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Are Wolf-Rayet winds driven by radiation?

Götz Gräfener & Wolf-Rainer Hamann

Department of Physics, University of Potsdam, D-14469 Potsdam, Germany

Abstract. Recent results with the Potsdam Wolf-Rayet (PoWR) models have shown that Wolf-Rayet mass loss can be explained by radiative wind driving. An inspection of the galactic WR sample, however, reveals that a significant part of the observed WR stars is in conflict with our models. This group is chiefly formed by intermediate spectral subtypes. Among the population of late-type WN stars we find that the enigmatic WN 8 subtypes, which are well-known for their photometric variations, are in disagreement with our models. So are there other driving mechanisms working in these objects?

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 (see Gräfener & Hamann 2005; Hamann & Gräfener 2003; Koesterke et al. 2002; Gräfener et al. 2002). In these models the wind structure ($\rho(r)$, $v(r)$, and $T(r)$) is computed in line with the full set of non-LTE populations and the radiation field in the co-moving frame (CMF). In this numerically rather expensive approach no simplifying assumptions for the computation of the radiative acceleration $a_{\rm rad}$ are made. In contrast to all previous wind models $a_{\rm rad}$ is obtained by direct integration instead of making use of the Sobolev approximation

$$a_{\rm rad} = \frac{1}{c}\int \chi_\nu F_\nu {\rm d}\nu. \tag{1}$$

In contrast to all previous wind models $a_{\rm rad}$ is obtained by direct integration, 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. The models thus describe the conditions in WR atmospheres in a realistic manner, in particular also at large optical depth. Moreover they provide synthetic spectra, i.e. they allow for a direct comparison with observations.

Utilizing these models, we obtained the first fully self-consistent Wolf-Rayet wind model (Gräfener & Hamann 2005), for the case of an early-type WC star. Moreover we have recently examined the mass loss from late-type WN stars and its dependence on metallicity (Gräfener & Hamann 2006a; Gräfener & Hamann 2006b). To illustrate the complexity of the involved processes we show in Fig. 1 the distribution of the radiative flux, the opacity, and their product (i.e., the radiative acceleration per frequency interval) within the WC model. It can be clearly seen that the initial FUV flux, originating from the bottom of the wind,

