High-mass X-ray Binaries: Illuminating the Passage
from Massive Binaries to Merging Compact Objects
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Testing how massive stars evolve, lose mass, and collapse at low metal content

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Abstract. In order to test massive star evolution above 25 M⊙, we perform spectral analysis on a sample of massive stars in the Small Magellanic Cloud that includes both O stars as well as more evolved Wolf-Rayet stars. We present a grid of non-LTE stellar atmospheres that has been calculated using the CMFGEN code, in order to have a systematic and homogeneous approach. We obtain stellar and wind parameters for O stars, spectral types ranging from O2 to O6, and the complete sample of known Wolf-Rayet stars. We discuss the evolutionary status of both the O and WR stars and the links between them, as well as the most likely evolutionary path towards black hole formation in a low metallicity environment, including testing theoretical predictions for mass-loss rates at low metallicities.

Keywords. stars: early-type, stars:Wolf-Rayet, Small Magellanic Cloud, stars: fundamental parameters

1. Introduction

The Small Magellanic Cloud is a galaxy of low metallicity, and an excellent environment to constrain stellar evolution at metallicities resembling the early Universe. Stellar evolution of massive stars at different metallicities is not identical. Metallicity plays a role in the evolutionary path that each star follows until reaching its final stage. Quantitative spectroscopy provides a useful tool to obtain several stellar parameters to understand how massive stars evolve in several environments when comparing to evolutionary models. Progenitors of Wolf-Rayets (WR) have not been defined in the Small Magellanic Cloud (SMC), and there are multiple channels for their origin.

One possible channel considers an O star, rapidly rotating and going through chemically homogeneous evolution (CHE) to reach the WR stage. However, constraints obtained via spectropolarimetry of WR stars view this as unlikely, and a more classical post-LBV mass loss scenario is more probable (Vink & Harries, 2017). This channel is partially supported by quantitative spectral analysis of single WR stars in the SMC (Hainich *et al.* 2015); a possible exception might be the binary system AB5 (Shenar *et al.* 2016).

Massive stars have been reported to be in binary systems with a ~50% likelihood, where they can interact with their companion by merging, mass transfer, or they are expected to be spun up (Sana *et al.* 2013). Bouret *et al.* (2013) hinted at binary systems for some putatively single O dwarfs in the SMC to explain their high luminosities.

Then, a possible channel for the formation of WR stars in the SMC is binary interaction via mass transfer, to account for the surface abundances and luminosities obtained through quantitative analysis of these single WR stars (Hainich *et al.* 2015). Though, this scenario has been challenged by contemporary results for WR binaries, where the primaries would have gone through a WR phase independent of binary interaction, questioning mass transfer as the dominant mechanism (Shenar *et al.* 2016).

The origin of WR stars in the SMC is unclear, and future research is needed in this matter to solve the discrepancy between empirical results and the ones predicted by evolutionary models. Shedding some light on the origin of WR stars in the SMC might be expected by homogeneous analysis of O dwarfs, O supergiants and WR stars in this galaxy, covering a wide range of parameters for O star evolution in the Hertzprung-Rusell diagram.

2. Spectral fitting

Previous work on O and WR stars have been done with different radiative transfer codes (CMFGEN, POWR), and there is a lack of analyses of O supergiants in the SMC. In order to have realistic error bars a homogeneous and systematic approach has been taken to perform the quantitative analysis of the O and WR stars spectra, using the radiative transfer code CMFGEN to create a grid of models in the parameter range of O dwarfs, O supergiants and WR stars in the SMC.

A fine multidimensional grid will be ideal to model systematically the spectra of these stars, however it would require a large computational time. It is important to choose parameters that have a large influence on stellar lives to reduce the computational time developing the grid. Therefore our grid has as main parameters the effective temperature ($T_{\rm eff}$ at $\tau = 2/3$) and the transformed mass-loss rate ($\dot{M}_{\rm t}$) (Gräfener & Vink, 2013). The abundances used are scaled solar (1/5 $Z_\odot$) by Asplund *et al.* (2009), and including ions of H, He, C, N, O, Si, P, S and Fe.

The use of the transformed mass loss rate will allow us to preserve the spectral shape for different values of mass loss rate if the luminosity, wind terminal velocity and clumping factor are kept constant. The basic grid has a fixed: $\log(g) = 4.0$, luminosity $L = 10^6\ L_\odot$, terminal velocity $V_\infty = 2800\,{\rm km\,s^{-1}}$, clumping factor $f_v = 0.1$ and a β value of the wind acceleration of $\beta = 1$.

The main parameters of the two-dimensional grid, effective temperature ($T_{\rm eff}$) and transformed mass loss rate $\dot{M}_{\rm t}$, range from 35.5 to 56.2 kK and $\log(\dot{M}_{\rm t})$ [$M_\odot\,{\rm yr}^{-1}$] from -6.28 to -4.78 respectively.

To cover the parameter range by WR stars in the SMC models with higher temperatures and higher $\log(g)$ values are needed, for transformed mass loss rates values ranging from $\log(\dot{M}_{\rm t})$ [$M_\odot\,{\rm yr}^{-1}$] of -5.16 to -4.78. These models are currently running, and future work is pending.

The quality of the fitting between models and data is measure through a χ^2_{fit} method similar to that of Bestenlehner *et al.* (2014), where only the sum of equivalent widths of diagnostic lines are taken into account to constrain the transformed mass loss rate and the effective temperature.

