Are WNL stars tracers of high metallicity?

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We present new atmosphere models for Wolf-Rayet stars that include a self-consistent solution of the wind hydrodynamics. We demonstrate that the formation of optically thick WR winds can be explained by radiative driving on Fe line opacities, implying a strong dependence on metallicity (Z). Z-dependent model calculations for late-type WN stars show that these objects are very massive stars close to the Eddington limit, and that their formation is strongly favored for high metallicity environments.

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1. PoWR hydrodynamic model atmospheres

The Potsdam Wolf-Rayet (PoWR) hydrodynamic model atmospheres combine fully line-blanketed non-LTE models with the equations of hydrodynamics (for details see Gräfener & Hamann 2005; Hamann & Gräfener 2003; Koesterke et al. 2002; Gräfener et al. 2002). The wind structure ($\rho(r)$ and $v(r)$) and the temperature structure $T(r)$ are computed in line with the full set of non-LTE populations, and the radiation field in the co-moving frame (CMF). In contrast to all previous approaches, the radiative wind acceleration $a_{\rm rad}$ is obtained by direct integration

$$a_{\rm rad} = \frac{1}{c}\int \chi_\nu F_\nu {\rm d}\nu, \qquad (1.1)$$

instead of making use of the Sobolev approximation. In this way, complex processes like strong line overlap, or the redistribution of radiation, are automatically taken into account. Moreover, the models include small-scale wind clumping (throughout this work we assume a clumping factor of $D = 10$, for details see also Hamann & Koesterke 1998). The models describe the conditions in WR atmospheres in a realistic manner, and provide synthetic spectra, i.e. they allow for a direct comparison with observations.

Utilizing these models, we recently obtained the first fully self-consistent Wolf-Rayet wind model, for the case of an early-type WC star with strong lines (Gräfener & Hamann 2005). Moreover, we have examined the mass loss from late-type WN stars and its dependence on metallicity (Gräfener & Hamann 2006a; Gräfener & Hamann 2006b).

2. Spectral analyses of galactic WR stars

A comprehensive study of galactic WR stars, based on spectral analyses with line-blanketed PoWR models (Hamann et al. (2006) for WN stars, Barniske et al. (2006) for WC stars), revealed a bimodal WR subtype distribution in the HRD, where the H-rich WNL stars are located to the right of the ZAMS with luminosities above $10^6\,L_\odot$, whereas the (mostly H-free) early- to intermediate WN subtypes, as well as the WC stars, show lower luminosities and hotter temperatures (see Fig. 1).

This dichotomy already implies that the H-rich WNL stars are the descendants of very massive stars, possibly still in the pase of central H-burning, whereas the earlier subtypes (including the WC stars) are more evolved, less massive, He-burning objects. Note, however, that distance estimates are only available for a small part of the WNL sample. Some of these objects thus might have lower luminosities and be the direct progenitors of the earlier subtypes.

