}} \sim 2.3$ for their (however limited) sample, we conclude that our calculations are in agreement with other studies and that our results may indicate that the terminal velocities of SMC hot stars are slightly lower than that of Galactic hot stars.

Similarly to Galactic O stars, there is a large scatter of both observed and theoretical $v_\infty/v_{\text{esc}}$ values (see Fig. 2). The scatter of the theoretical values of $v_\infty/v_{\text{esc}}$ is slightly higher for SMC stars than for Galactic stars (KK1). The origin of this scatter is probably partly connected with the high sensitivity of the terminal velocities on detailed wind parameters in the outer wind regions (see Puls, Springmann & Lennon 2000 and also Section 4.3) and also with the uncertain values of the terminal velocities.

The comparison of calculated mass-loss rates and mass-loss rates derived from observations in Fig. 3 shows relatively good agreement for stars with higher mass-loss rates ($M \gtrsim 10^{-7} M_\odot$ yr$^{-1}$), in many cases better than for stars in our Galaxy (KK1). This is probably due to the fact that the distance to the SMC is known with a relatively high precision and, thus, the basic stellar parameters are known also with a high precision (probably with the exception of some systematic effects, such as the wind-blanketing effect, which may influence parameters of both stellar groups). However, there is a significant disagreement between theoretical and observed values for lower mass-loss rates ($M \lesssim 10^{-7} M_\odot$ yr$^{-1}$). In this case the predicted mass-loss rates are more than 10 times higher than those derived from spectral analysis of observed data. This is not only a problem with our models; the predictions of VKL show the same behaviour (see B03; Martins et al. 2004, 2005). To demonstrate this conclusion, we have added the mass-loss rate predictions of studied stars calculated using the VKL recipe into Fig. 3. The possible origin of this discrepancy will be discussed in Section 5.

Our results for possible young Vz stars with thin winds ($M \lesssim 10^{-7} M_\odot$ yr$^{-1}$) from the Mr04 sample do not show that the systematic disagreement between predicted mass-loss rates and mass-loss rates derived from observation is higher than for generally older stars with thin winds from the B03 sample (see Fig. 3).

For stars with very small mass-loss rates ($M \lesssim 10^{-7} M_\odot$ yr$^{-1}$), only the upper limits of their terminal velocities are available in the literature. The predicted terminal velocities of these stars are consistent with the upper limits. Note, however, that this is not a check of the models because the standard wind theory predicts that the terminal velocities and mass-loss rates are related – if the mass-loss rate of these stars is really much lower than the prediction derived in this paper, then their terminal velocities may be much higher.

The mass-loss rates derived by the VKL recipe are slightly higher than ours, although KK1 found a relatively good agreement between these theoretical rates. This is caused by using a different boundary flux. The line-blanketed fluxes from the OSTAR2002 grid used in this work have lower flux in the UV domain (this domain is important for the line-driving) than the H–He models used by KK1, and consequently the derived mass-loss rates are slightly lower. However, the effect of different boundary fluxes on the terminal velocities is small.

### 3.3 Wind momentum–luminosity relationship

The wind momentum–luminosity relationship (see Kudritzki & Puls 2000, and references therein) may provide an independent method...
for the determination of stellar, and consequently also galactic, distances. However, to achieve this, detailed calibration of this relationship is necessary, especially with respect to the metallicity. The low-metallicity environment of the SMC provides an ideal tool for such a calibration.

We compare the theoretical modified wind momentum–luminosity relationship \( \dot{M}v_{\infty}(R_*/R_\odot)^{\alpha_2/2} \) obtained for considered stars using our NLTE wind models with a relationship derived from observations of these stars (see Fig. 4). We excluded observed values for any stars for which only the upper limits of their terminal velocities were derived from observation. We conclude that there is a relatively good agreement between calculated values and those derived from observation. Note, however, that the agreement for excluded stars with unknown terminal velocities (for stars with derived from observation) is very poor (using either the lower limits of their terminal velocities or the terminal velocities derived from our calculations), since their predicted mass-loss rates are much higher than the observed ones. On the other hand, standard theory predicts that terminal velocities and mass-loss rates are related. In such a case the terminal velocities of these stars could be much higher and the agreement between the predicted and the observed wind momentum–luminosity relationship could be improved.

