Spectral analyses of the Wolf-Rayet stars in the Small Magellanic Cloud

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Abstract: We have performed spectral analyses of all known Wolf-Rayet stars (single or binary) in the SMC. For this purpose, we have employed the Potsdam Wolf-Rayet (PoWR) model atmosphere code. For the 11 WR stars of the nitrogen sequence (WN), we calculated four grids of models with different hydrogen abundances. Futhermore, we established a series of O-star models, in order to construct the composite spectra of WN+O binaries. The only WO-type (i.e. oxygen-sequence WR) star in the SMC was also analyzed with the help of an adequate grid of models.

The preliminary results are in a rough agreement with the expectation, considering the lower mass loss in the SMC's metal-poor environment. In conflict with the evolutionary models is the high hydrogen abundance found in the single WN stars. The low luminosity of one WN star (SMC AB 2) is also not explainable.

1 Introduction

WR stars mark a late state of stellar evolution of the most-massive stars. Metallicity is one parameter that influences their evolution via the mass-loss rate. The theory of radiatively driven winds predicts a correlation between the mass-loss rate and the metallicity of a star, $\dot{M} = Z^{0.5}$ (Kudritzki et al. 1989). The metallicity in the SMC is about ten times lower than in the Milky Way. Consequently, the SMC stars may not develop a wind sufficiently strong to remove their hydrogen-rich envelope and to enter the Wolf-Rayet phase. There are two possible solutions to explain how WR stars can form at low metallicity. One possibility is that the WR stars in the SMC lose a lot of their mass via mass transfer (Roche-lobe overflow: RLOF) in close binary systems. Another solution is that only single O stars rotating the fastest can strip off their outer layers. In this study we focus on the binary assumption.

The evolution of massive binary systems can be very different from single-star evolution. Mass transfer via RLOF can dramatically influence the evolution of both components. Whether binary stars interact with each other depends on the physical parameters of the system, i.e. the initial orbital period, the initial distance between the components, and the initial mass ratio of the two stars.

Foellmi, Moffat & Guerrero (2003) searched for periodic radial velocity variations of the ten WN stars in the SMC at that time known and found that five of them are definitely binaries. A further WN star, SMC AB 11, also shows small radial velocity variations and highly blue shifted absorptions lines. However, Foellmi et al. (2003) argue that these lines come from the WR star itself and not from a companion and therefore classified the star as single. SMC AB/,12 was discovered by Massey, Olsen & Parker (2003) after the study of Foellmi et al. (2003) and seems to be a single WR star. The WO star SMC AB 8 is a well-established binary (Moffat, Breysacher & Seggewiss, 1985).

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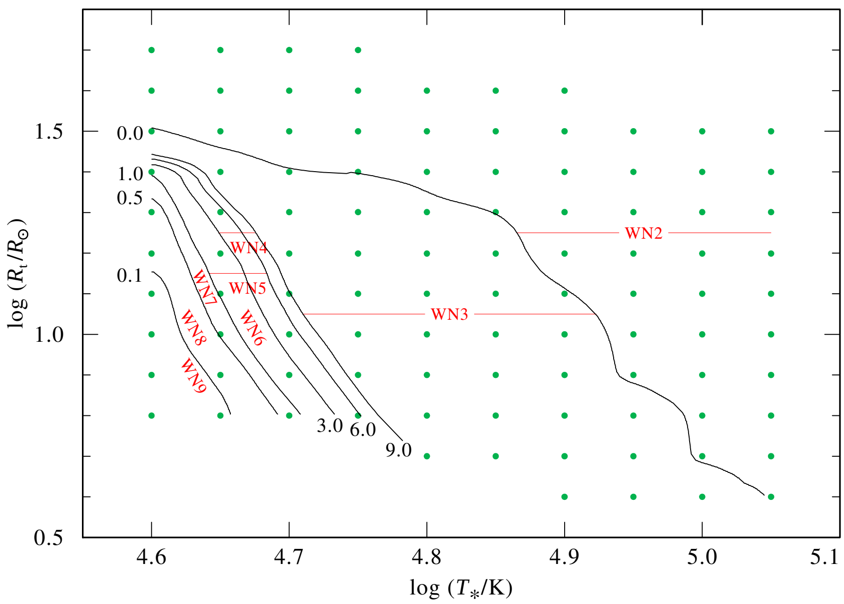

Figure 1: Calculated models (green dots) of the grid with 20% hydrogen in the R_t-T_*-plane. The domains of the WN subtypes after the classification of Smith, Shara & Moffat (1996) are labelled in red. The contour lines indicate the ratio of the equivalent width between He II (5412 Å) and He I (5875 Å).

