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# The Galactic WN stars: line-blanketed analyses versus evolutionary models

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**Abstract.** An almost complete sample of Galactic WN stars has been analyzed by means of the Potsdam Wolf-Rayet (PoWR) model atmospheres, which account for iron line blanketing and clumping. We obtain a homogeneous set of stellar parameters, partly revising earlier results. The Galactic WN population is compared with a synthetic population, generated from the Geneva tracks for massive star evolution. With the new Geneva models which account for rotationally induced mixing, the discrepancy between the synthetic and observed population is less dramatic than with the older tracks without rotation. Nevertheless, the observed bimodal distribution between WN-late stars of high luminosity and hydrogen-free WN-early stars of lower luminosity is not reproduced by the evolutionary models. We conclude that the evolution of massive stars is still not understood satisfactory.

## 1. Models and analyses

The Potsdam Wolf-Rayet (PoWR) model atmospheres (cf. Hamann & Gräfener 2004) are based on the "standard" assumptions (spherically symmetric, stationary mass-loss) and a pre-specified velocity law. Grids of these models (accessible via http://www.astro.physik.uni-potsdam.de/PoWR.html) are applied to analyze the almost complete set of Galactic WN stars, omitting binaries with composite spectra. Note that, in contrast to our previous comprehensive study of the Galactic WN stars (Hamann & Koesterke 1998), the models now account for iron line blanketing. Partly we employ new observational data, including the 2MASS near-IR photometry which greatly helps to constrain the interstellar reddening parameter. We fit the spectral energy distribution from UV (if available) to infrared wavelengths, as well as the detailed UV and visual line spectrum.

Figure 1 displays the "transformed radius" $R_{\rm t}$ versus the "stellar temperature" $T_*$ for all program stars. Note that these "spectroscopic parameters" are independent from the stellar distance. The transformed radius is related to the mass-loss rate $\dot{M}$ ($R_{\rm t} \propto \dot{M}^{-2/3}$, see e.g. Hamann & Gräfener 2004), while $T_*$ is the effective temperature referring to the stellar radius defined by a Rosseland optical depth of 20. Figure 1 reveals that the cooler, late-type WN stars have generally thin winds and show atmospheric hydrogen, while the hotter, early-type stars (WN2 ... WN6) have thicker winds and are mostly hydrogen-free. A few early-type WN stars with strong lines (suffix -s) fall into the domain of parameter degeneracy, where the whole emergent spectrum is formed in rapidly expanding layers and depends only on the product $R_{\rm t} T_*^2$.

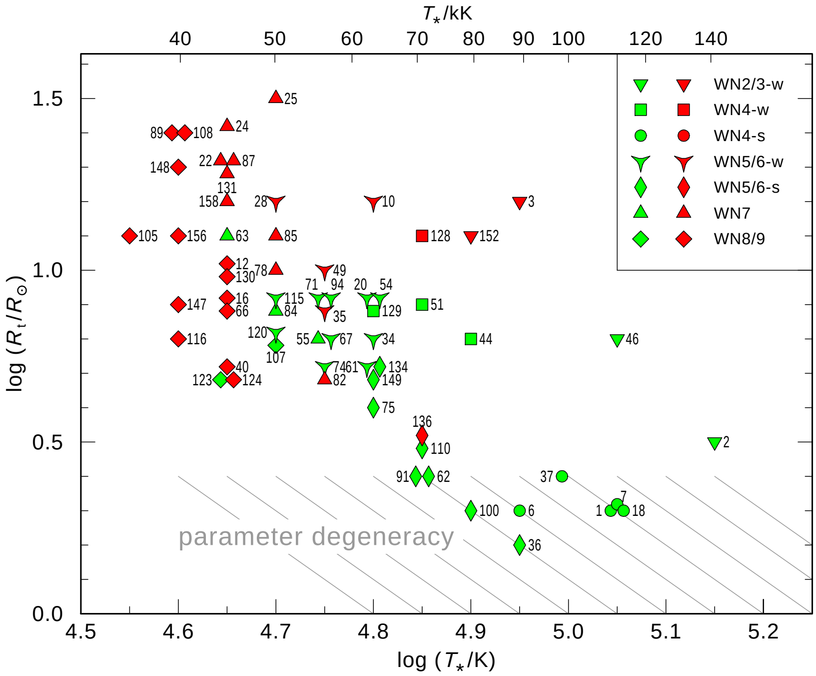


Figure 1. Parameters of the Galactic WN stars (labels: WR-Numbers). Shown is the "transformed radius" $R_{\rm t}$ (see text) versus the stellar temperature $T_*$. Dark (red) filled symbols refer to stars with detectable hydrogen, while light (green) filled symbols denote hydrogen-free stars. In the lower, hatched part of the diagram the winds are very thick, and the parameter space is degenerate such that any stars located in this part can be arbitrarily shifted parallel to the grey lines.