We also calculated the linear regression of both theoretical and observed modified wind momentum–luminosity relationship for considered stars:

\[
\log [\dot{M}v_{\infty}(R_*/R_\odot)^{\alpha_2/2}] = x \log (L/L_\odot) + \log D_0 \quad \text{(CGS)},
\]

and compared it with the theoretical values derived for Galactic stars (Table 3). First, due to the relatively good agreement of mass-loss rates, there is a good agreement between the theoretical and observed modified wind momentum–luminosity relationship for SMC stars (excluding stars with thin wind). Moreover, due to the lower mass-loss rates of SMC stars, the \( D_0 \) value is significantly lower than that for Galactic stars. Also, the slope is slightly different. The roughly 5–6 times lower modified wind momentum derived in the present study, as compared to that derived by KK1 for Galactic stars, is mostly due to lower wind mass-loss rates caused by the low metallicity of the SMC and, to a lesser extent, by a downward revision of mass-loss rates due to the use of blanketed model atmospheres.

### 4.1 Effective temperature and stellar mass

A comparison of mass-loss rates and terminal velocities for studied stars, calculated with the original set of parameters and with stellar effective temperature increased by 1000 K is given in Fig. 5. Apparently, for a higher effective temperature the mass-loss rate is higher, in agreement with other theoretical predictions (see equations 2 and

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**Table 3.** Comparison of modified wind momentum–luminosity relationship (see equation 1) taken from different sources. SMC denotes sample considered in this paper, either calculated from theoretical values or from values derived from observation (again excluding the observed values for stars with very weak winds).

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \log D_0 )</th>
<th>( x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic (Vink et al. 2000)</td>
<td>18.68 ± 0.26</td>
<td>1.825 ± 0.044</td>
</tr>
<tr>
<td>Galactic (KK1)</td>
<td>18.7 ± 2.3</td>
<td>1.83 ± 0.40</td>
</tr>
<tr>
<td>SMC (theoretical)</td>
<td>16.6 ± 0.2</td>
<td>2.08 ± 0.04</td>
</tr>
<tr>
<td>SMC (observed)</td>
<td>16.6 ± 2</td>
<td>2.1 ± 0.4</td>
</tr>
</tbody>
</table>

---

**Fig. 4.** Comparison of the calculated (crosses) and observed (circles) modified wind momentum for considered stars. Note that observed values for stars with unknown terminal velocity were excluded from this plot as it is possible to obtain at most only the lower limits to their modified wind momentum (for stars with known observed mass-loss rates). The linear regression of calculated data of SMC and Galactic (KK1) stars is also plotted.

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**NLTE models of line-driven stellar winds – II**
4). From our calculations it is possible to derive that the mass-loss rate scales with the effective temperature, as
\[ \dot{M} \sim T_{\text{eff}}^{1.04}, \]  
from which the effective parameter \( \alpha' = 0.38 \). This scaling is in a relatively good agreement with the scaling of Vink et al. (2000, see equation 4), which implies \( \dot{M} \sim T_{\text{eff}}^{0.8} \). The dependence of the terminal velocity on the effective temperature (Fig. 5) is more scattered.

The variations of the mass-loss rate and the terminal velocity with stellar mass are more stringent (Fig. 6). With increasing stellar mass the mass-loss rate decreases: on average,
\[ \dot{M} \sim M^{-1.60}, \]  
with fair agreement with equations (2), (4) for the derived value \( \alpha' = 0.38 \). The terminal velocity is proportional to the escape velocity. From our calculations we derive the average relation
\[ v_{\infty} \sim M^{0.52}, \]  
which clearly reflects this proportionality.

It is clear that some part of the discrepancy between observed and theoretical wind parameters may be attributed to the uncertainties in the determination of the stellar parameters (mass and the effective temperature). Especially, the downward revision of the stellar mass by a factor of 1.5 (e.g. due to the difference between the spectroscopic and evolutionary masses) would cause a downward revision of the terminal velocities by a factor of about 1.3 and would double the mass-loss rate. On the other hand, since the distance to the SMC is known with a relatively high degree of precision, we conclude that another source of discrepancy between observed and predicted wind terminal velocities is probably also present. Moreover, if the scatter in higher terminal velocities is given purely by the uncertainties of determination of stellar mass and effective temperature, then a similar effect should be also present in KK1, where slightly better agreement between theoretical and observed terminal velocities was derived.