2 Spectral analyses

For the spectral analyses we use the Potsdam Wolf-Rayet (PoWR) model atmosphere code which solves the non-LTE radiative transfer in a spherically expanding atmosphere in the co-moving frame. Complex model atoms of hydrogen, helium and the CNO elements are taken into account. The iron group elements are included in a super-level approximation. We establish four grids of models with different hydrogen content, reaching from 0%, 20%, 40% to 60 % H by mass fraction. The terminal wind velocity $v_\infty = 1600\,\mathrm{km/s}$, the clumping factor $D = 4$, the luminosity $\log\, L/\mathrm{L}_\odot = 5.3$ and the chemical composition are kept constant over all grids. Figure 1 shows one of the model grids. The main parameters of a model grid are the stellar temperature T_* and the so-called "transformed radius" R_t (see Hamann et al. these proceedings).

The WN subtypes are defined as an ionisation sequence, which is reflected by their location in the R_t-T_*-plane. Higher ionization is obtained by higher temperatures (T_*) and lower wind densities (i.e. higher R_t). The domains of the WN subtypes are defined by certain ranges of the ratio between the equivalent widths of the classification lines from He II and He I (see Fig. 1). The presence of hydrogen, if obvious from the strength of the Balmer-line blends with He II lines compared to the unblended members of the He II Pickering series, is indicated in the classification by the letter "h".

As first step of our analyses, we identify the grid model which fits best to the observed line spec-

Table 1: Comparison of different spectral analyses of SMC AB 4

T_* [kK]	$\log\, L/\mathrm{L}_\odot$	v_∞ [km/s]	$\log\, \dot{M}$ [$\mathrm{M}_\odot$/yr]	Reference
42.0	5.70	1300	-5.05	Crowther (2000)
43.1	5.90	1000	-5.00	Martins et al (2009)
47.3	5.88	1000	-4.98	present study