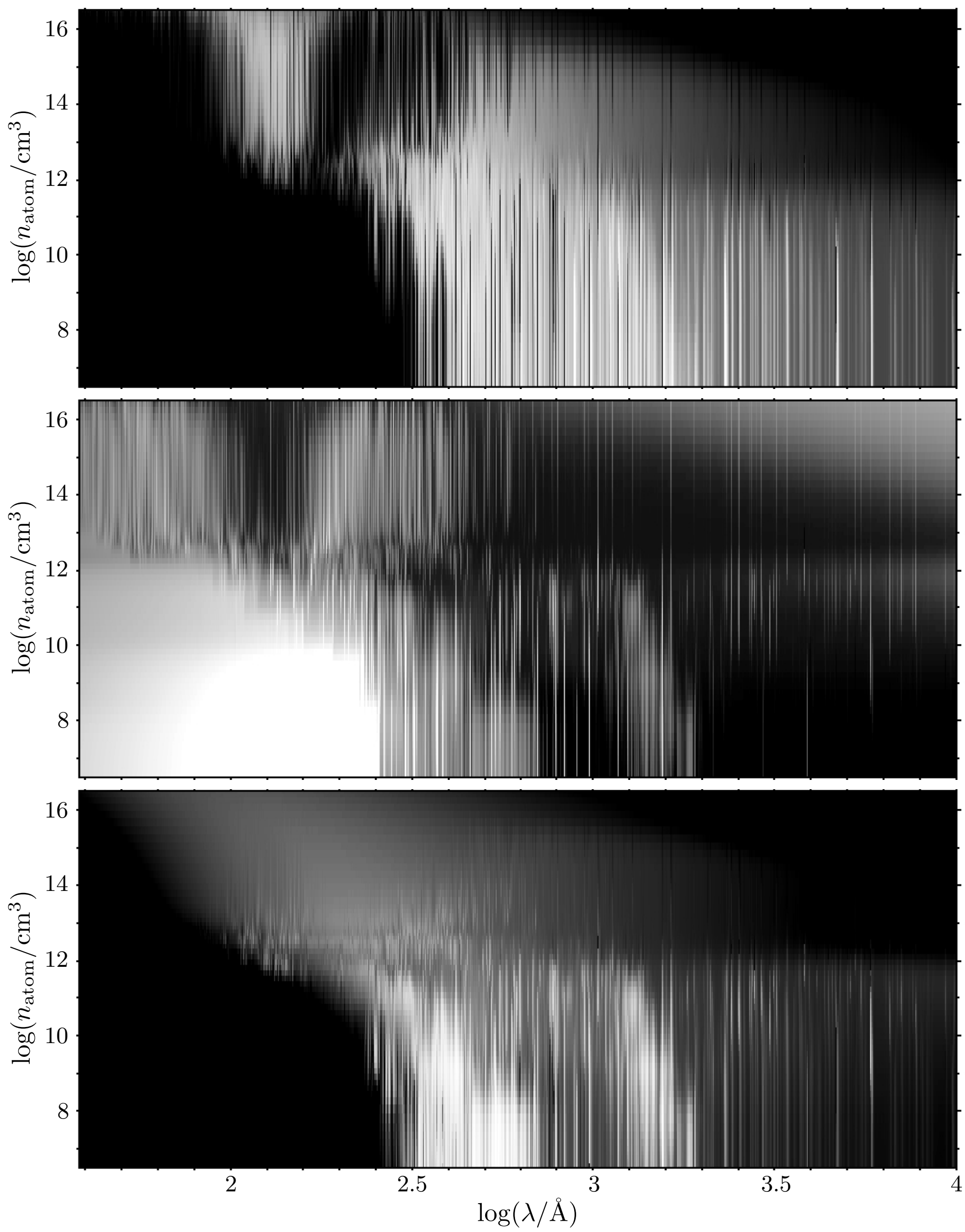

Figure 1. Self-consistent wind model for an early-type WC star from Gräfener & Hamann (2005): radiative flux (top), mass absorption coefficient (middle), and the resulting radiative acceleration per frequency interval (bottom) are plotted vs. wavelength, and wind density (as depth index). The wavelength ranges from X-ray to IR and the depth from the inner boundary at $\tau_{\rm Ross} = 20$ outward to $\approx 1000\,R_\star$. The opacity distribution shows successively recombining continua due to C, O, and He in the FUV, and strongly overlapping line opacities in the UV. The radiative acceleration is mainly due to Fe-group line opacities absorbing the complex radiative flux.

is blocked by successively recombining continua. This radiation is re-emitted at lower frequencies in the form of emission lines, forming the typical WR emission line spectrum. The radiative acceleration predominantly arises from Fe-group line opacities absorbing this radiation. These lines partly form the observable iron forest short-ward of 1500 Å. They show a pronounced ionization structure and contribute by themselves to the complex 'background' flux. This coexistence of line emission and absorption, in combination with strong overlap, is the most probable reason for substantial deviations from the standard theory of line-driven winds (Castor et al. 1975, see also Bjorkman this volume). In our WR models we tend to detect extremely small or even negative force multiplier parameters (see Gräfener & Hamann 2005), which can be explained by a 'statistical' line locking effect due to the strong overlap.

In addition to the complex radiative processes we find a strong influence of wind clumping on the dynamics of O and WR star winds (Gräfener & Hamann 2003, 2005). Wind clumping particularly affects the recombination rates because these scale with $n_{\rm e}^2$. A down-scaling of $\dot{M} \propto 1/\sqrt{D}$ (where D denotes the clumping factor) thus preserves the emission measure in the atmosphere. Because WR atmospheres are dominated by recombination processes, the ionization structure as well as the emission line spectrum are, approximately, preserved under such a transformation (Hamann & Koesterke 1998). The same holds for the radiative *force*. The resulting radiative *acceleration* thus scales with $\sqrt{D}$ under this transformation.

2. Spectral analyses of galactic WR stars

Before we discuss the results from our hydrodynamic models we give an overview of recent spectral analyses of galactic WR stars, based on line-blanketed PoWR models. In Fig. 2 we show an empirical HRD with stellar temperatures and luminosities taken from Hamann et al. (2006, WN stars) and Barniske et al. (2006, WC stars). According to these new analyses, the galactic WR stars form two distinct groups in the HR diagram, which are distinguished by their luminosities. The first group is formed by H-rich WNL stars with luminosities above $10^6\,L_\odot$. These stars are found to the right of the ZAMS. The second group are early- to intermediate subtypes with lower luminosities and hotter temperatures. The majority of these objects is found to be H-free.

The observed dichotomy among the WN subtypes implies that the H-rich WNL stars are the descendants of very massive stars, possibly still in the pase of central H-burning. The earlier subtypes (including the WC stars) are less massive, He-burning objects. Note that distances are only known for a small part of the WNL sample. Some of these objects might thus have lower luminosities and be the direct progenitors of the earlier subtypes.