4.2 Abundances

To study the variations of wind parameters with metallicity we recalculated wind models with the same stellar parameters as in Table 2, however with the abundance of heavier elements 1.5 times higher. Comparison of the mass-loss rates and the terminal velocities calculated with different metallicities is given in Fig. 7.

For higher metallicity, the radiative force is higher and consequently also the mass-loss rate is higher. We have found that for studied stars the relation
\[ \dot{M} \sim Z^{0.67}, \]  
holds. This is in a good agreement with VKL (see equation 5).
The situation with the variations of the terminal velocity with the metallicity is more complicated. In Section 3.2 we concluded that the ratio of the terminal velocity of wind to the stellar escape velocity $v_\infty/v_{esc}$ may be slightly higher for Galactic stars than for SMC stars. When the metallicity is varied, the wind density changes; consequently the wind ionization and the excitation state vary, and hence the terminal velocities of studied stars also vary. However, these variations are not monotonic, as can be seen from Fig. 7. For some stars the terminal velocity does not significantly change with metallicity, for some of them it increases, and for some of them it decreases. On average, the terminal velocity slightly increases with increasing metallicity for studied SMC stars:

$$v_\infty \sim Z^{0.06}.$$  

From the calculations of Kudritzki (2002), we can infer a steeper proportionality, roughly $v_\infty \sim Z^{0.12}$.

### 4.3 Sensitivity of $v_\infty$ on the conditions in the outer wind

Although on average the value of $v_\infty$ depends only slightly on metallicity, the high scatter between terminal velocities derived using different metallicities in Fig. 7 may seem surprising. However, a similar effect was, in a different context, reported by other authors (e.g. Puls et al. 2000). The O star winds in the outer regions are accelerated mainly by a few dozen lines of lighter elements (such as C, N and O; see Pauldrach 1987; Vink, de Koter & Lamers 1999 and also Figs 8 and 9 of this paper). In such a case, the line acceleration is very sensitive to the detailed wind structure (i.e. temperature, density and chemical composition). Parity due to this, large variations of $v_\infty/v_{esc}$ (both observed and theoretical, see Lamers et al. 1995 and Pauldrach et al. 1990) occur for individual stars. This is also likely to be the cause for the high scatter between the terminal velocities derived using different metallicities in Fig. 7. This scatter also occurs when variations of terminal velocity with temperature (see Fig. 5) are studied. To a lesser extent this is also true for the variations of stellar mass (see Fig. 6).

The metallicity of studied stars is not known with a high degree of precision. For many stars we just used the scaled Galactic chemical composition, although significant deviations from this scaling exist (e.g. B03; they are also probably manifested by a different number ratio of WN to WC stars in the Clouds, see Mikulášek 1969). Moreover, we do not have any information on the abundance of many elements that are important for the radiative driving at all (e.g. Ne, Ar). Even worse, there are large differences in the chemical composition of individual stars (e.g. B03). To conclude, some part of the higher level of scatter between observed and predicted terminal velocities can be attributed to the poorly known chemical composition of most of the studied stars. The uncertainties of the determination of other stellar parameters, i.e. the stellar mass and the effective temperature, may (besides the approximations involved in our code) also contribute to this scatter.

### 5 MULTICOMPONENT EFFECTS

Stellar winds of hot stars are accelerated mainly by the absorption of radiation in the resonance lines of heavier elements. The radiative acceleration acting on individual elements is, however, different, and consequently individual elements have different velocities. As a result, stellar winds of hot stars have a multicomponent nature (e.g. Springmann & Pauldrach 1992, KKII). For many stars the velocity differences are small, thus the wind multicomponent nature can be neglected in this case. Krtečka et al. (2003) showed that the velocity differences between wind components are larger in the low-metallicity environment, meaning that multicomponent effects are more important. However, as was noted e.g. by Mr04, even for the relatively low-metallicity environment of the stellar wind of SMC stars, the multicomponent effects can be neglected.

On the other hand, these considerations are based on the assumption that the heavier elements can be described by one component.
only. In other words, usually it is assumed that the atomic mass of heavier ions is the same, the radiative acceleration on heavier elements is the same and consequently these elements have the same mean velocity. However, in reality individual elements have different masses, the radiative acceleration acting on them is also different and consequently these elements have different mean velocities. Hence, multicomponent effects may occur for higher densities and metallicities than previously assumed.