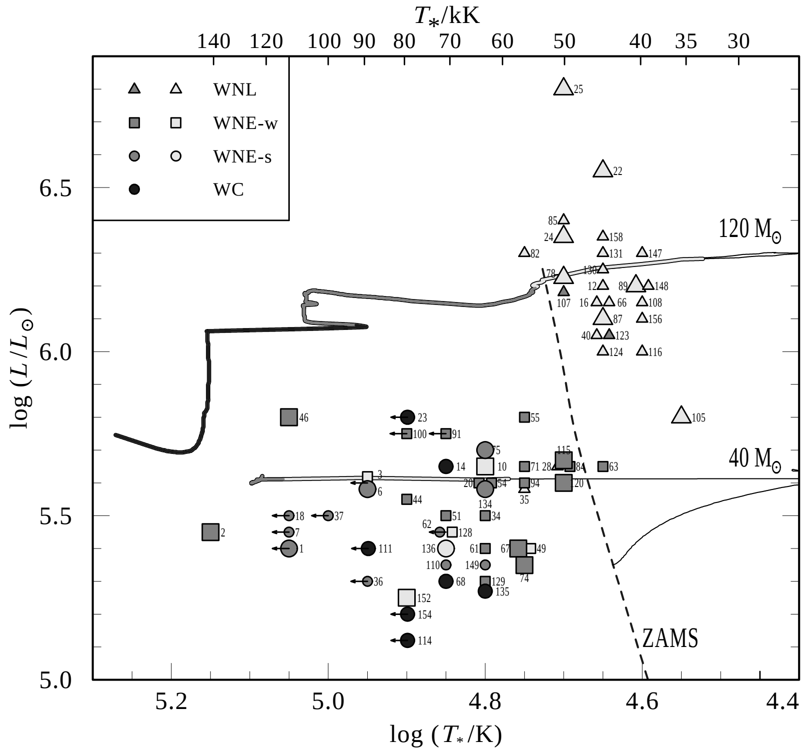

FIGURE 1. Recent spectral analyses of galactic WR stars with line-blanketed models, according to Hamann et al. (2006) and Barniske et al. (2006): symbols in light grey denote H-rich WR stars, whereas H-free objects are indicated in dark grey. WC stars are indicated in black. For objects with large symbols distance estimates are available (van der Hucht 2001), whereas objects with small symbols are calibrated by their spectral subtype. Evolutionary tracks for non-rotating massive stars (Meynet & Maeder 2003) are shown for comparison.

3. Hydrodynamic atmosphere models for WNL stars

In a recent work we have investigated the properties of the luminous, H-rich WNL stars with our hydrodynamic PoWR models (Gräfener & Hamann 2006a). The most important conclusion from that work is that WR-type mass loss is primarily triggered by high L/M ratios or, equivalently, Eddington factors $\Gamma_\mathrm{e} \equiv \chi_\mathrm{e} L_\star / 4\pi c G M_\star$ approaching unity. Note that high L/M ratios are expected for very massive stars *and* for He-burning objects, giving a natural explanation for the occurrence of the WR phenomenon.

In Fig. 2 we show the results from grid computations for WNL stars with a fixed luminosity of $10^{6.3}\,L_\odot$, and stellar temperatures $T_\star$ in the range of 30–60 kK. For the stellar masses, values of 67 and 55 $M_\odot$ are adopted, corresponding to Eddington factors of $\Gamma_\mathrm{e} = 0.55$ and 0.67. Notably, the mass loss strongly depends on Γ_e and $T_\star$. The obtained synthetic spectra nicely reflect the observed sequence of *weak-lined* WNL subtypes, starting with WN 6 at 55 kK to WN 9 at 31 kK. From a more detailed investigation of the WN 7 component in WR 22, an eclipsing WR+O binary system in Car OB1, we infer a stellar mass of 78 $M_\odot$ ($\Gamma_e = 0.67$), in agreement Rauw et al. (1996) who obtained $72\pm3\,M_\odot$ from the binary orbit. Such high stellar masses imply that the weak-lined WNL stars are still in the pase of central H-burning, suggesting an evolutionary sequence of the form O → WNL → LBV → WN → WC for very massive stars.

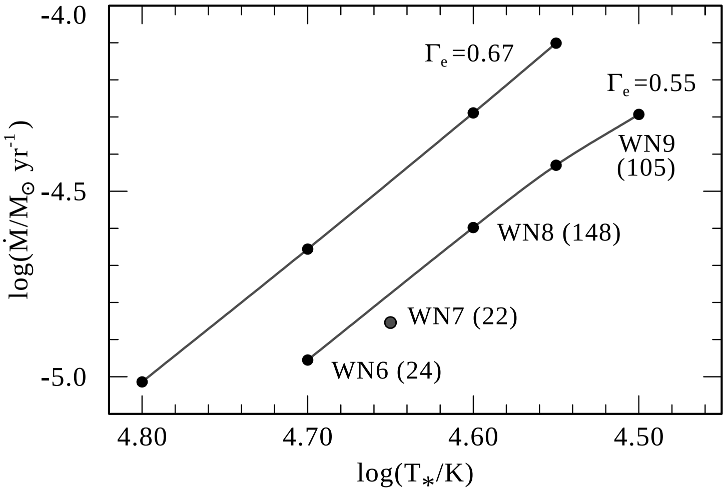

FIGURE 2. Wind models for galactic WNL stars: mass loss rates for different stellar temperatures $T_\star$ and Eddington factors Γ_e. The corresponding spectral subtypes are indicated together with WR numbers of specific galactic objects (according to van der Hucht 2001, in brackets), showing a good agreement with the synthetic line spectra. Note that the models are computed for a fixed stellar luminosity of $10^{6.3}\,L_\odot$. The WN 7 model (WR 22) is slightly offset from the standard grid models because it is calculated with an enhanced hydrogen abundance (see text).

