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WC Stars and their Role in the Life Cycle of Massive Stars

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Abstract. The spectral analysis of Wolf-Rayet stars requires the detailed modeling of expanding stellar atmospheres in non-LTE. The Galactic WN stars have been comprehensively analyzed with such models already some years ago. With a similarly comprehensive study, we now analyzed the Galactic WC stars, using the the Potsdam Wolf-Rayet (PoWR) model atmosphere code. Stellar and atmospheric parameters have been derived for more than 50 Galactic WC and two WO stars, covering almost the whole Galactic WC population as far as the stars are single and un-obscured in the visual. From comparing the empirical WC positions in the Hertzsprung-Russell diagram (HRD) with evolutionary models, and from supernovae statistics, we conclude that WC stars have evolved from initial masses between 20 and 45 $M_\odot$. Only the WO stars might originate from progenitors that have been initially more massive than 45 $M_\odot$. In combination with our previous results from WN analyses, the empirical HRD indicates that stars with initial masses above 60 $M_\odot$ generally do not reach the WC stage, but retain some of their hydrogen envelope thus appearing as a WNL star or LBV till they explode as a supernova.

1. Introduction

The Wolf-Rayet (WR) stars of the carbon sequence, usually referred to as WC stars, are a late evolutionary stage in the life of a massive star that has lost its hydrogen layers and displays the products of helium burning in the atmosphere. We analyzed a sample of 56 WC, WO and WN/WC stars with grids of Potsdam Wolf-Rayet (PoWR) models. The basic model parameters and the obtained results are discussed in Sander et al. (2012) and Sander & Hamann (these proceedings). WC stars are composed of 45% helium, 40% carbon, and 5% oxygen by mass. The WN/WC spectra rather resemble WN type stars (Hamann, Gräfener, & Liermann 2006), but with an enhanced carbon abundance. For the WO stars, models with an extended iron model atom, increased oxygen fraction and a very high terminal velocity of $\upsilon_\infty = 5000\,\mathrm{km\,s^{-1}}$ are needed.

2. WC Parameters

Table 1 lists the mean WC star parameters per subtype as obtained from our analyses. The subtypes form a clear temperature sequence and also show a significant correlation with the terminal wind velocity. However, there is no luminosity trend.

The best-fitting model provides the stellar temperature T_* and with a known distance or an estimated absolute magnitude from a subtype calibration, we can obtain the luminosity L for a Galactic WC star from the spectral energy distribution fit. Hence,

Table 1. Mean WC star parameters per subtype. The given mass-loss rates are calculated with a volume filling factor of $f_V = 0.1$.

Subtype	T_* [kK]	v_∞ [km s^{-1}]	R_* [R$_\odot$]	log $\dot{M}$ [M$_\odot$ yr^{-1}]	log L [L$_\odot$]
WO2	200	5000	0.6	−5.01	5.8
WC4	117	3310	1.4	−4.42	5.5
WC5	83	2800	2.2	−4.62	5.3
WC6	78	2300	3.4	−4.50	5.6
WC7	71	2000	3.8	−4.62	5.5
WC8	60	1800	3.6	−4.91	5.2
WC9	44	1400	6.8	−4.79	5.2

both parameters that determine the position of a star in the Hertzsprung-Russell diagram are given. Figure 1 shows the positions of the Galactic WC single stars in the HR diagram with color- and symbol-codes to indicate the different subtypes. We find the cool WC9 stars in a cool and relatively low luminosity region close to the zero age main sequence (ZAMS). The other WC subtypes are on the hotter left side of the ZAMS, with temperature and subtype mostly correlated. The WC4 stars are close to the so-called He-ZAMS which marks the theoretical ZAMS for pure helium stars. The two WO2 stars with $T_* \approx 200\,$kK have temperatures that are significantly above the He-ZAMS and are more luminous than most of the WC stars.