To obtain the helium abundance, crucial to determine the evolutionary status of these stars, an extra dimension is needed for the grid. This ranges from 25 % to 47 % on helium content in the basic grid, included in the χ^2_{fit} analysis. To determine luminosities and extinction values SED fitting is performed using photometric data obtained from Bonanos *et al.* (2010) and the Cardeli extinction law (Cardelli *et al.* 1989).

3. Preliminary results

Fitted spectra of an O dwarf and a Wolf-Rayet star are shown in Figures 1 and 2. The best fit CMFGEN model for the O dwarf AzV 243 classified as an O6 V, reproduced the

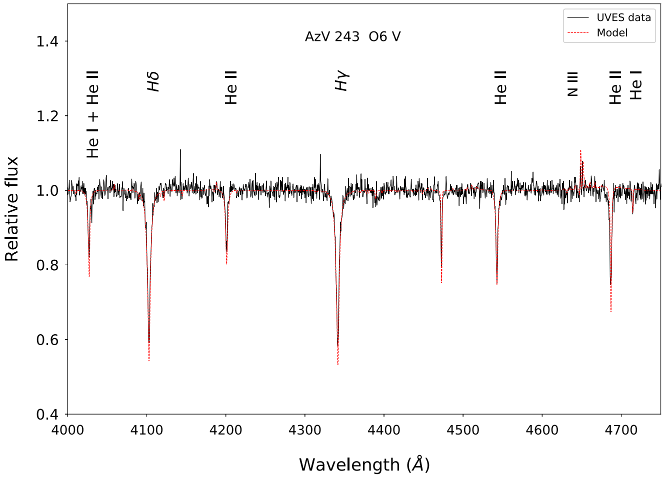

Figure 1. Normalised spectra of AzV 243 compared with the best fitting CMFGEN model from the grid. The normalised spectra for AzV243 is shown as a black solid line, while the CMFGEN model is shown as a red dashed line.

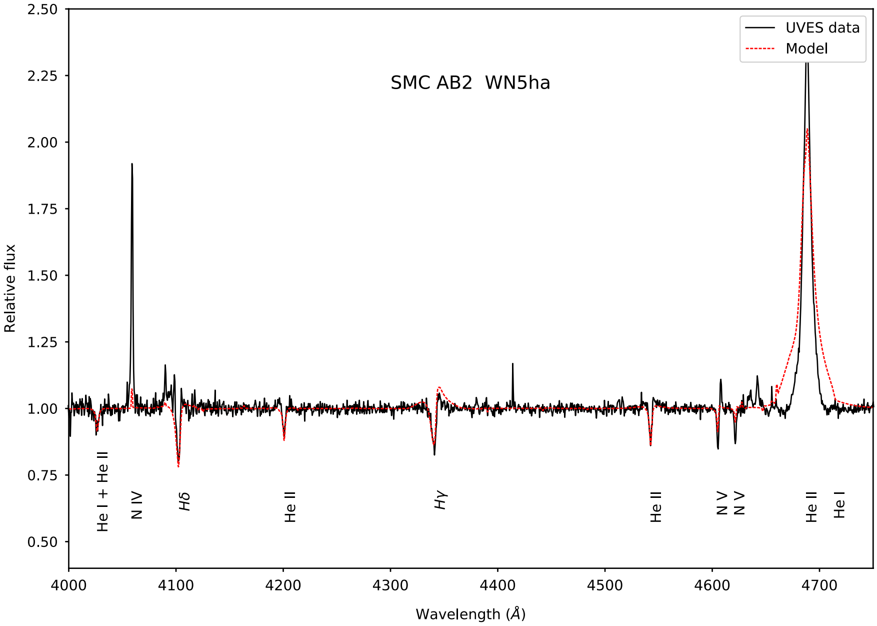

Figure 2. Normalised spectra of SMC AB2 compared with the best fitting CMFGEN model from the grid. The normalised spectra for SMC AB2 is shown as a black solid line while the CMFGEN model is shown as a red dashed line.

line profile for all absorption lines present in its UVES spectrum. While the strength of the lines is not fully reproduced, effective temperature and mass loss rate values obtained are similar to the ones reported by Bouret *et al.* (2013).

In the case of the Wolf-Rayet SMC AB2 classified as a WN5ha the line profile of HeII λ 4686 Å is not reproduced by the model. This is caused by our fixed value for the wind terminal velocity (V_∞), indicating a lower value for V_∞ in agreement with results by Hainich *et al.* (2015). Also the strength of NIV λ 4058 Å is not reproduced, pointing to a higher abundance for this element than $1/5\,Z_\odot$ corresponding with the WN nature of the star. Regardless of the fitting the obtained values for the effective temperature and mass loss rate are comparable to the ones obtained by Hainich *et al.* (2015).

In the current analysis of the O dwarfs and cooler WR stars in the SMC, the best fitted models from the grid (see Figs. 1 and 2) do not reproduce entirely the strength or line profiles displayed by the data. However the effective temperature and mass loss rate values, obtained through the method described in the previous section, are comparable to the ones found by Hainich *et al.* (2015) and Bouret *et al.* (2013); ergo validating our systematic and homogeneous approach. It is expected then that our objective method once applied to the O supergiants sample will obtain reliable values for their effective temperature and mass loss rate. This can be compared without a subjective component to the rest of the sample, eliminating systematic errors, and most probably unveiling links between these evolutionary phases.

4. Future Work

Further model computation to extend the parameter range of the grid to cover different $\log(g)$ values and higher temperatures is needed: to be able to model O supergiants; hotter Wolf-Rayets in the sample; and also to obtain He, C, and N abundances. Once the sample has been fully analysed a comparison with stellar evolutionary models is essential to unveil links between evolutionary stages and possible WR progenitors.

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