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The most luminous stars in the Galaxy and the Magellanic Clouds

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Abstract: Some of the Wolf-Rayet (WR) stars are found to have very high bolometric luminosities ($\log L/L_{\odot} > 6$). We employ the Potsdam Wolf-Rayet (PoWR) model atmospheres for their spectral analysis, which yields the bolometric corrections. Distance and interstellar reddening also enter the luminosity estimates.

Among the Galactic stars, there is a group of very luminous WNL stars (i.e. WR stars of late subtype from nitrogen sequence with hydrogen being depleted in their atmospheres, but not absent). Their distances are often the major source of uncertainty. From K-band spectroscopy we found a very luminous star ($\log L/L_{\odot} = 6.5$) in the Galactic center region, which we termed the Peony Star because of the form of its surrounding dusty nebula. A similar group of very luminous WNL stars is found in the Large Magellanic Cloud (LMC). In the Small Magellanic Cloud (SMC) the majority of WR stars resides in binary systems. The single WNL stars in the SMC are not very luminous.

We conclude that a significant number of very luminous WNL stars exist in the Galaxy and the LMC. With initial masses above 60 $M_{\odot}$, they apparently evolved directly to the WNL stage without a prior excursion to the red side of the HRD. At the low metallicity of the SMC, the binary channel may be dominant for the formation of WR stars.

1 Introduction

Very luminous stars, with bolometric luminosities exceeding $10^6 L_{\odot}$, appear spectroscopically mainly as Wolf-Rayet (WR) types. However, hot stars emit most of their radiation in the extreme ultraviolet which is not accessible to observation. Hence the determination of their luminosity L must rely on adequate model atmospheres. Our "Potsdam Wolf-Rayet" code (PoWR – see Hamann & Gräfener 2003 and references therein) solves the non-LTE radiative transfer in a spherically symmetric expanding atmosphere. Detailed and complex model atoms are taken into account especially for H, He, and the CNO elements, while the iron-group elements are treated in the superlevel approximation. Wind inhomogeneities are accounted for in a first-order approximation ("microclumping"). The code has been applied mainly for the wind-dominated emission-line spectra of WR stars (see `http://www.astro.physik.uni-potsdam.de/PoWR.html` for grids of models), but can also be used for fitting photospheric absorption spectra. In the standard version of the PoWR code, mass-loss rate and velocity field are free parameters of the model, while they are determined consistently with the radiation pressure only in the hydrodynamical version (Gräfener & Hamann 2005, 2008). Another PoWR code option not used here is "macroclumping" (Oskinova et al. 2007).

2 How reliable are spectroscopic luminosities ?

In order to discuss the reliability of WR luminosities, we briefly describe the procedure of their spectroscopic determination. The first step is the fit of the normalized line spectrum. Spectra from stellar-wind models depend mainly on two parameters, the stellar temperature T_* and the so-called "transformed radius" R_t. The terminal wind velocity v_∞ controls the widths of the profiles. Furthermore, the lines depend of course on the chemical abundance of their species.

The stellar temperature T_* is the effective temperature related to the luminosity L and the stellar radius R_* via the Stefan-Boltzmann law. R_* refers by definition to the point of the atmosphere where the Rosseland mean optical depth reaches 20.

The "transformed radius" is defined as $R_\mathrm{t} = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \Big/ \frac{\dot{M}\sqrt{D}}{10^{-4}\,M_\odot\,\mathrm{yr^{-1}}} \right]^{2/3}$. Its name, historically coined by Schmutz et al. (1989), is actually misleading since R_t has not the meaning (although the units) of a radius. More suggestive is to consider R_t^{-3}, which might be called a "normalized emission measure". Being proportional to the volume integral of the density squared, divided by the stellar surface, R_t^{-3} scales with the emission from recombination lines normalized to the continuum. This explains why different combinations of R_*, v_∞, and mass-loss rate $\dot{M}$ result in approximately the same normalized WR emission-line strengths as long as R_t (or R_t^{-3}) is kept at the same value. (D is the clumping factor for which we assume $D = 4$ throughout the work described here.)