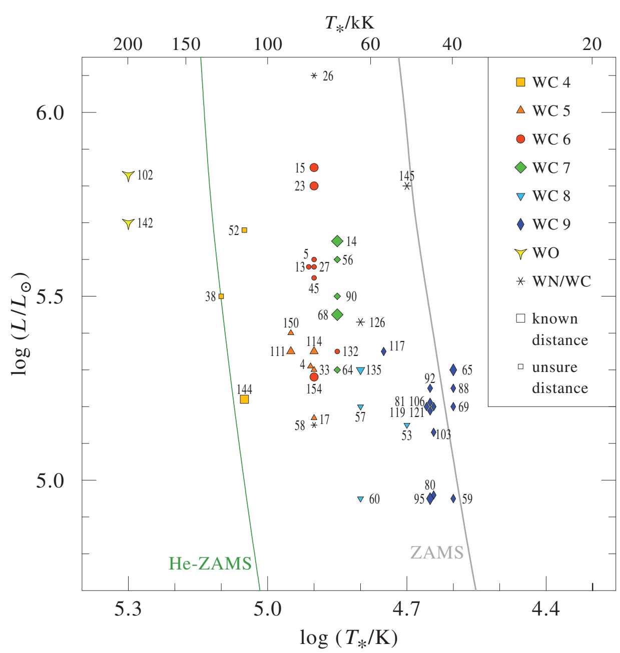

Figure 1. Hertzsprung-Russell diagram with the empirical positions of the Galactic WC stars. Large symbols indicate stars with known distances. The numbers are referring to the WR catalog from van der Hucht (2001).

As WC stars are hydrogen-free, one would expect them on or close to the He-ZAMS. However, the WC stars turn out to reside in a cooler temperature range. This could be explained by extended, sub-photospheric layers that separate the hot, He-burning core from the wind region where the spectral appearance is formed. There have been indications (Ishii, Ueno, & Kato 1999; Petrovic, Pols, & Langer 2006) for such layers in the past. Recently, Gräfener et al. (these proceedings) have shown that such layers would indeed shift the HRD position of such stars away from the He-ZAMS.

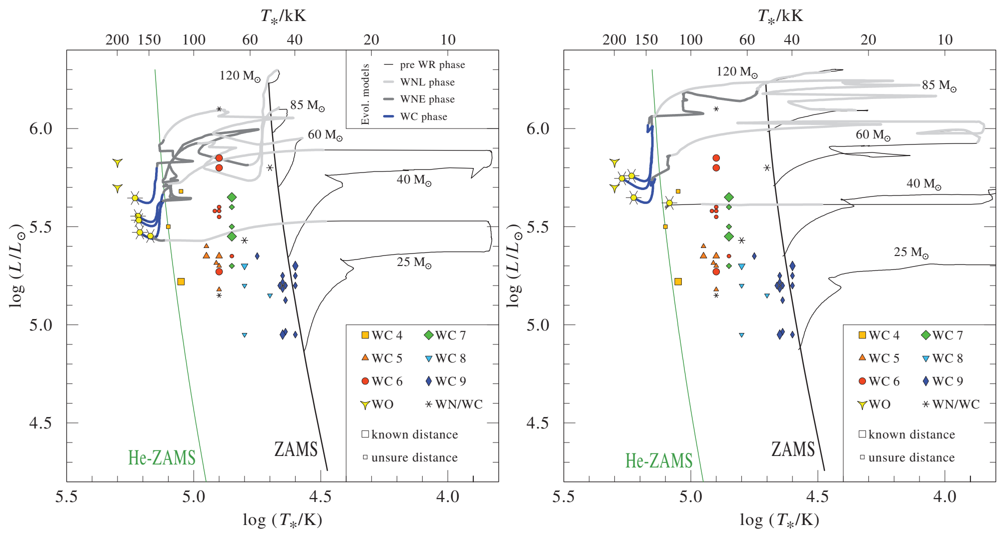

Figure 2. Galactic WC star positions in the HRD compared to the Geneva tracks from Meynet & Maeder (2003) with (left panel) and without (right panel) initial rotation.