## 2. Comparison with evolutionary models

The left panel of Fig. 2 shows the empirical HRD for the Galactic WN stars. Only for some of the stars the distance is known from cluster or association membership. For the other stars we adopt a brightness "typical" for their subtype and represent them by smaller symbols indicating that their $L$ is uncertain. In order to restrict the discussion to single-star evolution, we grey-shaded those stars which are known to have a close companion. Remember (from Fig. 1) that eight of the observed hydrogen-free stars fall in the range of "parameter degeneracy" (see above) and can be arbitrarily shifted to higher temperatures.

The right panel of Fig. 2 shows a synthetic population of WR stars, calculated from the most recent evolutionary models from Meynet & Maeder (2003) which account for the effects of stellar rotation. We adopt a "Salpeter" initial mass function, and a constant star formation rate which produces about the observed total number of WN stars. The color coding distinguishes between WN stars, adopting a realistic hydrogen detection threshold of 5% by mass.

The empirical HRD shows a dichotomy between the hydrogen-containing, late-type WN and the hydrogen-poor WN-early subtypes. The synthetic population does not reproduce this distinction. It does not predict the observed high

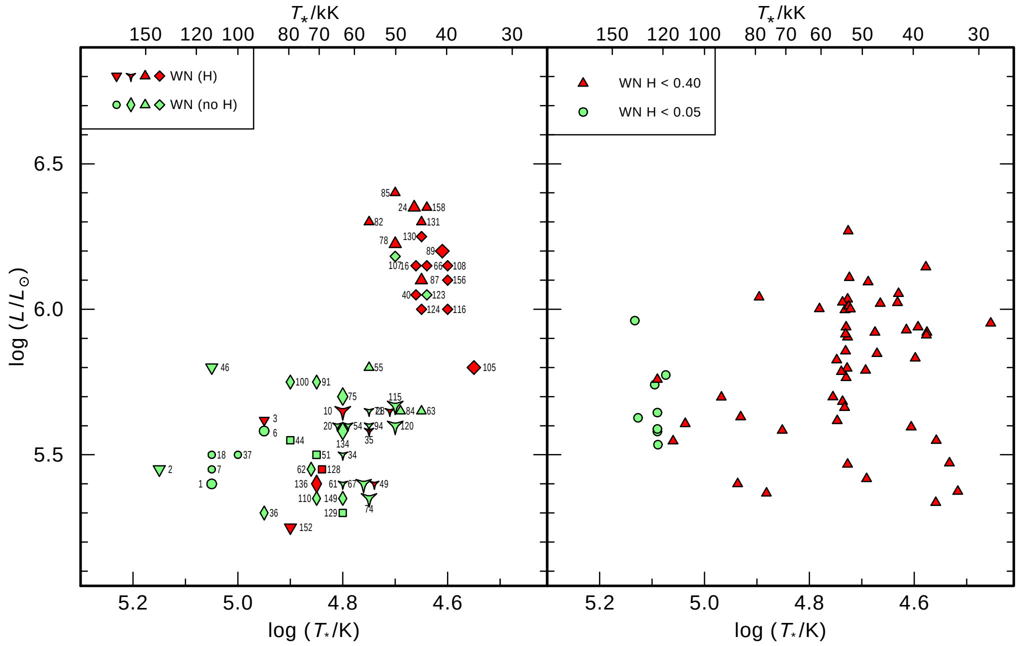


Figure 2. *Left:* Hertzsprung-Russell diagram of 58 Galactic single WN stars (see also Fig. 1 for the meaning of the symbols). Stars having a close companion are shown in grey. The bigger symbols refer to stars whose distances are known from cluster/association membership. *Right:* Synthetic WN population, based on the Geneva tracks (Meynet & Maeder 2003) accounting for rotation. The filling color reflects the surface composition (dark/red: with hydrogen; light/green: almost hydrogen-free).

