Wolf-Rayet Stars
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Massive Wolf-Rayet stars on the verge to explode: the properties of the WO stars

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The enigmatic oxygen-sequence Wolf-Rayet stars represent a rare stage in the evolution of massive stars. Their properties can provide unique constraints on the pre-supernova evolution of massive stars. This work presents the results of a quantitative spectroscopic analysis of the known single WO stars, with the aim to obtain the key stellar parameters and deduce their evolutionary state.

X-Shooter spectra of the WO stars are modeled using the line-blanketed non-local thermal equilibrium atmosphere code CMFGEN. The obtained stellar parameters show that the WO stars are very hot, with temperatures ranging from 150 kK to 210 kK. Their chemical composition is dominated by carbon (>50%), while the helium mass fraction is very low (down to 14%). Oxygen mass fractions reach as high as 25%. These properties can be reproduced with dedicated evolutionary models for helium stars, which show that the stars are post core-helium burning and very close to their eventual supernova explosion. The helium-star masses indicate initial masses or approximately $40 - 60 M_{\odot}$.

Thus, WO stars represent the final evolutionary stage of stars with estimated initial masses of $40 - 60 M_{\odot}$. They are post core-helium burning and may explode as type Ic supernovae within a few thousand years.

1 Introduction

The enigmatic oxygen sequence Wolf-Rayet (WO) stars are the rarest kind of Wolf-Rayet (WR) stars, with currently only nine members of the class known. Their spectra are characterized by strong emission of O VI, in particular the doublet at 3811-34 Å.

Since their discovery, the WO stars have typically been interpreted as being in a short evolutionary stage following the more common WC stage. In this case the oxygen emission results from an enhanced abundance as the deep layers of the star are revealed by the stripping through the stellar wind (e.g., Langer 2012). An alternative scenario is that the stars originate from higher mass progenitors than the WC stars, and the O VI emission is purely an excitation effect due to the higher stellar temperature and not necessarily reflects a higher oxygen abundance (Hillier & Miller 1999).

To investigate the nature of the WO stars, we have performed a quantitative spectroscopic analysis of the known single WO stars using CMFGEN (Hillier & Miller 1998). We use dedicated evolutionary models to reproduce the obtained stellar parameters and determine the evolutionary state of the WO stars.

2 Observations & Analysis

The spectra of six single WO stars were obtained using the X-Shooter spectrograph on ESO's Very Large Telescope. Only the recently discovered WO star LMC195-1 (Massey et al. 2014) is not included in our sample. Table 1 gives an overview of the observed WO stars. Data reduction has been done using the X-Shooter pipeline v2.2.0. The flux-calibrated spectra were dereddened using the CCM extinction laws (Cardelli et al. 1989; O'Donnell 1994), using a CMFGEN WO star model as a template for the slope of the continuum.

The modeling of the spectra is described in detail in Tramper et al. (2013) and Tramper et al. (2015). The observed magnitudes of the stars were used to correct for errors in the flux calibration in order to derive proper luminosities. The obtained stellar parameters are given in Table 2. The given mass-loss rates assume a clumping factor of 10. The location of the stars in the Hertzsprung-Russell diagram (HRD) is shown in Figure 1.

Tab. 1: List of the observed WO stars.

ID	R.A. (J2000)	Dec. (J2000)	Spectral Type	Galaxy	$\frac{Z}{Z_\odot}$	Other IDs
WR102	17:45:47.56	−26:10:26.9	WO2	MW	1	Sand 4
WR142	20:21:44.35	+37:22:30.6	WO2	MW	1	Sand 5
WR93b	17:32:03.31	−35:04:32.4	WO3	MW	1	
BAT99-123	05:39:34.31	−68:44:09.1	WO3	LMC	0.5	Sand 2, Brey 93
LH41-1042	05:18:11.01	−69:13:11.3	WO4	LMC	0.5	
DR1	01:05:01.61	+02:04:20.6	WO3	IC1613	0.15	B17

Tab. 2: Derived properties of the single WO stars.

ID	$\log L/L_\odot$	T_* (kK)	R_* ($R_\odot$)	$\dot{M}$ (km s^{-1})	v_∞	$\frac{N_C}{N_{He}}$	$\frac{N_O}{N_{He}}$	X_{He}	X_C	X_O
WR102	5.45	210	0.39	-4.92	5000	1.50	0.45	0.14	0.62	0.24
WR142	5.39	200	0.40	-4.94	4900	1.00	0.16	0.26	0.54	0.21
WR93b	5.30	160	0.58	-5.00	5000	0.60	0.15	0.29	0.53	0.18
BAT99-123	5.20	170	0.47	-5.14	3300	0.63	0.13	0.30	0.55	0.15
LH41-1042	5.26	150	0.62	-5.05	3500	0.90	0.20	0.22	0.60	0.18
DR1	5.68	150	1.06	-4.76	2750	0.35	0.06	0.44	0.46	0.10

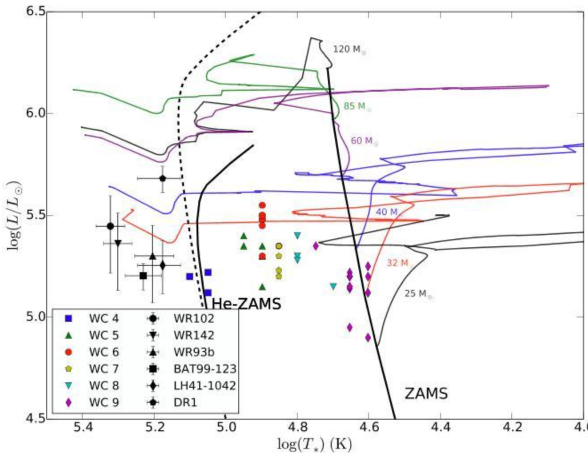

Fig. 1: Location of the single WO stars in the HRD. Also indicated are the WC stars analyzed by Sander et al. (2012) and evolutionary tracks from Ekström et al. (2012).