4. WNL stars at different metallicities

In Fig. 3 we present results from a grid of models for luminous WNL stars at different metallicities (Gräfener & Hamann 2006a). The models are computed for a fixed luminosity of $10^{6.3}\,L_\odot$, a stellar temperature of $T_\star = 45\,$kK, and a hydrogen surface mass fraction of $X_\mathrm{H} = 0.4$. In addition to the metal abundances we have varied the Eddington factor Γ_e (or equivalently the stellar mass). Note that we have scaled all metals with Z, assuming a CNO-processed (i.e. N-enriched) WN surface composition. The wind driving in our models is chiefly due to radiation pressure on Fe-group line opacities. In accordance with Vink & de Koter (2005) we thus find a strong dependence on Z. However, as in our previous computations, the proximity to the Eddington limit plays an equally important role. We find that optically thick winds with high WR-type mass loss rates are formed over the whole range of metallicities, from 1/1000–3 $Z_\odot$, if the stars get close enough to the Eddington limit. Only the limiting value of Γ_e where the WR-type winds start to form, changes. For solar Z, values of $\Gamma_e = 0.5$–0.6 are leading to the formation of weak-lined WNL stars. As we have seen for the case of WR 22, this corresponds to very massive, slightly over-luminous stars in a late phase of H-burning. Note that it is indeed observed that the most massive stars in very young galactic clusters are in the WNL phase (e.g., Figer et al. (2002), Najarro et al. (2004) for the Arches cluster; Drissen (1999), Crowther & Dessart (1998) for NGC 3603).

For higher values of Z, the limit for the formation of WR-type winds shifts towards even lower values of Γ_e. For $3\,Z_\odot$, we find that stars with $\Gamma_e \approx 0.4$ already show typical WNL mass loss rates (see Fig. 3). This corresponds to objects with $120\,M_\odot$ on the ZAMS. We thus expect that metal rich stars with very high masses already start their life in the WNL phase, i.e., the occurrence of WNL stars in young massive clusters is strongly favored for high metallicities.

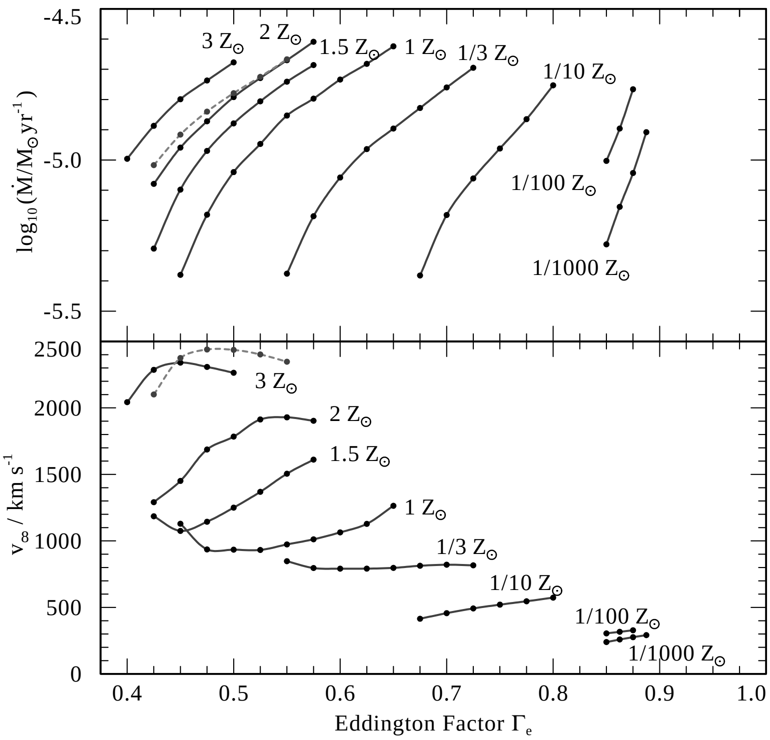

FIGURE 3. WNL star mass loss over a broad range of metallicities (Z): Mass loss rates (top) and terminal wind velocities (bottom), as obtained from our hydrodynamic models, are plotted vs. the Eddington factor Γ_e. The solid curves indicate model series for WNL stars where Γ_e is varied for a given value of Z. The dashed grey lines indicate models with $3\,Z_\odot$ and $X_H = 0.7$, corresponding to very massive, metal rich stars on the ZAMS.

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