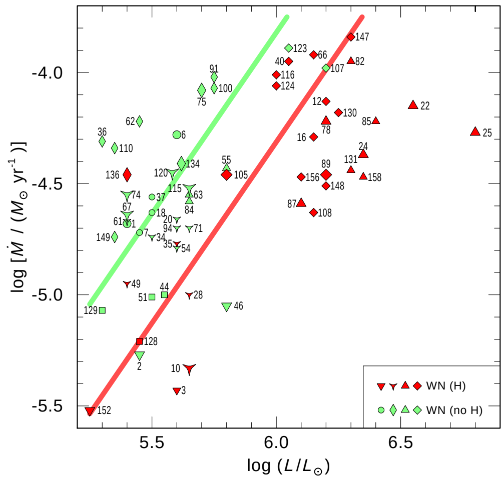


Figure 3. Empirical mass-loss rate versus luminosity for the Galactic WN stars. Dark (red) filled symbols refer to stars with detectable hydrogen, while light (green) filled symbols denote hydrogen-free stars. Binaries are shown in grey. The thick straight lines correspond to the mass loss – luminosity relation proposed by Nugis & Lamers (2000) for hydrogen-free WN stars (upper line) and for a 40% hydrogen mass fraction (lower line).

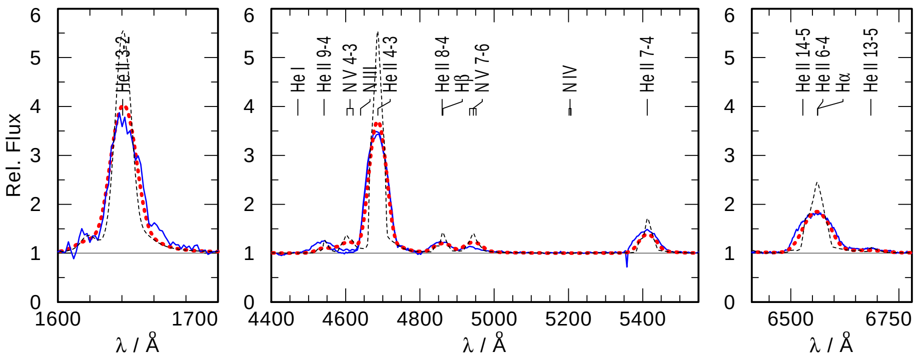


Figure 4. Observed line profiles of WR 2 (solid line), compared to a model without rotation (dashed) and after convolution corresponding to $v_{\rm rot} \sin i =$ 1900 km/s (dotted).

luminosities of the late-type WN stars ($\log L/L_{\odot} = 6.0...6.3$), and produces too few (virtually) hydrogen-free stars (here 8 out of 58), while the observed ratio is about 1:1. The few predicted hydrogen-free WN are on the average more luminous than observed. Different IMF slopes cannot solve these problems. Despite of the rough agreement, we conclude that the discrepancies are severe and might indicate that the evolution of massive stars is still not understood satisfactory.

Figure 3 shows the empirical mass-loss rates of the Galactic WN stars versus their luminosities. The frequently used formula from Nugis & Lamers (2000) gives the correct order-of-magnitude, although the WN-late do not really show any $\dot{M}$-$L$-correlation. One should also keep in mind that the empirical $\dot{M}$ is based on an adopted clumping contrast of 4. If this number is actually as high as 10, for which we have several indications, this will lower all empirical $\log \dot{M}$ by 0.2.

## 3. WR 2 - a rapidly rotating WN star?

A short glance on the atlas of Galactic WN spectra (Hamann et al. 1995) reveals that the weak-lined WN2 star WR 2 is unique with respect to the shape of its line profiles. Such round profiles are not reproduced by any of our models, unless very rapid rotation is assumed. Figure 4 shows line profiles of WR 2, comparing observation with model profiles before and after flux convolution (which is only a very crude approach to a rotating wind, admittedly) with 1900 km/s rotational velocity. Note that WR 2 is the hottest ($T_{*} = 140$ kK) and most compact ($R_{*} = 0.9\,R_{\odot}$) Galactic WN star. A rotational velocity of 1900 km/s would imply that the star is spinning at its break-up limit.

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