3 WO star properties and lifetimes

In Figure 1 the WO stars are located left of the helium terminal-age main sequence, a first indication that they are likely post core-helium burning. To further investigate their evolutionary state, we use the *Binary Evolution Code* (BEC, Yoon et al. 2006, 2010; Brott et al. 2011) to model the WO stars starting from the helium zero-age main sequence. The aim is to reproduce their observed luminosity, temperature, and surface helium abundance. The derived mass-loss rates in Table 2 are much higher than the rates from Nugis & Lamers (2000) that are normally used in BEC. We therefore calculate new models assuming a fixed mass-loss rate throughout the core-helium burning evolution and beyond. The observed non-clumped mass-loss rates set an upper limit to the modeled mass loss, while the need to reveal the layers with the observed helium abundances provides a lower limit, as well as a tentative constraint on the clumping factor.

With this approach the observed stellar properties can be well reproduced by the models. In Figure 2 we show an example of the modeling of WR102. We find that all WO stars are indeed in a post core-helium burning phase. With the exception of DR1, they may all explode within 10 000 years. Table 3 shows the helium star masses, final masses, and estimated time to supernova explosions for each of the WO stars. The mass-loss rate that is needed to model the star is also given, as well as the clumping factor this implies.

Tab. 3: Derived masses and lifetimes for the WO stars.

ID	$M_{\rm He,ini}$ ($M_\odot$)	$M_{\rm final}$ ($M_\odot$)	$t_{\rm SN}$ (yr)	$\dot{M}_{\rm evol}$ ($10^5 M_\odot$ yr^{-1})	f_c
WR102	22	9.8	1500	2.8	> 0.4
WR142	17	8.8	2000	1.7	> 0.4
WR93b	17	8.8	8000	1.7	> 0.3
BAT99-123	15	7.7	7000	1.4	> 0.3
LH41-1042	17	8.4	9000	1.8	> 0.4
DR1	23	15.4	17000	1.8	0.1

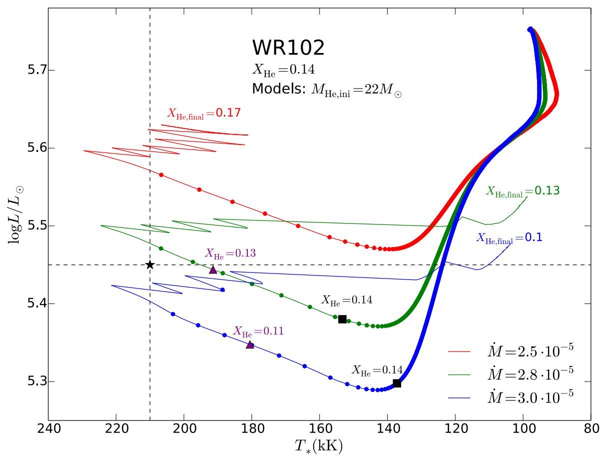

Fig. 2: HRD with evolutionary models for WR102. The best-fit parameters are indicated, as well as some of the surface helium abundances of the models. the dots indicate 1000 year time intervals.

4 Conclusions

The WO stars represent a final stage in massive star evolution. The stars are post core-helium burning and will explode as type Ic supernovae within a few thousand years. If the evolutionary models are representative for the WO stars, they have evolved from early-type WC stars with similar surface abundances, as these do not change appreciatively during their bluewards evolution. The derived helium-star masses indicate that the WO stars originate from massive stars with initial masses around $40-60 M_\odot$.

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Andy Pollock: If you sacrificed the rest of the spectrum and fit O VI, what would the temperature then be?

Frank Tramper: The temperature would not be greatly affected; instead, a much lower $\dot{M}$ is needed to fit O VI 3811–34 Å.

Anthony (Tony) Moffat: So you are saying that WO stars are not merely an extension of the WC sequence to higher T_*, right? This makes them a different animal. This raises the question if there is intra-subtype evolution, e.g. WO4 → WO3 → WO2 → WO1, as peeling off occurs and the O/C abundance increases, while He decreases.

Frank Tramper: From our models it seems that the WO stars do evolve from WC stars. Since the surface abundances do not change very much when the evolutionary tracks migrate to the very hot temperatures, early-type WC stars with similar low helium abundances would be expected. The WO subtype of the star is dependent on the initial mass of the helium star and the amount of mass that is lost during helium burning. However, it is indeed possible that there is sub-type evolution as the star migrates to the hot temperature regime after core-helium exhaustion. This would be purely a temperature effect and the abundances would not change significantly considering the short timescales involved (see e.g. the very similar helium abundances of the WO2, WO3 and WO4 stars which are mostly between 20 and 30% by mass, with exception of WR102 and DR1). Mass loss also determines if a star undergoes a WO phase at all; for low mass-loss rates (e.g. Nugis & Lamers) the models do not migrate to the hot region of the HRD after helium exhaustion.

Helge Todt: Do you include sodium in your models? The O VI 3811/34 doublet is sensitive to metallicity effects, and Keller et al. (2011) report that a consistent modeling of the O V and O VI lines needs the inclusion of sodium in the model.

Frank Tramper: Sodium is currently not included in our models. Thanks for the suggestion.