Wolf-Rayet Stars
W.-R. Hamann, A. Sander, H. Todt, eds.
Potsdam: Univ.-Verlag, 2015
URL: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus4-84268

The WN population in the Magellanic Clouds

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A detailed and comprehensive study of the Wolf-Rayet stars of the nitrogen sequence (WN stars) in the Small Magellanic Cloud (SMC) and the Large Magellanic Cloud (LMC) is presented. We derived the fundamental stellar and wind parameters for more than 100 massive stars, encompassing almost the whole WN population in the Magellanic Clouds (MCs). The observations are fitted with synthetic spectra, using the Potsdam Wolf-Rayet model atmosphere code (PoWR). For this purpose, large grids of line-blanket models for different metallicities have been calculated, covering a wide range of stellar temperatures, mass-loss rates, and hydrogen abundances. Our comprehensive sample facilitates statistical studies of the WN properties in the MCs without selection bias. To investigate the impact of the low LMC metallicity and the even lower SMC metallicity, we compare our new results to previous analyses of the Galactic WN population and the late type WN stars from M 31. Based on these studies we derived an empirical relation between the WN mass-loss rates and the metallicity. Current stellar evolution tracks, even when accounting for rotationally induced mixing, partly fail to reproduce the observed ranges of luminosities and initial masses.

1 Introduction

The Magellanic Clouds (MCs) offer the almost unique possibility to study massive stars on all scales, from putatively single stars to massive binary systems, to fairly complete stellar populations. Due to the low interstellar extinction in the direction of the MCs and within the MCs, most of their WR population is known, although some objects escaped detection so far (see e.g. Massey et al., these proceedings). Moreover, because of the known distance to the MCs, the results obtained from the spectral analysis of their massive star population are free from uncertainties inferred from unsure distances, which is in strong contrast to the Milky Way (MW).

Although the WN phase is an important stage in the life of massive stars, the evolution of these objects is not yet completely understood. One essential factor that affects the evolution of massive stars is the mass loss due to their stellar winds. Especially, the dependence of the mass-loss rates of WR stars on the initial metallicity is so far only poorly studied. Due to the sizable number of WN stars in the MCs and the significant sub-solar metallicities that characterize these extraordinary galaxies, the MCs provide an ideal opportunity to address this issue.

2 PoWR model atmospheres

The spectral analysis was performed with synthetic spectra calculated with the Potsdam Wolf-Rayet (PoWR) model atmosphere code. PoWR is a state-of-the-art code for expanding atmospheres, which accounts for both a quasi hydrostatic domain and an rapidly expanding stellar wind. The code assumes a stationary, spherically symmetric outflow. The equations of statistical equilibrium are solved iteratively with the radiative transfer that is calculated in the co-moving frame, while energy conservation is ensured. For further details to the applied methods and the implemented physics we refer to Hamann & Koesterke (1998), Gräfener et al. (2002), and Sander et al. (these proceedings).

2.1 Model grids

For the analysis of the WN stars in the MCs, we calculated three model grids with LMC metallicities and four grids with SMC metallicities. The main parameters of these grids are the stellar temperature T_* and the so-called transformed radius

$$R_\mathrm{t} = R_* \left(\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \middle/ \frac{\dot{M}\sqrt{D}}{10^{-4}\,M_\odot\,\mathrm{yr}^{-1}} \right)^{2/3} , \quad (1)$$

which is related to the emission measure of the wind (e.g. Hamann, these proceedings). For more details on the model grids we refer to Hainich et al. (2014), Hainich et al. (2015), and Todt et al. (2015). These grids are available online on the PoWR website[1].

3 Mass-loss rates

On average, the winds of the WN stars in the MCs are weaker and the mass-loss rates are lower than what is observed for their counterparts in the Galaxy. Figure 1 shows the averaged mass-loss rates of the WN stars in the Milky Way (Hamann et al. 2006; Martins et al. 2008; Liermann et al. 2010; Oskinova et al. 2013), M 31 (Sander et al. 2014), the LMC (Hainich et al. 2014), and the SMC (Hainich et al. 2015) as a function of their initial metallicities,

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[1] `www.astro.physik.uni-potsdam.de/PoWR.html`

which are assumed to be the metallicity of the corresponding host galaxies. From this figure, it is obvious that the mass-loss rates of the WN stars clearly decline with a decreasing content of heavy elements. A linear regression to the averaged mass-loss rates of the WN stars in the MCs, the Galaxy, and M 31 results in a power law with an exponent of 1.2 ± 0.1, which is significantly higher than the ≈ 0.7 predicted and observed for OB-type stars (Vink et al. 2000, 2001; Mokiem et al. 2007). It also is larger than the 0.8 predicted by Vink & de Koter (2005) for late-type WN stars.