A fundamental problem arises from the frequent detection of H-free WR stars of intermediate spectral subtypes, with stellar temperatures of $T_\star = 50$–100 kK. Due to their high mean molecular weight, these stars are actually expected to lie on the He main-sequence with effective core temperatures above 100 kK. Although the new spectral analyses with line-blanketed models tend to give higher values of $T_\star$, this long-standing problem still persists. Note that for a part of these stars the wind is so thick that the effective photosphere lies far

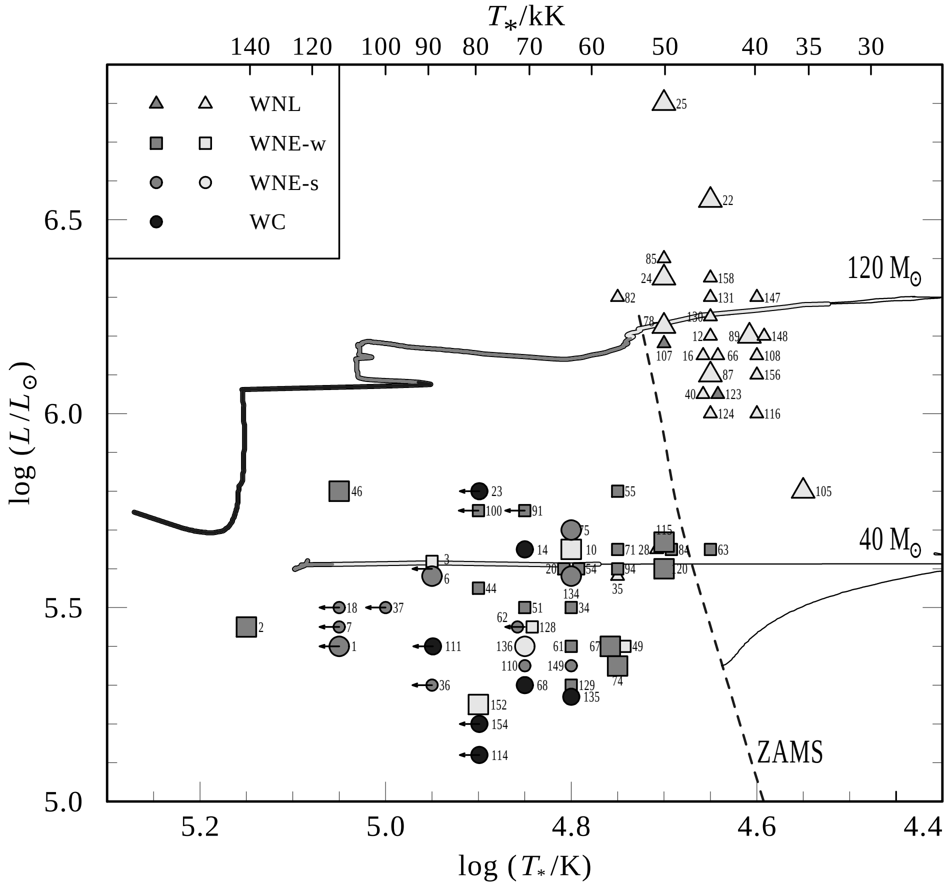

Figure 2. Recent spectral analyses of galactic WR stars with line-blanketed models, according to Hamann et al. (2006) and Barniske et al. (2006): symbols in light grey denote H-rich WR stars, whereas H-free objects are indicated in dark grey. WC stars are indicated in black. For objects with large symbols direct 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.

above the hydrostatic radius. For these cases, $T_\star$ which is the effective temperature related to $R(\tau_{\rm Ross} = 20)$ only gives a lower limit for the hydrostatic core temperature.

3. Hydrodynamic models for early spectral subtypes

As mentioned earlier, our hydrodynamic model atmospheres are capable to reproduce the observed properties of early-type WC stars in a self-consistent manner (Gräfener & Hamann 2005). In agreement with Nugis & Lamers (2002) we find that high critical-point temperatures (≈ 200 kK) are needed to match the region where the "hot Fe opacity peak" becomes active. According to our