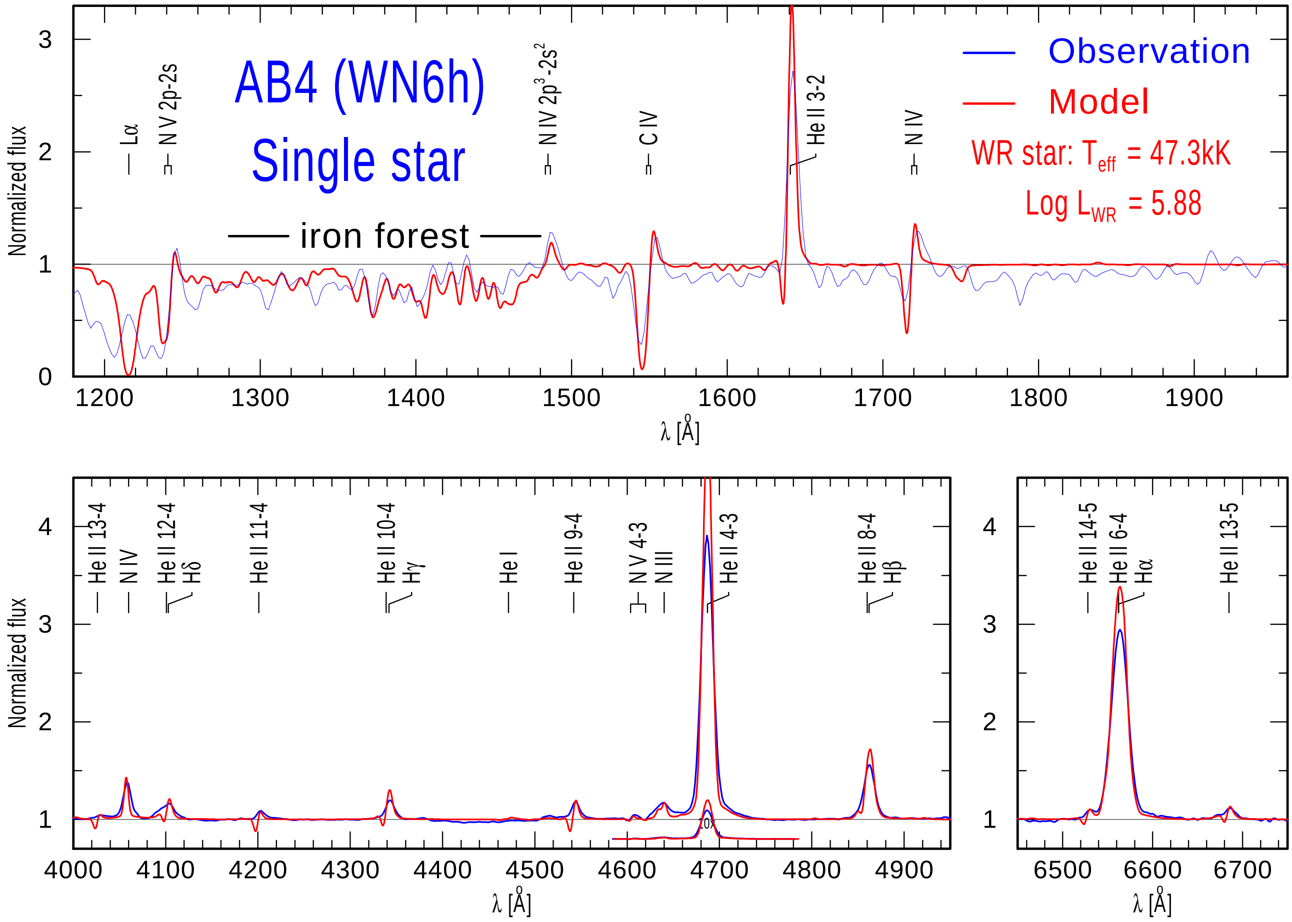

Figure 2: Model fit (red) to the observed spectrum (blue) of the WN6h single star SMC AB 4 in the UV and optical regime.

trum. Secondly, the spectral energy distribution is fitted by adjusting the luminosity and reddening. As an example, Fig. 2 shows the line fit for SMC AB 4, one of the six single WR stars in the SMC. The observed spectra are from Foellmi et al. (2003)[1] (optical) and IUE. The lines of all nitrogen ionisation stages are well reproduced. This star has been analyzed by other groups before. Our parameters are in good agreement with the results of Crowther (2000) and Martins et al. (2009). The results are listed in Table1.

To analyse the composite spectra of binaries we also calculated models for the O star companions. For example, SMC AB 6 is a SB2 binary, i.e. spectral lines from both stars are visible (see Fig. 3). The absorption features of He I 4471 Å and 5875 Å which are due to the O star, indicate an effective temperature between 30 and 35 kK. Secondly, we choose a suitable WN model which reproduces the emission lines. SMC AB 6 shows strong He II lines which are diluted by the continuum of the O-type companion. The ratio between the line strengths of He II 4686 Å and H α 6562 Å determines the hydrogen abundance. Finally, the two models spectra are added, while the luminosity ratio is adjusted such that the narrow absorption features from the O star and the broad emission lines from the WN star are reproduced simultaneously. Note that the flux in the optical and UV range of SMC AB 6 is dominated by the O star although both components have similar luminosities.