Taking advantage of this approximate parameter degeneracy, the analysis can start from models with an arbitrarily adopted luminosity (our grids are mostly calculated for $\log(L/L_\odot) = 5.3$) and find the optimum fit of the normalized line spectrum by varying T_* and R_t (using models of adequate v_∞ and chemical composition). The spectral fits that can be achieved are satisfactory (cf. Fig. 1), but also often leave characteristic discrepancies which we attribute mainly to deviations from wind symmetry and homogeneity. The fit parameters can be typically determined to an accuracy of ± 0.05 in $\log T_*$ and ± 0.1 in $\log R_\mathrm{t}$.

In a second step, the luminosity is determined from fitting the spectral energy distribution of the model to observations (flux-calibrated spectra or photometry) over the widest available range (see Fig. 2). The slope and form of the model SED is fitted by adjusting the color excess E_{B-V}, and by chosing an adequate reddening law (and its parameters). Sometimes the (circumstellar?) reddening is clearly anomalous, as demonstrated in the example of Fig. 2 by the weak 2200 Å feature. The absolute value is adjusted by scaling the model in luminosity (i.e. a vertical shift in the double logarithmic plot).

In order to discuss the error margins of the derived luminosity, we consider $M_\mathrm{bol} = 4.72 - 2.5 \log L/L_\odot$. This absolute bolometric magnitude follows from the observed apparent magnitude m_i in some band i (where i may stand for, e.g., the visual band V, or for the near-IR K band in case of

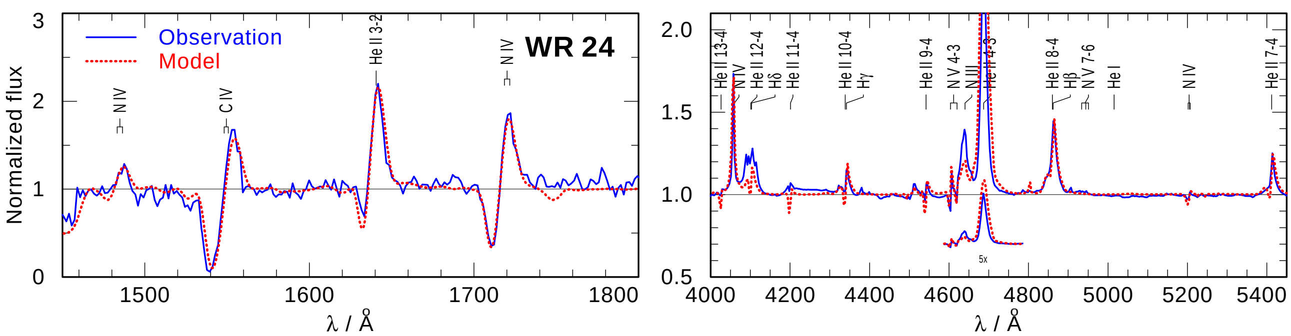

Figure 1: Example of line fit for the Galactic WN6h star WR 24, showing P Cygni type line profiles in the UV (*left panel*) and strong emission lines in the optical (*right*). Main parameters of the model (red-dotted) are T_* = 50 kK, $\log R_\mathrm{t}$ = 1.35, X_H = 0.44 and v_∞ = 2160 km/s (after Hamann et al. 2006).

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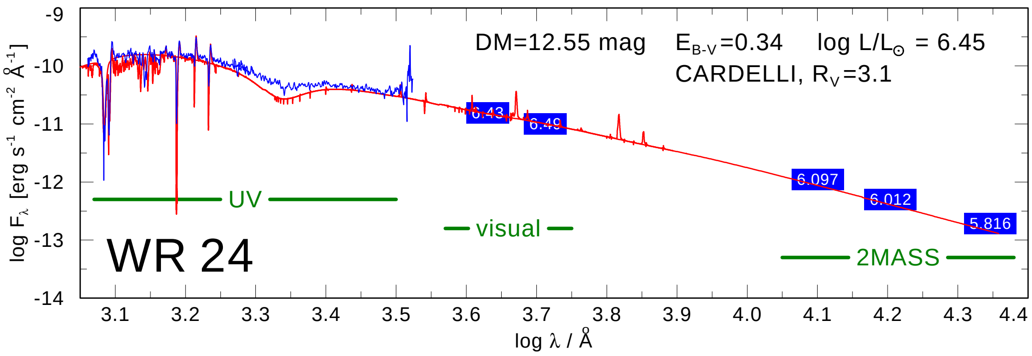