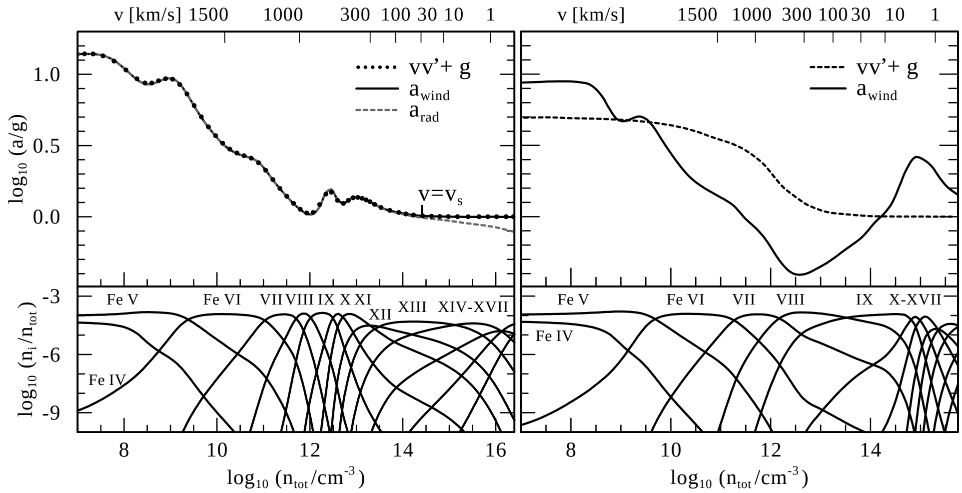

Figure 3. Wind acceleration within our models in units of the local gravity, vs. wind density as depth index (compare Fig. 1). The left panel shows our hydrodynamic WC model with $T_\star = 140\,\mathrm{kK}$. Self-consistency is obtained throughout the complete atmosphere ($a_{\mathrm{wind}} = vv' + g$). The right panel shows a cooler model with $T_\star = 85\,\mathrm{kK}$. For this model no consistency is obtained. The hot Fe-peak opacities (Fe IX–XVII) are located so deep inside the atmosphere, that they are missing in the wind acceleration region.

models, this also requires extremely high stellar temperatures of $T_\star > 100\,\mathrm{kK}$. Otherwise, as illustrated in Fig. 3, the hot Fe-peak moves so deep inside the atmosphere that no line opacities are available for the acceleration of the wind base. For intermediate spectral subtypes with $T_\star = 70$–$100\,\mathrm{kK}$ our models thus predict no WR-type mass loss. The existence of H-free WR stars in this temperature range is thus ruled out by the theory of stellar structure *and* our wind models.

Nevertheless, we have seen that such objects are commonly observed (see Fig. 2). The additional extension of their envelopes, as well as their strong mass loss, can not be explained by standard assumptions. We thus conclude that other processes might be important for these objects. In particular, this means that their stellar winds might not be purely radiatively driven. According to our models the lack of wind acceleration occurs at the bottom of the stellar wind. Fast rotation seems to be a good candidate for an additional support of the wind in this region.

4. Hydrodynamic models for late spectral subtypes

In a recent work we have investigated the properties of luminous, H-rich WNL stars with hydrodynamic PoWR models (Gräfener & Hamann 2006b). 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. Due to the increase of the density scale height at low effective gravities, the formation of optically thick winds seems to be

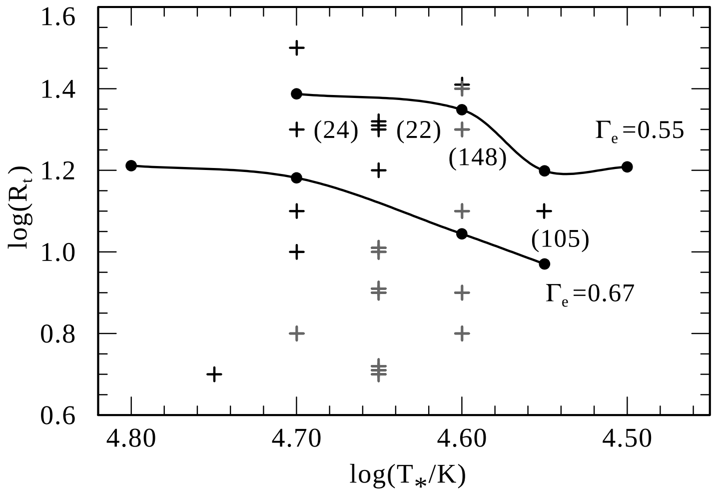

Figure 4. Wind models for galactic WNL stars: wind densities compared to observed values according to Hamann et al. (2006). In the $R_{\rm t}$–$T_\star$ plane, our models (solid curves) reproduce the *upper* part of the observed WNL sample (crosses), corresponding to WNL stars with *low* wind densities (see text for the definition of $R_{\rm t}$). The objects belonging to the enigmatic class of WN 8 spectral subtypes are indicated in grey.