5.1 Velocity differences in the stellar wind

To estimate the importance of multicomponent effects in the stellar wind of SMC stars we calculate the approximate velocity differences between the individual heavier elements \( h \) (accelerated by the line absorption) and the passive wind component \( p \) (hydrogen + helium) using the momentum equation of individual wind elements. In the case of stationary spherically symmetric stellar wind this equation reads (cf. Burgers 1969, KKII)

\[
v_{a,a} \frac{dv_{a}}{dr} = g_{a}^{\text{rad}} - g - \frac{1}{\rho_{a}} \frac{d}{dr} \left( \alpha_{a} \rho_{a} \right) + \frac{q_{a}}{m_{a}} E + \frac{1}{\rho_{a}} \sum_{b \neq a} K_{ab} G(x_{ab}) \left( \frac{n_{a} - n_{b}}{n_{a} - n_{b}} \right),
\]

where \( v_{a,a} \) and \( \rho_{a} \) are the velocity and the density of component \( a \) (\( a = p \) or \( a = h \)), \( \alpha_{a} \) is the isothermal sound speed, \( E \) is the charge separation electric field, \( g \) is the gravitational acceleration, \( g_{a}^{\text{rad}} \) is the radiative acceleration and \( q_{a} \) and \( m_{a} \) are charge and mass of particle \( a \), respectively. The frictional parameter has the following form:

\[
K_{ab} = n_{a} n_{b} \frac{4 \pi q_{a} q_{b}^{2}}{k T_{ab}} \ln \Lambda,
\]

where \( n_{a} \) and \( n_{b} \) are the number densities of individual components, and the mean temperature of both components is

\[
T_{ab} = \frac{m_{a} T_{b} + m_{b} T_{a}}{m_{a} + m_{b}}
\]

\[\text{(13)}\]

\( T_{a} \) and \( T_{b} \) are temperatures of the wind components \( a \) and \( b \) and \( \ln \Lambda \) is the Coulomb logarithm. The argument of the Chandrasekhar function \( G(x_{ab}) \) is

\[
x_{ab} = \frac{|v_{b,a} - v_{a,a}|}{\alpha_{ab}},
\]

where

\[
\alpha_{ab} = \frac{2k (m_{a} T_{a} + m_{b} T_{b})}{m_{a} m_{b}}.
\]

For low velocity differences (\( x_{ab} < 1 \)), the flow is well coupled. However, for higher velocity differences (\( x_{ab} \geq 1 \)), the Chandrasekhar function is decreasing and this behaviour may enable the dynamical decoupling of wind components (see Springmann & Paudrach 1992, KKII).

In the momentum equation of heavier ions (equation 11) the left-hand term and the pressure term can be neglected. The gravitational acceleration and the electric polarization field term can also be neglected. Finally, due to the high number density of the passive component (hydrogen + helium) compared to the number density of heavier elements the only important frictional term is that between passive and other components. Consequently, the approximate momentum equation of heavier element \( h \) is

\[
\dot{s}_{h}^{\text{rad}} = \frac{1}{\rho_{h}} K_{hp} G(x_{hp}).
\]

This equation states that the whole momentum obtained by individual heavier elements due to the line-absorption is transferred by friction to the passive component. Using the Taylor expansion of the Chandrasekhar function (appropriate for \( x_{hp} < 1 \))

\[
G(x_{hp}) \approx (2x_{hp})/(3\sqrt{\pi} x_{hp}),
\]

the relative velocity difference between passive component and a given heavier ion \( h \) is

\[
x_{hp} \approx \frac{3k T}{\alpha_{hp} n_{p}^{8/3} q_{p}^{2} \ln \Lambda},
\]

where we have assumed \( T_{p} \approx T_{h} \approx T \). For our discussion the relevant quantity is not the radiative acceleration \( g_{h}^{\text{rad}} \) itself, but the radiative force \( f_{h}^{\text{rad}} = \rho_{h} \dot{s}_{h}^{\text{rad}} \) (per unit volume). Thus,

\[
x_{hp} \approx \frac{3k T}{n_{p} \alpha_{hp}} \rho_{h}^{2} \frac{8}{3} \sqrt{\pi} q_{p}^{2} \ln \Lambda.
\]

The work done by the radiative acceleration is used to lift the wind material from the stellar gravitational well. Thus, for stars with the same mass-loss rates (and the same velocity field) the radiative force (at corresponding radii) shall be similar. These stars with lower metallicities have lower \( n_{h} \) and consequently higher \( x_{hp} \).