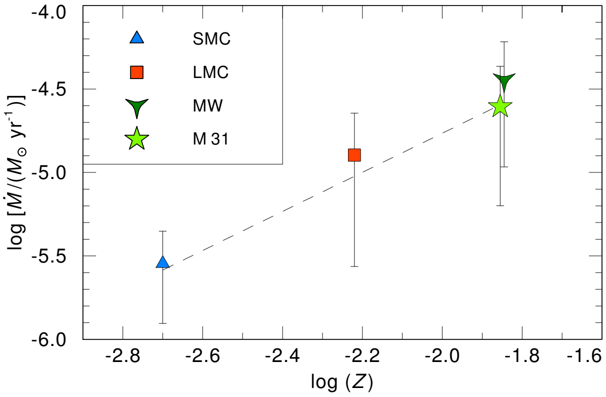

Fig. 1: Averaged mass-loss rate of the WN population in the SMC, LMC, M 31, and the Galaxy plotted versus the metallicity of the corresponding host galaxy. The error bars are the standard deviation within each sample. The dashed line is a linear regression to these data points.

For the determination of the $\dot{M}$-Z-relation, we also utilized the modified wind-momentum luminosity relation (WLR, Kudritzki et al. 1999). The modified wind-momentum

$$D_{\rm mom} = \dot{M} v_\infty R_*^{1/2} \qquad (2)$$

shows the same dependence on the metallicity as the mass-loss rate, since the terminal wind velocity v_∞ and the stellar radius R_* are not metallicity dependent in a first-order approximation. Because of the deviations in the exponents of the individual WLRs, these relations need to be evaluated at a specific luminosity. We choose a value of $\log L/L_\odot = 5.8$, since it is right in the middle of the luminosities where these relations overlap. This method results in an exponent for the $\dot{M}$-Z-relation of 1.3 ± 0.1, confirming the value that is obtained from the rather simplistic approach described above.

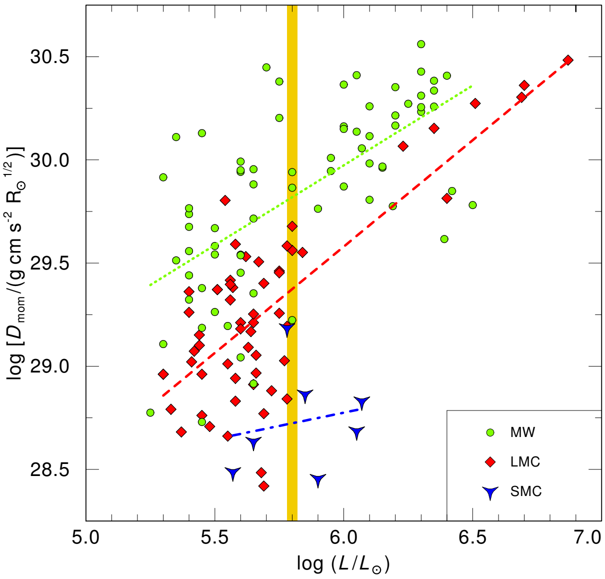

Fig. 2: Modified wind-momentum of the WN stars in the SMC, LMC, and the Galaxy vs. the corresponding luminosity. The straight lines denote the WLRs for the SMC (blue dashed dotted line), the LMC (red dashed line), and the MW (green dotted line). The vertical orange bar refers to the luminosity that we chose to evaluate the different WLRs.

4 Stellar evolution

Our comprehensive spectral analysis of the WN stars in the MCs allows to test the predictions of stellar evolution calculation at low metallicities. The comparison between empirical HRD positions with stellar evolution models reveals that the corresponding tracks partly fail to reproduce the observed WN parameter range.

Figure 3 shows the Hertzsprung-Russell diagram (HRD) of the putatively single WN stars from the LMC (left panel) and the SMC (right panel). For comparison, we also plot stellar evolution tracks computed by Meynet & Maeder (2005) and Eldridge & Vink (2006) for LMC and SMC metallicities, respectively. In both cases the evolution models are not able to reproduce the HRD positions of those objects with the lowest luminosity. Thus, these models overpredict the initial mass necessary to reach the WR phase. Therefore, population synthesis calculations that rely on these models will potentially underestimate the total number of WR stars. Moreover, stellar evolution tracks predict surface hydrogen abundances at the empirical HRD positions of most SMC WN stars that are significantly lower than observed.

We note that the stellar evolution tracks plotted in Fig. 3 are just exemplary and that similar conclusions are obtained with other evolution tracks that