strongly favored for such objects. 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. 4 we show a quantitative comparison of the results from our hydrodynamic models with observations of the galactic WNL sample (according to Hamann et al. 2006). For this comparison we employ the transformed radius

$$R_{\rm t} = R_\star \left[\frac{v_\infty}{2500\,{\rm km\,s^{-1}}} \Bigg/ \frac{\sqrt{D}\dot{M}}{10^{-4}\,{\rm M_\odot\,yr^{-1}}} \right]^{2/3}, \qquad (2)$$

which is a luminosity-independent measure of the wind density. Models with the same $R_{\rm t}$ are scale invariant, and show a very similar spectral appearance for given $T_\star$ and given surface chemistry (see Hamann & Koesterke 1998). In the $R_{\rm t}$-$T_\star$ plane, our models with Eddington factors $\Gamma_{\rm e} = 0.55$ and 0.67 reproduce the observed WNL stars with large $R_{\rm t}$. These are the WNL stars with relatively *low* wind densities. The resultant mass loss rates depend strongly on the stellar temperature (with $\dot{M} \propto T_\star^{-3.5}$), nicely reflecting the observed sequence of spectral subtypes from WN 6 to WN 9.

The high wind density objects, however, are not reproduced by our models. Notably, these objects are dominated by the enigmatic WN 8 subtypes, which tend to show strong emission lines in combination with photometric variations (e.g. Marchenko et al. 1998; Lefèvre et al. 2005). Because of the apparent dependence of $\dot{M}$ on $\Gamma_{\rm e}$ in Fig. 4, one might think that higher mass loss rates can easily be obtained by a further increase of $\Gamma_{\rm e}$. In our models, however, this leads to a point where the radiative acceleration exceeds gravity in the hydrostatic layers.

For the relatively cool WNL stars this situation occurs due to the hot Fe-peak which causes an inward increase of the Rosseland mean opacity from a certain point on. If gravity is exceeded by the resulting radiative force, a stationary solution can only be obtained if the excess acceleration is compensated by an outward increase of the gas pressure, i.e. a density inversion. In reality this will presumably lead to a non-stationary situation. Dorfi et al. (2006) have recently shown that the observed variability in WN 8 subtypes can indeed be explained by instabilities which are caused by the hot Fe-peak. The obtained timescales around 0.5 d are in rough agreement with the observed period of 9.8 h for WR 123 (Lefèvre et al. 2005), and with the dynamical timescale of the wind ($R_\star/v_\infty \approx 4\,\mathrm{h}$). We thus conclude that the observed pulsations will most probably influence the mass loss of these objects, i.e., their winds are not purely radiation driven. Note that the non-detection of X-ray emission from WN 8 subtypes (Oskinova 2005) might also be a hint on a different wind driving mechanism for these objects.

Another reason for our difficulties with the WN 8 subtypes might be related to the fact that the distances of these objects are only poorly known. They might thus fall into the category of core He-burning post-RSG stars with much lower luminosities. A detailed investigation of the influence of $L_\star$ on our wind models, however, remains a topic of future investigations.

Finally, due to their proximity to the Eddington limit, our models allow to estimate the masses of WNL stars. Because of the strong dependence of $\dot{M}$ on the L/M ratio, we can give reliable mass estimates, that only depend on the adopted distance to the object. For the H-rich, weak-lined WNL stars our models tend to give very high masses, in agreement with very massive stars in a late stage of the H-burning phase. For the case of WR 22, a weak-lined WN 7h subtype with $L_\star = 10^{6.3} L_\odot$, we derive a stellar mass of $78\,M_\odot$. This value is in agreement with the work of Rauw et al. (1996), who derived $M_\star \sin^3 i = (72 \pm 3)\,M_\odot$ from orbital elements.

5. Conclusions

Our hydrodynamic atmosphere calculations for WR stars have shown that WR-type stellar winds can be driven alone by radiative acceleration. In particular we found that the proximity to the Eddington limit is the primary trigger of the enhanced mass loss of WR stars. Nevertheless, difficulties remain with H-free objects of intermediate spectral subtype, and late-type WN stars with strong stellar winds (mostly of spectral type WN 8). In both cases, problems are caused by the gap between the 'hot' and the 'cool' Fe opacity-peaks. For the intermediate subtypes this gap causes a deficiency of line opacities at the wind base. This problem could be overcome by an additional support due to fast stellar rotation. For the WN 8 stars, the inward increase of the radiative force due to the hot Fe opacity-peak causes problems in the hydrostatic layers, presumably leading to the observed variability. These oscillations most probably affect the mass loss of these stars.

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