Figure 9. The contribution of lines with different strengths to the radiative force at the critical point (\( r \approx 1.05 R_{*} \), left-hand panel) and in the outer wind region (\( r \approx 18.5 R_{*} \), right-hand panel) for the star AzV 238. The total relative contribution to the radiative force \( f_{\text{line, tot}}^{\text{rad}}/f_{\text{rad}} \) summed over lines with given individual contribution to the radiative force \( f_{\text{line}}^{\text{rad}}/f_{\text{rad}} \) is plotted using boxes. The solid line denotes the number of spectral lines whose relative contribution to the radiative force lies in a given interval. Radiative acceleration close to the star is mainly due to hundreds of lines whose \( f_{\text{line}}^{\text{rad}}/f_{\text{rad}} \) lies in the interval \((10^{-3}-10^{-2})\), whereas the acceleration in the outer regions is given just by few dozens lines with \( 10^{-2} < f_{\text{line}}^{\text{rad}}/f_{\text{rad}} < 10^{-1} \).
stars with lower metallicities also have lower mass-loss rates, lower \( n_p \) and consequently even higher \( x_{hp} \). Due to these two effects (see also Krtička et al. 2003), stars with lower metallicities have higher velocity differences between wind components. The crucial point is, however, that heavier elements which are not abundant in the stellar wind (i.e. \( n_s \ll n_p \)) and which significantly contribute to the radiative acceleration (i.e. their \( f_{rad}^s \) is large) may have large relative velocity differences (\( x_{hp} \)); in many cases \( x_{hp} \approx 1 \). In such a case, instability connected with the decoupling of the considered element may occur.

Let us first roughly estimate in which situation this may occur. Let \( u_{hp}^k \) be the relative contribution of a given element \( h \) to the total radiative force \( f_{rad}^k \), i.e.

\[
 f_{rad}^k = u_{hp}^k f_{rad}.
\]

(19)

Neglecting the gravity, the pressure term and the electric polarization field, the total radiative force can be approximated from the momentum equation (equation 11) of the passive component as

\[
f_{rad} \approx \rho v_r \frac{dv_r}{dr}.
\]

(20)

where \( v_r \) is the mean wind velocity, we may assume \( v_r \approx v_{zp} \). The velocity gradient can be estimated as

\[
 v_r \frac{dv_r}{dr} \approx \frac{v_r^2}{r_s};
\]

(21)

for \( n_h \) we can write, from the approximate continuity equation,

\[
n_h \approx Z_h \frac{M}{4\pi R_s^2 v_{sc,mh}}
\]

(22)

where \( Z_h \) is the density of a given element relative to the bulk density \( \rho \) in the stellar atmosphere (\( \rho_s = Z_h \rho \). Consequently, using equations (18)–(22), we derive

\[
x_{hp} \approx u_{hp}^k v_{sc,mh}^3 \frac{m_{h} \sqrt{3\kappa T}}{Z_h M^2 2 q_p^* p m_{h} \ln \Lambda}
\]

(23)

In the case where the heavier ions are approximated by one component only, we have \( u_{hp}^k = 1 \) and we arrive at equation (6) of Krtička et al. (2003). However, in many cases the abundance of individual element \( Z_h \) is much lower than \( q_0 \) (the ratio of the total density of the heavier 'absorbing' ions and the passive component in the atmosphere) and, thus, the predicted velocity differences are larger. Equation (23) can also be rewritten in a more convenient form, as

\[
x_{hp} \approx 0.015 u_{hp}^k v_{sc,mh}^3 R_{12} \frac{A_{h}}{Z_h M^2 11 \sqrt{\pi \ln \Lambda}^2},
\]