The comparison with the Geneva stellar evolution models from Meynet & Maeder (2003) in Figure 2 reveals not only a temperature discrepancy, but also a luminosity discrepancy between the empirical HRD positions and the WC phase of the evolutionary tracks. While the two WO2 stars nicely agree with the endpoints of the non-rotating tracks, the WC stars have significantly lower luminosities. The tracks including initial rotation slightly decrease the luminosity discrepancy, but cannot really provide an explanation as there are several stars below the luminosity range predicted by the tracks, even if disregarding the temperature discrepancy.

The Geneva track with the lowest initial mass that leads to a WC star belongs to an initial mass of 40 $M_\odot$ and has a minimum luminosity of $\log L/L_\odot \approx 5.4$ during the WR stages. However, there are several stars in our sample below this limit, including some with distances known from cluster or association memberships. This implies that WC stars can also form from single stars with initial masses lower than 40 $M_\odot$. Of course this crucially depends on the distance values. Although not all of them are really well known, there are no indications for a systematic error that would lead to an overall underestimation of the luminosities.

A way to obtain WC stars at lower luminosities than in the Geneva models has been shown be Vanbeveren et al. (1998). A crucial parameter that determines if a star might eventually become a WR star is the mass-loss rate during the red supergiant (RSG) stage. However, these mass-loss rates still have high uncertainties (see e.g. Meynet et al. 2011), so usually the standard assumption from de Jager, Nieuwenhuijzen, & van der Hucht (1988) is used in stellar evolution codes like the Geneva code. Vanbeveren et al. (1998) instead used a different relation between mass loss and luminosity leading to higher RSG mass-loss rates. The resulting tracks are shown in the left panel of Figure 3. They cover the same area in the HRD as our WC star sample. The initial masses corresponding to the tracks also corroborate our assumption from the Geneva tracks that WC stars originate from initial masses lower than 40 $M_{\odot}$.

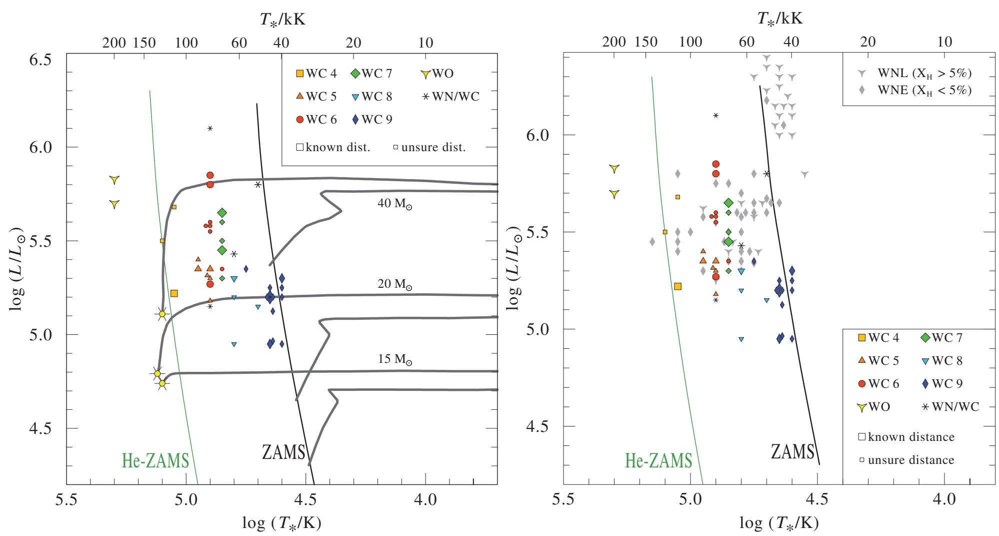

Figure 3. Left: Galactic WC star positions compared to tracks from Vanbeveren et al. (1998). Right: The obtained positions of the Galactic WC stars compared to those of the Galactic WN stars analyzed by Hamann et al. (2006).