[1] We retrieved these data from http://wikimbad.obs.ujf-grenoble.fr/Home

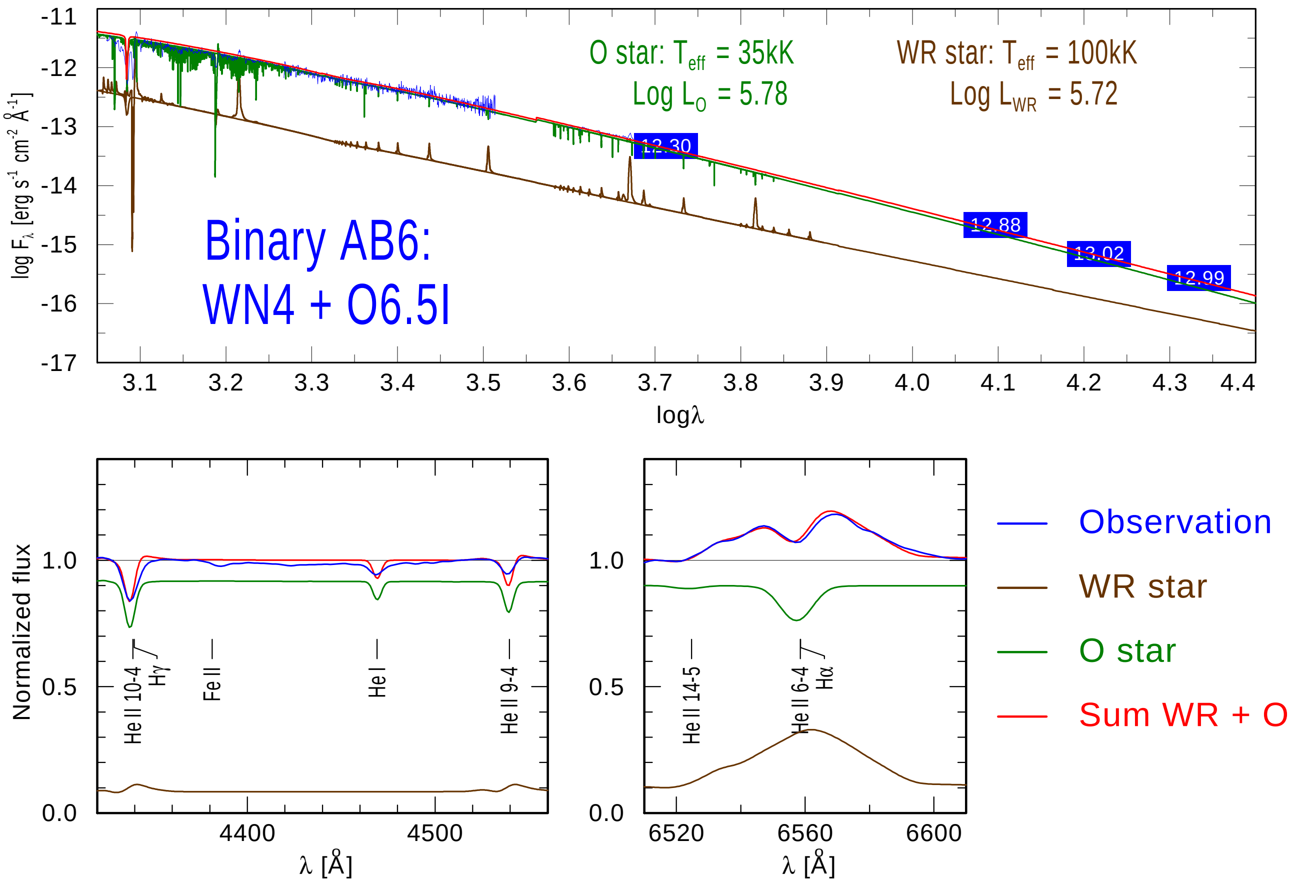

Figure 3: Composite spectrum of SMC AB 6, fitted by the sum of a WN and O star model (see text)

3 Results and conclusions

Figure 4 shows the Hertzsprung-Russell diagramm of all twelve WR stars in the SMC and their binary companions. It is remarkable that in contrast to the Galactic WR stars we do not find any hydrogen-free WNE stars at luminosities lower than $\log L/\mathrm{L}_\odot \approx 5.5$ in the SMC.

