An explanation for the curious mass loss history of massive stars: From OB stars, through Luminous Blue Variables to Wolf-Rayet stars

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Abstract. The stellar winds of massive stars show large changes in mass-loss rates and terminal velocities during their evolution from O-star through the Luminous Blue Variable phase to the Wolf-Rayet phase. The luminosity remains approximately unchanged during these phases. These large changes in wind properties are explained in the context of the radiation driven wind theory, of which we consider four different models. They are due to the evolutionary changes in radius, gravity and surface composition and to the change from optically thin (in continuum) line driven winds to optically thick radiation driven winds.

Key words. stars: evolution – stars: mass-loss – stars: Luminous Blue Variables Stars: OB – stars: Wolf–Rayet

1. Introduction

In this paper we present an explanation for the drastic changes in mass loss rate and wind velocity during the evolution of massive stars.

The stellar winds of massive stars show a large variation in mass-loss rates and terminal velocities during their evolution from O-star through the Luminous Blue Variable (LBV) phase to the Wolf-Rayet (WR) phase. O-stars have a relatively small mass-loss rate (\(\dot{M} \approx 10^{-6} \text{ to } 10^{-5} \text{ M}_\odot \text{ yr}^{-1}\)) but high wind velocity (\(v_\infty \approx \text{few } 10^3 \text{ km s}^{-1}\)), LBVs have a high mass-loss rate (\(\text{few } 10^{-5} \text{ M}_\odot \text{ yr}^{-1}\)) but a small wind velocity (\(\text{few } 10^{2} \text{ km s}^{-1}\)) and WR-stars have a high mass-loss rate (\(\text{few } 10^{-5} \text{ M}_\odot \text{ yr}^{-1}\)) and a high wind velocity (\(\text{few } 10^{3} \text{ km s}^{-1}\)). The luminosity remains approximately unchanged during these phases. The question is: what causes these changes in mass-loss rate and in wind velocity?

The mass-loss rates of OB-stars and LBVs during their quiescent phase have been explained in terms of radiation driven winds, where the driving is done by multitudes of spectral lines (Castor et al. 1975; Pauldrach et al. 1986; Vink et al. 2000). Line driven winds are optically thin in their continuum. Nugis & Lamers (2002, hereafter NL) have shown that the mass-loss rates of Wolf-Rayet stars can in principle be explained by optically thick radiation driven winds. In this paper we explain the large changes in \(M\) and \(v_\infty\) in terms of transitions between four types of radiation driven wind models, due to changes mainly in the stellar parameters and to a smaller extent also in the surface abundance during the stellar evolution. We discuss the properties of two types of optically thin and two types of optically thick radiation driven wind models, which we then apply to nine characteristic massive stars with increasing evolution stages.

2. Evolutionary changes of the stellar parameters of massive stars

The evolution of stars initially more massive than about 50 \(M_\odot\) proceeds as follows (e.g. Maeder & Meynet 1987). After the main sequence phase the star expands and becomes a blue supergiant with a radius of about \(10^2 \text{ R}_\odot\) and with an enhanced He and N surface abundance. For a reason that is poorly understood the star becomes an unstable LBV with multiple outbursts (Humphreys & Davidson 1994; Leitherer 1997). Even during quiescence the mass-loss rates of LBVs are significantly higher than during the main sequence phase but the wind velocity is much lower. After the LBV-phase the star contracts and becomes a WR star with a N-rich (WN-type) and later a C, O-rich (WC-type) surface. The hydrostatic radius of the star is only a few \(R_\odot\), but the high mass-loss rate produces an optically thick wind with a sonic point radii of about 15
to $30 \, R_\odot$ for hydrogen-rich WNl-phase and about 1.5 to 10 $R_\odot$ for the H-poor WNE/WC phase (see NL). Very massive stars ($M > 60 \, M_\odot$) may skip the LBV phase (Bohannan & Crowther 1999).

We adopt nine typical massive stars of about the same luminosity and initial mass to characterize the changes in the stellar and wind parameters during the evolution of a massive star. They represent different evolutionary phases. The stars are listed in Table 1 in order of increasing evolutionary stage: one Of-star ($\zeta$ Pup), one LBV (P Cyg), three stars with spectra in between those of Of and late-WN (HD 151804, HD 152408, HD 152386), three WN-stars (WR 105, WR 136 and WR 139) and one WC-star (WR 111). Notice the large changes in $M$ and $v_\infty$ and the general increase of the atmospheric He/H-ratio and of the momentum transfer efficiency, $\eta = M_{\text{tot}}/(L/c)$, with evolution stage. The radii of the four genuine WN and WC-stars in this table are the radii of the sonic point, derived by NL, and the value of $T_{\text{eff}}$ at that radius.