(24)

where we have assumed \( m_p = m_{H}, q_p = e z_p, q_h = e z_h \) and \( m_{h} = A_{h} m_{H} \), where \( e \) is the elementary charge and \( m_{H} \) is the proton mass, and the scaled quantities are \( M_{-11} = M/(10^{-11} M_{\odot} \text{yr}^{-1}) \), \( v_{sc} = v_{sc} (10^4 \text{cm s}^{-1}) \), \( R_{12} = R_s / (10^{12} \text{cm}) \), and \( T_4 = T / (10^4 \text{K}) \). From equation (24) it follows that for heavier elements (\( A_h \approx 10 \)) with low abundance (\( Z_h \approx 10^{-5} \)) and which significantly contribute to the radiative force (i.e. \( n_s \approx 0.1 \)), the decoupling (\( x_{hp} \gtrsim 1 \)) can occur for relatively large mass-loss rates (of order \( 10^{-8} M_{\odot} \text{yr}^{-1} \)). The mass-loss rate for which the decoupling occurs in the winds of SMC stars is approximately five times higher than the mass-loss rate for which the decoupling occurs in the winds of Galactic stars, since \( Z_A_{\odot} \approx 0.2Z_{A_{SMC}} \).

Equation (24) only provides a very approximate expression for the velocity difference, mainly due to a very simplified velocity gradient assumed in equation (21). For a more reliable estimate it is much better to use equation (18).

Note that this picture of decoupling is somehow different from that presented by other studies, i.e. Springmann & Pauldrach (1992) and KKII, and as discussed by Mr04. These studies assumed that all heavier ions which are accelerated by line-transitions decouple from the mean (passive) flow. However, now we discuss the more realistic description that individual ions decouple from the mean flow separately.

5.2 Velocity differences in the winds of studied SMC stars

We used our NLTE wind code to calculate approximative velocity differences in studied SMC stellar winds. For this purpose we applied equation (18), where both the contribution of a given element to the radiative force \( u_{hp} \) and charges of wind components \( q_p \) and \( q_h \) are calculated using our NLTE wind code.

The calculated values of \( x_{hp} \) for individual stars and individual elements are given in Fig. 10. Generally, the relative velocity differences are smallest close to the star, where the stellar wind is relatively dense. As the stellar wind accelerates, the wind density is lower and the velocity differences are higher. At some point the velocity differences reach a maximum and, for larger radii, decrease downwards due to the decreasing velocity gradient. This general behaviour of the relative velocity differences was described elsewhere (KKII). In our case the behaviour is more complicated, mainly due to the processes of ionization and recombinations.

For most of the stars and for most of the elements the velocity differences are rather low (\( x_{hp} \ll 1 \)), thus there occurs no decoupling in this case. However, in some cases, especially in those where the wind density is low, the relative velocity difference between argon (or sulphur) and the passive component becomes higher and close to 1. This is caused by the fact that argon and sulphur have very low metallicity (\( Z_{A_{SMC}} \approx 3 \times 10^{-3} \)) and significantly contribute to the radiative force (\( u_{hp} \approx 0.1 \)). The velocity differences are so high that they may cause large frictional heating.

5.3 Multicomponent wind models

To test the possibility of frictional heating, we have calculated some four-component wind models, where the fourth component is either argon, sulphur or carbon, depending on which element has a maximum velocity difference for a given star. The other three components are heavier ions, the passive component (hydrogen + helium) and free electrons.

First, we tested whether the simple equation (equation 18) is able to reliably predict the velocity differences. We plot the result only for the case of star NGC 346 WB 1 (see Fig. 11), however the result that equation (18) is able to very reliably predict the approximate velocity differences is similar also for other stars.

For stars with the highest velocity differences, the frictional heating occurs. This is shown in Figs 12 and 13, where we compare four-component models (with wind components sulphur, the remaining heavier ions, the passive component and electrons) with...
Figure 10. Relative velocity differences between individual heavier elements and passive component calculated using equation (18). Only values for elements with the highest relative velocity differences are plotted. The velocity differences for other heavier elements are much lower.
approximation lower ionization stages (e.g. CIV, S IV) are lower in the frictionally heated wind. The ionization fractions of NV and O V) of frictionally heated wind is higher than in the wind with negligible frictional heating, whereas the ionization fractions of lower ionization stages (e.g. C IV, Si IV) are lower in the frictionally heated wind. The differences are about a factor of 2.

The velocity differences in the case of frictionally heated four-component wind models are larger than those estimated using the approximate expression equation (18) and a four-component model. Clearly, in the case of negligible frictional heating equation (18) is able to correctly predict velocity differences.

We have tested whether the mentioned systematic disagreement between the theoretical and observed values of mass-loss rates can be caused by the decoupling of some metals from the mean flow. We have shown that the velocity differences are small (and thus there is no decoupling of wind components) for stars with a relatively good agreement between the predicted quantities and those derived from observations. However, for smaller mass-loss rates the agreement is rather poor; predicted mass-loss rates are significantly higher than those derived from observation. Note that this is not an effect of our models only; there is a similar disagreement between the observations and models of V Kl (see B03 and Mr04).