Figure 2: Example of a fit of the spectral energy distribution (SED) for WR 24 (red: model, blue: observation), using the model selected from the line fit (cf. Fig. 1). The distance modulus DM is known from cluster membership. Free parameters are the reddening and the luminosity scaling.

visually obscured objects), by applying the bolometric correction BC_i and the extinction A_i in the considered band, and the distance modulus DM (all in mag),

$$M_{\text{bol}} = m_i - BC_i - A_i - DM \tag{1}$$

The bolometric correction is predicted by the model (see Fig. 3) and amounts to 3–5 mag for most WN stars, but can reach 6.5 mag for the hottest subtypes. Since the observed band lies in the Rayleigh-Jeans domain of the SED, the bolometric correction ($10^{0.4BC}$) scales roughly with T_*^3. Hence a typical fit uncertainty of ± 0.05 in $\log T_*$ propagates to ± 0.4 mag in BC or ± 0.15 in $\log L$.

The extinction can introduce a noticeable error especially when it is high. If the available wavelength basis is as long as in the example shown in Fig. 2, the color excess E_{B-V} can be determined from the spectral slope to a few hundredths of a magnitude. However, the extinction law itself can vary between different lines of sight. For the visual band, for instance, R_V may deviate considerably from 3.1 as the Galactic standard value, which affects the visual extinction $A_V = R_V\, E_{B-V}$.

For Galactic WR stars, the largest uncertainty often comes from the distance. Only when a star can be assigned to an open cluster or association, we can adopt the distance of the latter. Stars in

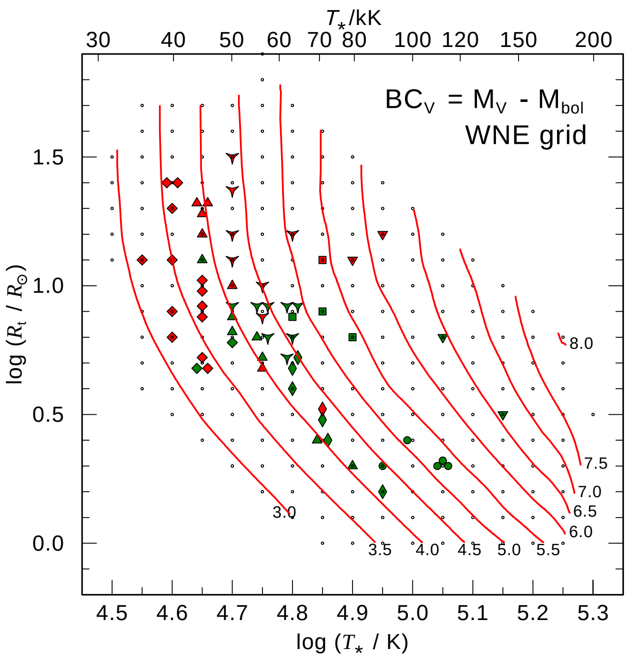

Figure 3: Contours of the same Bolometric Correction to the visual magnitude (labels: BC_V in mag) for PoWR models of hydrogen-free WN stars. Small dots mark the WNE grid models, and colored symbols show the parameters of Galactic WN stars from Hamann et al. (2006).

the Galactic Center, and especially objects in the LMC and SMC, have the clear advantage of a well-known distance.

Summarizing, the reliability of spectroscopically determined luminosities of WN stars depends very much on the individual circumstances. When the stellar temperature is well constrained from the line fit of different ions, the distance is known, and good photometry is available in spectral bands with not too high extinction, the error margins combine to ± 0.2 in $\log L$, typically.