3. Radiation driven wind models

3.1. Optically thin line driven winds

For line driven wind models, which are optically thin in the continuum, the predicted terminal velocity $v_\infty$ is

$$v_\infty \approx C_{\text{ld}} \sqrt{\alpha/(1-\alpha)} \, v_{\text{esc}}$$  

(Caster et al. 1975; Kudritzkii et al. 1989), where $\alpha$ is a force multiplier parameter with $0.5 \lesssim \alpha \lesssim 0.7$ for hot massive stars of $T_{\text{eff}} \gtrsim 8000 \, \text{K}$ and $v_{\text{esc}}$ is the effective escape velocity, i.e. corrected for radiation pressure by electron scattering. Lamers et al. (1995) have shown that $C_{\text{ld}} \sqrt{\alpha/(1-\alpha)} \approx 2.7$ if $T_{\text{eff}} \gtrsim 21 \, 000 \, \text{K}$ and 1.3 if $10 \, 000 \lesssim T_{\text{eff}} \lesssim 21 \, 000 \, \text{K}$. Observations and theory both show that the mass-loss rate of a line driven wind increases by about a factor 5 and the terminal velocity decreases by about a factor two when the effective temperature of the star drops below about 21 000 K (Lamers et al. 1995; Vink et al. 1999). This is the bi-stability jump, which is due to the change in ionization in the lower wind layers near the sonic point (Vink et al. 1999). Detailed calculations of line driven wind models with multiple scattering by Vink et al. (2001) have shown that the mass-loss rate of galactic OB-stars in $M_s \, \text{yr}^{-1}$ is

$$\log M = -6.86 + 2.194 \log (L/10^{35}) - 1.313 \log (M/30) + 0.933 \log (T_{\text{eff}}/40 \, 000) - 10.92 \log (T_{\text{eff}}/40 \, 000)^2$$

(2)

on the “hot side” of the jump, $T_{\text{eff}} \gtrsim 21 \, 000 \, \text{K}$, and

$$\log \dot{M} = -6.39 + 2.210 \log (L/10^{35}) - 1.339 \log (M/30) + 1.07 \log (T_{\text{eff}}/20 \, 000)$$

(3)

on the “cool side” of the jump, $10 \, 000 \lesssim T_{\text{eff}} \lesssim 21 \, 000 \, \text{K}$, with $M$ and $L$ in solar units. We will use Eqs. (1)–(3) to predict $v_\infty$ and $\dot{M}$ for line driven winds.

3.2. Optically thick radiation driven winds

NL have shown that in optically thick radiation driven winds the opacity has to increase outwards at the sonic point. They showed that

$$M \approx C \frac{T_{\text{eff}}^2 R_s^3}{M} = 4.66 \times 10^{-29} \frac{T_{\text{eff}}^{1.5} R_s^3}{M} \sqrt{\frac{(1+\gamma)}{\mu}}$$

(4)

in $M_\odot$ yr$^{-1}$, where $R_s$ (in $R_\odot$) and $T_{\text{eff}}$ (in K) are the radius and temperature at the sonic point, $M$ is in $M_\odot$, $v_\infty$ is the isothermal sound speed, $\gamma$ is the mean number of free electrons per atom and $\mu$ is the mean atomic weight in atomic mass units. We see that $M$ of an optically thick radiation driven wind is proportional to $T_{\text{eff}}^{1.5}$. At first sight this might suggest that an arbitrary high mass-loss rate can be reached by moving the sonic point deeper into the star where the optical depth and the temperature are higher. However, this is not the case, because the transition from subsonic to supersonic velocity at the sonic point sets requirements for the opacity and its gradient. The opacity and its gradient at the sonic point are (see NL)

$$\chi_s \approx \frac{4\pi c GM}{L}, \quad \left(\frac{\text{d} \chi_s}{\text{d} r}\right)_s \approx \frac{3\alpha c a_1 T_s}{GM} = \frac{12\pi c a_1 T_s}{L} > 0,$$

(5)

where $\alpha_1 = k (y + 1)/\mu m_p$). Equations (5) and (6) imply that the transonic transition can only occur in the layers where the opacity increases outwards and where it reaches a value set by the luminosity and mass of the star (Eq. (5)). From the OPAL-opacity tables (Iglesias & Rogers 1996) we find that this occurs only in limited temperature regimes where $\chi(T)$ shows a bump. These regimes are in the ranges of $156 \, 000 \lesssim T_s \lesssim 162 \, 000 \, \text{K}$, and $37 \, 000 \lesssim T_s \lesssim 71 \, 000 \, \text{K}$, where respectively a large and a small Fe-opacity peak occur (see NL). We will use Eq. (4) to predict $M$ for optically thick winds. For $v_\infty$ we adopt the scaling predicted by the models. We derived from WR models of NL that

$$v_\infty \approx (2 \pm 0.5) v_{\text{esc}}^s$$

(7)

with $v_{\text{esc}}^s$ at the sonic point. We will use this scaling law to estimate $v_\infty$ for optically thick radiation driven winds. Notice that $v_\infty$ increases with decreasing sonic radius.