We have presented NLTE wind models of cooler O stars in the SMC. These models enable the prediction of basic wind parameters, i.e. the mass-loss rates and the terminal velocities. We have compared these predicted wind parameters with those derived from observation. We have concluded that there is a relatively good agreement between observed and predicted terminal velocities with some scatter. This scatter can be partly attributed to the poorly known chemical composition of SMC stars. Moreover, the existence of unidentified binaries in our sample can also influence the comparison. Last but not least, the simplification involved in our code (e.g. a simplified treatment of the radiative transfer equation, such as neglecting the line overlaps) can also influence the results. However, the situation with mass-loss rates is different. For relatively high mass-loss rates (i.e. $M > 10^{-7} M_\odot yr^{-1}$) there is again a good agreement between the predicted quantities and those derived from observations. However, for smaller mass-loss rates the agreement is rather poor; predicted mass-loss rates are significantly higher than those derived from observation. Note that this is not an effect of our models only; there is a similar disagreement between the observations and models of VKL (see B03 and Mr04).

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We have tested whether the mentioned systematic disagreement between the theoretical and observed values of mass-loss rates can be caused by the decoupling of some metals from the mean flow. We have shown that the velocity differences are small (and thus there is no decoupling of wind components) for stars with a relatively good agreement between the observed and the predicted mass-loss rates. On the other hand, for stars for which the predicted mass-loss rates are systematically too high, either the instability connected with the decoupling of the wind components may occur or frictional heating increases the wind temperature. Note, however, that we have obtained the possibility of decoupling close to the stellar surface for velocities lower than the escape velocity.

We have shown that the velocity differences for some heavier elements are high for stars that have very low observed mass-loss rates. In such cases either frictional heating becomes important or even some elements may decouple from the wind. Note that these multicomponent effects are important already for theoretically derived mass-loss rates, i.e. those that are much higher than the observed ones. Because the frictional heating increases the wind temperature only in the outer wind regions (for velocities higher than that corresponding to the critical point velocity), its influence on the mass-loss rate is negligible.

Fall-back of the wind material (which may cause the lowering of wind mass-loss rate) may occur only if the wind components decouple below the point where the wind velocity is equal to the escape velocity. In this case the runaway instability connected with decoupling may lead to the fall-back of the wind material (Porter & Skouza 1999; Votrub et al. 2006) and consequently lower the mass-loss rate. This occurs only for star SMC-N81 #3. For other stars we have not obtained the possibility of decoupling close to the stellar surface, for velocities lower than the escape velocity. This means that the presented models are, with one exception, close to the star stable with respect to multicomponent instabilities. Consequently, we are not able to explain very low observed mass-loss rates using multicomponent models for all except one star. Only for star SMC-N81 #3 may the low observed mass-loss rate be connected with multicomponent effects.

6 DISCUSSION AND CONCLUSIONS

We have presented NLTE wind models of cooler O stars in the SMC. These models enable the prediction of basic wind parameters, i.e. the mass-loss rates and the terminal velocities. We have compared these predicted wind parameters with those derived from observation. We have concluded that there is a relatively good agreement between observed and predicted terminal velocities with some scatter. This scatter can be partly attributed to the poorly known chemical composition of SMC stars. Moreover, the existence of unidentified binaries in our sample can also influence the comparison. Last but not least, the simplification involved in our code (e.g. a simplified treatment of the radiative transfer equation, such as neglecting the line overlaps) can also influence the results. However, the situation with mass-loss rates is different. For relatively high mass-loss rates (i.e. $M > 10^{-7} M_\odot yr^{-1}$) there is again a good agreement between the predicted quantities and those derived from observations. However, for smaller mass-loss rates the agreement is rather poor; predicted mass-loss rates are significantly higher than those derived from observation. Note that this is not an effect of our models only; there is a similar disagreement between the observations and models of V Kl (see B03 and Mr04).