The Galactic WC stars cover the same area as the hydrogen-free Galactic WN stars – later referred to as WNE stars – analyzed by Hamann et al. (2006). However, the hydrogen-rich WN stars – from now on called WNL stars – are located in a different region as we can see in the right panel of Figure 3. This distinct separation of WNL stars on the one hand and WNE and WC stars on the other hand raise the question if especially WNL and WNE stars are really just different stages in an evolutionary sequence of the same star. Instead they might belong to different evolutionary branches. While WNE stars can evolve to WC stars, WNL stars may never reach the WNE or WC stage.

With WNE and WC stars possibly arising from lower initial masses than previously expected, WNL stars might not even be core-helium burning stars as it is usually assumed. Their HRD positions on the cool side next to the main sequence could be reached by very massive core-hydrogen burning stars. In the last years new results (e.g. Liermann et al. 2010; Crowther & Walborn 2011) indicate that the transition in the spectral sequence from O via Of and Of/WN to WN might not just be an empirical classification system, but also reflect the upper mass end of the main sequence. This would be in line with the result that the most massive stars in very massive clusters are found to be of type WN5ha or WN6ha (Crowther et al. 2010).

With the idea of WNL stars not reaching the WNE and WC stage, it becomes clear that these stars might explode as a supernova (SN) with significant fractions of hydrogen left. Already in the evolutionary scenario from Langer et al. (1994) it was suggested that hydrogen-rich WNL stars might evolve to LBVs. LBVs show enormous eruptive mass loss making them a candidate for type IIn SN precursors. This type of hydrogen-containing SN requires huge eruptive mass losses exceeding the WR mass-loss rates in the last stage before the explosion. Indeed an LBV has been found as a progenitor for the type IIn SN 2005gl (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009).

Smith et al. (2011) analyzed the core collapse supernovae (CCSN) statistics from the Lick Observatory Supernovae Search and tried to assign the observed SNe fractions to initial mass bins using a Salpeter initial mass function. The result is depending on the fraction of CCSNe which are produced by binary evolution. Smith et al. (2011) provide a hybrid scenario which fits with our suggested evolutionary scenario. In their scenario, all stars with initial masses above $23.1\,M_\odot$ explode either as type Ib/c or as type IIn SNe. This would be in line with our findings that the (not yet detected) progenitors of the type Ib/c SNe are WNE and WC stars, while the latter could arise from high mass WNL stars that evolved to LBVs like SN 2005gl. Hence the scenario for $M_{\rm init} \geq 60\,M_\odot$ would be:

$$\mathrm{O} \rightarrow \mathrm{WNL} \rightarrow \mathrm{LBV} \rightarrow \mathrm{SN\,IIn}.$$

For the WNE and WC stars the tracks from Vanbeveren et al. (1998) and the obtained HRD positions suggest a post-RSG scenario without a WNL stage. However, there is an upper mass limit for RSG, so the post-RSG scenario might not be sufficient in explaining all of the WC stars, especially not those with initial masses around $40\,M_\odot$. In these cases LBVs of lower masses than those with WNL progenitors that do not explode but rather evolve to WNE stars might do the transition to the WR stage. So our suggested evolutionary scenario for $20\,M_\odot \leq M_{\rm init} \leq 45\,M_\odot$ leading to a WC star is:

$$\mathrm{O} \rightarrow \mathrm{RSG\,(or\,LBV)} \rightarrow \mathrm{WNE} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN\,I}.$$

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Discussion

Hillier: Before I came, Luc Dessart told me to stress to the massive-star community that, contrary to popular opinion, most Ib/Ic SNe appear to arise from binary systems, not from massive stars.

Sander: Indeed, no WR star has been observed as a SN progenitor so far. However, if WC stars make a SN explosion it would have to be of type I, as there is no hydrogen left. The scenario I presented was taken from Smith et al. (2010) and already included the assumption that the larger fraction of Ib/c SNe originates from binary systems.

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