3.3. Four types of wind models

The description above has shown that radiation driven winds from hot stars come in four types:

1. line driven winds which are optically thin in the continuum for stars with $T_{\text{eff}} \gtrsim 21 \, 000 \, \text{K}$, i.e. on the hot side of the bi-stability jump: “line hot” models. For these winds we adopt Eqs. (1) and (2);
2. line driven winds for stars with $T_{\text{eff}} \lesssim 21 \, 000 \, \text{K}$, i.e. on the cool side of the bi-stability jump: “line cool” models. We adopt the Eqs. (1) and (3) for these models;
3. “thick cool” continuum driven winds, with the sonic point in the temperature range of $38 \, 000 < T_s < 71 \, 000 \, \text{K}$, where the
Table 1. Nine characteristic massive stars.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>log $L/L_\odot$</th>
<th>$R_\odot/R_\odot$</th>
<th>$T_{\text{eff}}$ K</th>
<th>$M/M_\odot$</th>
<th>$v_{\infty}$ km s$^{-1}$</th>
<th>$M_{\text{He}}/M_\odot$</th>
<th>$M_{\odot}$ yr$^{-1}$</th>
<th>$v_\infty$ km s$^{-1}$</th>
<th>$\eta$</th>
<th>Ref.(^{(4)})</th>
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<tr>
<td>ζ Pup</td>
<td>O4 If</td>
<td>6.00</td>
<td>19</td>
<td>42 000</td>
<td>70</td>
<td>953</td>
<td>0.15</td>
<td>$3 \times 10^{-6}$</td>
<td>2250</td>
<td>0.32</td>
<td>PU</td>
</tr>
<tr>
<td>P Cyg</td>
<td>B1.5 Ia*</td>
<td>5.86</td>
<td>76</td>
<td>19 300</td>
<td>23</td>
<td>223</td>
<td>0.30</td>
<td>$2 \times 10^{-5}$</td>
<td>210</td>
<td>0.28</td>
<td>PP</td>
</tr>
<tr>
<td>HD151804</td>
<td>O8 Iaf</td>
<td>5.84</td>
<td>37</td>
<td>26 700</td>
<td>46</td>
<td>581</td>
<td>0.25</td>
<td>$1.2 \times 10^{-5}$</td>
<td>1445</td>
<td>1.24</td>
<td>CB</td>
</tr>
<tr>
<td>HD152408</td>
<td>WN9ha</td>
<td>5.80</td>
<td>32</td>
<td>27 600</td>
<td>44</td>
<td>648</td>
<td>0.67</td>
<td>$2.4 \times 10^{-5}$</td>
<td>995</td>
<td>1.79</td>
<td>CB</td>
</tr>
<tr>
<td>HD152386</td>
<td>WN9ha</td>
<td>5.82</td>
<td>33</td>
<td>27 000</td>
<td>46</td>
<td>624</td>
<td>0.27</td>
<td>$2.7 \times 10^{-5}$</td>
<td>1650</td>
<td>3.45</td>
<td>BC</td>
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<tr>
<td>WR 105</td>
<td>WN 9</td>
<td>5.81</td>
<td>26</td>
<td>32 100</td>
<td>22</td>
<td>412</td>
<td>0.44</td>
<td>$2.8 \times 10^{-5}$</td>
<td>1200</td>
<td>2.6</td>
<td>NL</td>
</tr>
<tr>
<td>WR 136</td>
<td>WN 6b</td>
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<td>4.6</td>
<td>73 000</td>
<td>19</td>
<td>900</td>
<td>1.9</td>
<td>$6.3 \times 10^{-5}$</td>
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<td>WN 5</td>
<td>5.21</td>
<td>2.0</td>
<td>82 000</td>
<td>9.3</td>
<td>1129</td>
<td>5.0</td>
<td>$0.9 \times 10^{-5}$</td>
<td>1800</td>
<td>4.9</td>
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<tr>
<td>WR 111</td>
<td>WC 5</td>
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<td>2.3</td>
<td>81 000</td>
<td>10.6</td>
<td>1160</td>
<td>$\infty$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>2415</td>
<td>5.8</td>
<td>NL</td>
</tr>
</tbody>
</table>

\(^{(1)}\) For WR-stars the mean sonic radius of the models A1 and B1 of NL with the corresponding $T_{\text{eff}} = (L/(4\pi\sigma R^2))^{1/2}$ is listed.

\(^{(2)}\) Masses of O and WN9ha-stars were derived from evolutionary models.

\(^{(3)}\) $v_{\infty}$ is the effective escape velocity at the radius $R$, corrected for radiation pressure by electron scattering.