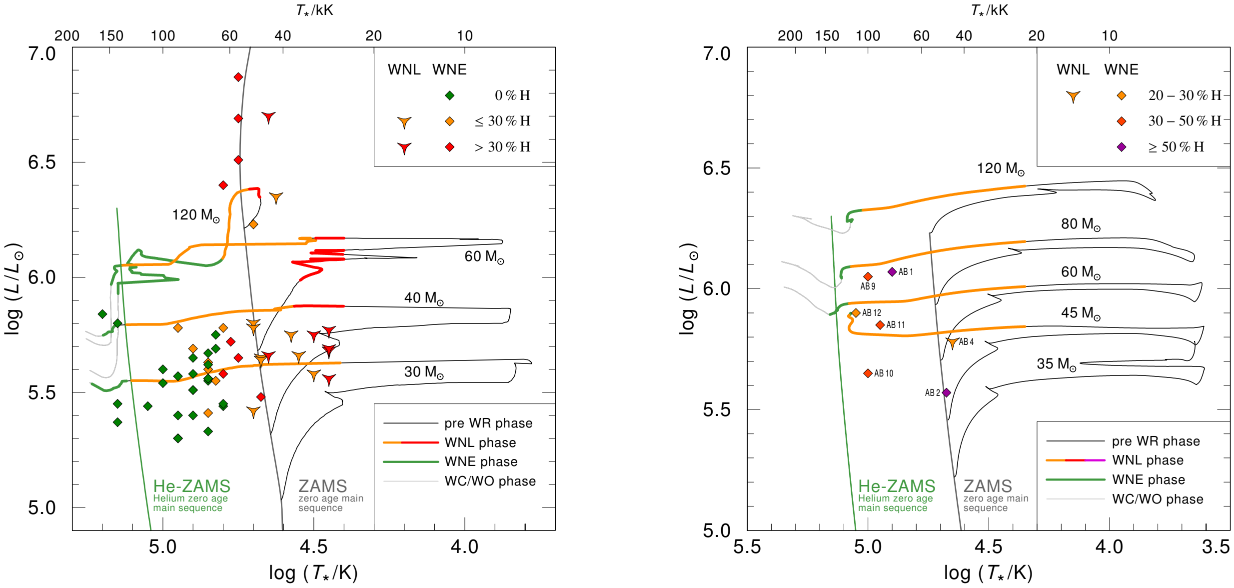

Fig. 3: Hertzsprung-Russell diagram of the single WN stars from the LMC (left panel) and form the SMC (right panel) compared to stellar evolution tracks calculated by Meynet & Maeder (2005) and Eldridge & Vink (2006), respectively. The labels at the tracks give the initial mass of the corresponding models. The filling color of the symbols and the color coding of the tracks refer to the surface hydrogen abundance.

are available. The only exception are such models that predict quasi-homogeneous evolution, owing to very fast initial rotation. These models (Brott et al. 2011) are able to reproduce the HRD positions of all SMC WN stars. However, the corresponding tracks also underestimate the surface hydrogen abundances. In the context of the results presented in Sect. 3, stellar evolution models that evolve quasi homogeneously and account for mass-loss rates lower than currently assumed might be able to reproduce the results obtained from our spectral analysis of the SMC WN stars.

5 Summary

We investigated nearly the complete WN population in the MCs, providing the first comprehensive analysis of this class of massive stars at low metallicities. Based on this work, we derived a clear relation between the initial metallicity and the mass-loss rates that is significantly steeper compared to what is known for OB-type stars. Moreover, we showed that the current generation of stellar evolution models are not able to completely reproduce the observed WN parameter range.

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Kathryn Neugent: We've hypothesized that the SMC WRs with absorption might somehow be related to the WN3/O3 stars found in the LMC. I see that you've fit all 7 of these SMC WRs. Did you find that their physical parameters (effective temperature, luminosity) were similar to the WN3/O3s? Additionally, it seems that the mass loss rates you find are quite low, which is to be expected in such a low metallicity galaxy as the SMC. However, do you think the low mass loss rates could be even lower than expected in a similar way as the WN3/O3s?

Rainer Hainich: By comparing our results with the parameters published by Massey et al. (2015) for one of the recently discovered WN3/O3 stars in the LMC, we find that the hydrogen abundances and the stellar temperatures are similar. However, the luminosity of the SMC WN stars are on average significantly higher compared to the LMC WN3/O3 stars. Moreover, the mass-loss rates derived for the SMC WN stars are higher than what is obtained by Massey et al. (2015), which is quite astonishing. It definitely raises some interesting questions regarding the evolutionary status of these objects.

Paul Crowther: Use of solely single WN stars in the SMC excludes the very strong lined WN binaries HD 5980.

Rainer Hainich: That is true. We are right now analyzing the WN binaries in the SMC, investigating whether these objects exhibit systematic differences compared to the single SMC WN stars (Shenar et al. in prep.).

Paul Crowther: The small numbers of low metallicity WN stars can be enhanced by addition of IC10, which hosts many more WN stars and has 1/3 solar composition.

Rainer Hainich: I completely agree. We should investigate more WN stars at low and intermediate metallicities and, IC10 is an ideal candidate for further studies.

Norbert Langer: Can you comment on the scatter of the mass-loss parameters for WN stars of a fixed luminosity, which is about a factor of 30?

Rainer Hainich: This scatter is seen in all WN populations analyzed so far, covering a wide range of metallities form solar-like values in the Galaxy and M 31 to low metallicity environments like the MCs. A certain fraction of this scatter might be attributable to assumptions made in the context of the spectral analyses of these objects, like a single clumping factor for a whole WN population. However, the major fraction of the scatter in the mass-loss rates of WN stars appears to be intrinsic to these kind of stars and probably reflects the different evolution stages and evolution histories of these objects. This also finds expression in other parameters like the stellar temperature and the hydrogen surface abundance, which could be very different for WNL and WNE stars.