We have tested whether the mentioned systematic disagreement between the theoretical and observed values of mass-loss rates can be caused by the decoupling of some metals from the mean flow. We have shown that the velocity differences are small (and thus there is no decoupling of wind components) for stars with a relatively good agreement between the observed and the predicted mass-loss rates. On the other hand, for stars for which the predicted mass-loss rates are systematically too high, either the instability connected with the decoupling of the wind components may occur or frictional heating increases the wind temperature. Note, however, that we have obtained the possibility of decoupling close to the stellar surface for velocities lower than the escape velocity only one star. (Note that in order to obtain fall-back of the wind material and consequently a lower wind mass-loss rate it is necessary that the decoupling occurs below the point where the wind velocity is equal to the escape velocity.) With this exception, the presented models are, to our knowledge, close to the star stable with respect to multicomponent instabilities. This means that, without any further assumptions, we are not able to explain the very low observed mass-loss rates of most studied stars with $M < 10^{-7} M_\odot yr^{-1}$ (although in the outer wind regions of these stars the multicomponent effects are important). However, there are several possibilities of how to (from the theoretical point of view) obtain decoupling of wind components for the velocities lower than the escape velocity for other stars (such as slightly different metallicity, overestimation of theoretical mass-loss rates, neglect of some heavier elements or improved treatment of the multicomponent flow). Another way to explain low wind mass-loss rates may be connected with the thin-wind effect (Puls et al. 1998; Owocki & Puls 1999).

The decoupling discussed here differs slightly from that studied so far (cf. Springmann & Pauldrach 1992; KKiI). In the previous studies it was usually assumed that metals and the passive...
component may decouple completely. We presented here a more detailed and more realistic picture of the decoupling of wind components. We showed that some elements which have very low abundance, but which significantly contribute to the radiative force, may decouple (or cause the instability connected with the decoupling) individually from the mean flow, which is basically not decoupled. Moreover, the decoupling may occur for higher mass-loss rates than was previously assumed. We present an approximate formula for the test of the importance of the discussed decoupling of individual heavier elements.

For our comparison we used mass-loss rates derived from the observation, assuming smooth winds. If the O star winds are clumped, as is indicated by the observations made by e.g. B03 or Martins et al. (2005), then the mass-loss rates of O stars are likely to be lower than those predicted by current hot star wind theory, and we obtain a disagreement between observations and theory for all stars. On the other hand, a better treatment of the opacity sources in the UV domain with account of the line overlaps and comoving-frame radiative transport may help to overcome this potential disagreement.

We have studied the dependence of wind parameters on metallicity. It is well-known that the mass-loss rate increases with increasing metallicity. We have derived that the mass-loss rate scales with the metallicity as $\dot{M} \sim Z^{0.67}$. The terminal velocity of individual stars

Figure 12. Comparison of the four-component (with sulphur as the fourth component, dashed line) and three-component (solid line) models for stars NGC 346 MPG 487 (left) and NGC 346 MPG 113 (right). Top panel: comparison of velocity of the passive component (hydrogen + helium) in individual models. Note that the velocities of all individual wind components in the four-component or three-component models are similar. Middle panel: comparison of wind temperatures. The wind temperatures of individual wind components in the three-component model are nearly equal. The wind temperature in the four-component model is higher due to the frictional heating, and the sulphur temperature is even higher than the temperature of the other components. Bottom panel: relative velocity difference between the passive component and sulphur in the four-component model. The velocity difference in the case of NGC 346 MPG 113 is close to 1 in the outer wind regions, thus potentially enabling instability due to sulphur decoupling.
Figure 13. The same as Fig. 12 for SMC-N81 stars #3 (left) and #11 (right). Note that for winds of both stars the friction between sulphur and the passive wind component (hydrogen + helium) is important for wind structure. In both cases the sulphur decoupling may occur. In the case of SMC-N81 #3 sulphur may decouple for velocities lower than the escape speed (the surface escape speed for this star is $v_{\text{esc}} = 1180\,\text{km s}^{-1}$) and in the case of SMC-N81 #11 sulphur may decouple for velocities slightly higher than the escape speed (the escape speed is also plotted on the graph of this star).

also varies with metallicity, mainly due to the sensitivity of the radiative force on the detailed wind state in the outer wind regions. However, on average the terminal velocity varies with metallicity only slightly (for studied values of metallicity) as $v_\infty \sim Z^{0.06}$. As a consequence, the ratio of the terminal velocity of wind to the surface escape velocity $v_\infty/v_{\text{esc}} \sim 2.3$ is only slightly lower than it is for Galactic stars.

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