\(^{(4)}\) PU = Puls et al. (1996); PP = Pauldrach & Puls (1990); CB = Crowther & Bohannan (1997); BC = Bohannan & Crowther (1999); NL = Nugis & Lamers (2002).

5. Discussion and conclusions

From the comparison between the predicted and the observed values of $M$ and $v_{\infty}$, we can explain the changes in mass-loss rate and wind velocities during the evolution of massive stars in terms of the four wind models.

1. O-stars on the main sequence and shortly thereafter have winds driven by lines on the hot side of the bi-stability jump.
2. The winds of LBVs are radiation driven by lines. The increase in $M$ and the decrease in $v_{\infty}$ from O-star to LBV is due to the crossing of the bi-stability jump. (However, not all LBVs become cool enough to reach the bi-stability jump: Leitherer 1997; Lamers 1997)
3. When the star has lost sufficient mass and the atmosphere has been He-enriched sufficiently to contract to the WNL-phase, the wind becomes optically thick and the sonic point moves into the region where the continuum opacity shows a small bump so that it can initiate an optically thick wind. This results in a (small) increase of $M$ and a large increase in $v_{\infty}$. The characteristics of the star HD 151804 suggest that the transition from line driven winds to “thick cool” is gradual.
4. When the star looses more mass and the surface becomes H-poor its wind may either stay “thick cool” (at $T_s \approx 40$ kK) or become “thick hot”. In the first case the star may appear as a H-poor WN7 or WN8-star (not studied here). In the latter case the star appears as a WNE-star, similar to WR 136 and WR 139. In both cases the star has a high $M$ and a high $v_{\infty}$. The transition from a “thick cool” to “thick hot” wind is determined by the variation of $\chi_s$ (see Eq. (5)). During the WNE-phase the $M/L$-ratio increases (Schaerer & Maeder 1992). When $\chi_s$ increases to values above $\approx 0.5$ cm$^2$ g$^{-1}$, the sonic point has to move to high temperature regime, because such a high value of $\chi_s$ is reached only near the main iron opacity peak (NL).
When the star evolves directly from Of to WN/Lh both the $M/L$-ratio and $v_{\infty}$ decrease.

5. It is difficult to predict the dependence of $M$ on $L$ for optically thick wind models accurately because $R_0$ and hence also $T_{\text{eff}}(R_0)$ is not well known. The wind models of NL for WNE/WCE stars predict that $R_0 \propto L^{0.7}$ and because $M \propto L^{0.6}$ (Schaerer & Maeder 1992), it follows that $M \propto R_0^3/L \propto L^{1.5}$ (Eq. (4)). This dependence agrees well with the empirical relation derived by Nugis & Lamers (2000) for WN stars. For the WC stars Nugis & Lamers (2000) found empirically that $M \propto L^{0.84}$ but with strong dependence on chemical composition. On the other hand, in a recent study of LMC WC-stars Crowther et al. (A&A in press) found a strong dependence of $M$ on $L (M \propto L^{1.38})$ which agrees well with our predicted dependence for optically “thick hot” wind models.

6. We find that the changes in $M$ and $v_{\infty}$ during the evolution of massive stars are mainly due to changes in the stellar parameters and to a lesser degree changes in the surface composition.

We have shown that the changes in $M$ and $v_{\infty}$ during the evolution of the massive stars from Of-star to WN-star are due to the adjustment of the wind to the changing conditions, mainly the $M$, $L$, $R$ and surface composition. We have not explained “how” these changes occur. The transition from line driven winds to “thick cool” winds is most likely due to the formation of a bump in the opacity curve when the He/H ratio increases. This transition can occur gradually because the temperature of the sonic point of a “line hot” wind overlaps with the range for “thick cool” winds. The transition from “thick cool” to “thick hot” is probably due to the fact that the hydrostatic radius of a WR-star shrinks and the $M/L$-ratio increases when the luminosity of the star decreases (Schaerer & Maeder 1992). This transition cannot be gradual, because the sonic point temperature in these models is very different, so the wind must be restructured during this transition.

We point out that at present, the optically thick wind models do not provide accurate predictions for $v_{\infty}$, so we adopted an empirical scaling law. However, Schmutz (1997) has shown that there is sufficient driving in the supersonic part of the winds of WR-stars to explain the observed high values of $v_{\infty}$.

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Table 2. Predictions for line driven (optically thin continuum) and optically thick winds versus observations.

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>log $M$ (M$_{\odot}$ yr$^{-1}$)</th>
<th>$v_{\infty}$ (km s$^{-1}$)</th>
<th>Best model</th>
</tr>
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<td></td>
<td></td>
<td>thin thick</td>
<td>thick</td>
<td>obs</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
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<td>40 kK   70 kK 160 kK</td>
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<td></td>
</tr>
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<td>O4 If</td>
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<td>2573 1906 2250</td>
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References