This can be explained as the effect of the low metallicity, which leads to smaller mass loss by radiation-driven winds. Indeed, we obtain $\dot{M} \approx 10^{-5.5}\mathrm{M}_\odot/\mathrm{yr}$ for the single WN stars in our sample. The evolutionary tracks predict that the minimum initial mass for single stars to return from the RSG branch and to reach the WR stage increases to $M_\mathrm{init} \approx 40\mathrm{M}_\odot$ at SMC metallicity, compared to the Galactic value of $M_\mathrm{init} \approx 22\mathrm{M}_\odot$ (with rotation).

Four of the five WN stars have high luminosities of $\log L/\mathrm{L}_\odot \geq 5.8$. This is compatible with the luminosity range where the tracks return to the hot side of the HRD. SMC AB 2, however, has a luminosity of only $\log L/\mathrm{L}_\odot = 5.5$ which is in contradiction to the evolutionary prediction. All single WN stars show hydrogen with mass fractions between 40 - 60%. This is significantly higher than predicted by the evolutionary tracks. For example, the $60\,\mathrm{M}_\odot$ track from Meynet & Maeder (2003) shows not more than 18% hydrogen at the surface when reaching a stellar temperature of $\log T_* = 4.9$.

For the binaries we obtained no or only little hydrogen (0 - 20%). These stars can lose their hydrogen envelopes via RLOF which is not metallicity dependent and therefore can explain the observed WN stars at lower luminosities ($\log L/\mathrm{L}_\odot = 5.5$). These stars are probably in the phase of core helium burning. With a lower mass than core hydrogen burning stars at same luminosity, they are closer to the Eddington limit. This can explain why we find higher mass-loss rates for the WN stars

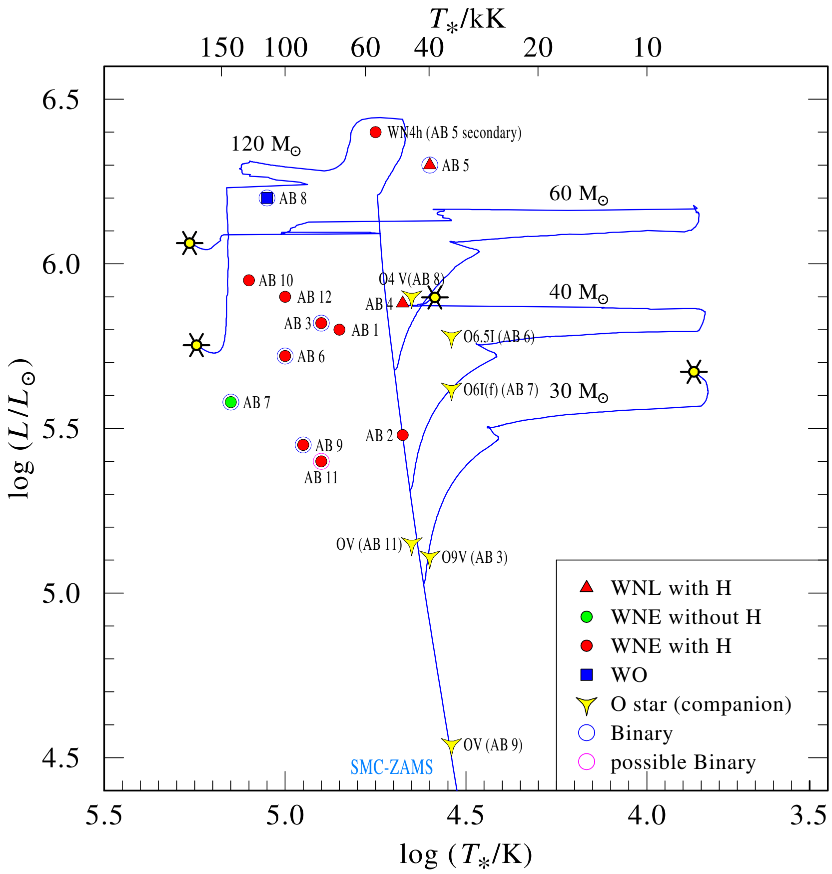

Figure 4: HRD with the WR stars of the SMC and their O-star companions compared to evolutionary tracks with rotation from Meynet & Maeder (2003)

in binary systems ($\dot{M} \approx 10^{-4.7} M_\odot/yr$) than for the single WN stars in our sample.

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