3 Results

The empirical Hertzsprung-Russell-diagram (HRD) for the Galactic WN stars, analyzed with the methods described above, is displayed in Fig. 4 (left panel). Two groups of stars are clearly distinguished. The hydrogen-free stars, usually termed WNE ("E" for early subtypes), are pretty hot and located between the hydrogen and the helium main sequence. Their luminosities $\log L/L_\odot$ are between 5.3 and 5.8, typically. In contrast, the WNL ("L" for late subtypes) stars are less hot than the ZAMS and contain hydrogen. Most of them are very luminous ($\log L/L_\odot > 6$). They are not WR stars in the classical understanding, but rather very massive stars with strong winds which are still in the hydrogen-burning phase. However, for a couple of the WNL stars in this diagram the distance is actually not known (indicated by their smaller symbols). Their luminosity is basically adopted from

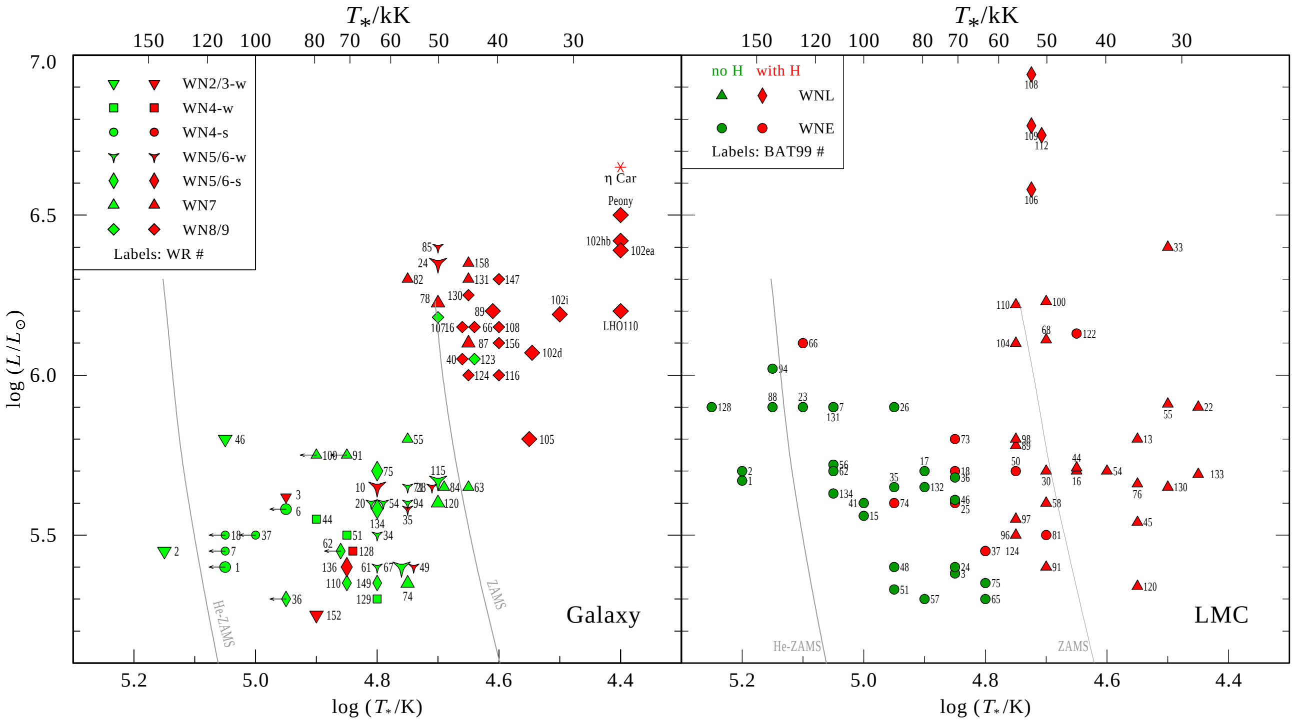

Figure 4: Empirical HRDs of WN stars in the Galaxy (*left*) and the LMC (*right*). The Galactic stars are from Hamann et al. (2006). Labels denote the WR catalog number, while red and green colors indicate whether photospheric hydrogen is detectable or not, respectively. The larger symbols refer to stars with independently known distances. Included are also the Galactic center stars WR 102hb, 102ea, 102i, 102d and LHO 110 analyzed by Liermann et al. (2010, 2011) and the Peony star (WR102ka) from Barniske et al. (2008). η Car (after Figer et al. 1998) is shown for comparison. The LMC stars in the right panel (identified by their BAT99 catalog number) are preliminary results from Rühling et al. (in prep.). The diamonds indicate four objects from the R136 cluster according to Crowther et al. (2010).

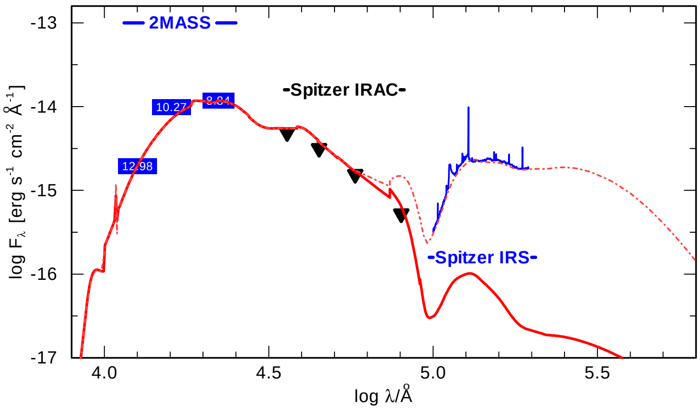

Figure 5: SED fit of the Peony star (WR 102ka) in the Galactic center region. Because of the strong interstellar extinction, the maximum of the observed flux is in the K band. The mid-IR excess observed with *Spitzer* indicates warm circumstellar dust (model: red dashed line), which was found here for the first time around a WN star. From Barniske et al. (2008)

similar stars of known distance. A couple of them might be in fact closer and less luminous.

Remarkable is the group of WNL stars from the Galactic center region. Being visually obscured, they have been analyzed only from their K-band spectra. Nevertheless, we believe that their luminosities are reliable. Figure 5 shows the SED fit for the Peony star. In the K band, the extinction A_K amounts only to about 3 mag. The analysis (Barniske et al. 2008) revealed that this star has the second-highest luminosity ($\log L/L_\odot$ = 6.5 $\pm$0.2) known in the Galaxy, after η Car.

In the LMC the group of very luminous WNL stars is less pronounced (Fig. 4, right panel). Instead there are many WNL stars with hydrogen, but moderate luminosities. It is not yet clear if we have missed such stars in the Galaxy because of the distance problem discussed above. The four extremely luminous stars represented in the figure by diamonds have been claimed recently by Crowther et al. (2010), and belong to the cluster R136 which we had avoided. The problem is to rule out accidental multiplicity in this very dense field of stars with identical spectral type.

The 12 WR stars (11 WN, 1 WO) known in the SMC are currently studied by Pasemann et al. (2011, and in prep.). Five of these stars appear to be single, while the remaining six are binaries for which we started to analyze the composite spectra. With $\log L/L_\odot < 6$ the single WN stars are not “very” luminous.

4 Conclusions

A couple of very luminous stars ($\log L/L_\odot > 6$) are found in the Galaxy and LMC. Apart from a few outstandingly bright LBVs, the most-luminous stars are of late WN type (WNL). Remarkable is the abundance of such stars in the Galactic center region. In the SMC, single WNL stars are also found despite of the low metallicity, but not with very high luminosities.

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Discussion

P. Williams: In the different possible de-reddenings of the WR 24 SED, it seems none of them cancelled the 2200 Å feature - how is that?
W.-R. Hamann: You have correctly spotted that in the shown SED fit of WR24 the interstellar 2200 Å feature is not correctly reproduced. The standard reddening laws (Cardelli et al., Fitzpatrick et al.) that we use provide only one adjustable parameter, R_v. The actual reddening function A_λ may considerably deviate from these laws for an individual line-of-sight, especially with regard to the broad 2200 Å feature.