

Helium stars: Towards an understanding of Wolf-Rayet evolution

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There are outstanding problems in trying to reproduce the observed nature of Wolf-Rayet stars from theoretical stellar models. We have investigated the effects of uncertainties, such as composition and mass-loss rate, on the evolution and structure of Wolf-Rayet stars and their lower mass brethren. We find that the normal Conti scenario needs to be altered, with different WR types being due to different initial masses as well as different stages of evolution.

1 Introduction

Wolf-Rayet (WR) stars are massive helium-burning stars that, through strong mass loss, have lost all or most of their hydrogen envelopes leaving a partially or fully exposed helium core. We have generated a grid of pure helium star models at various metallicities and shall only study the evolution from onset of core-helium burning onwards.

modified by various groups; herein, we employ the version described by Stancliffe & Eldridge (2009).

We make our selection of metallicities based on the expected environments of WR stars: $Z = 0.008$ for the Large Magellanic Cloud; $Z = 0.014$ and $Z = 0.02$ being, respectively, “new” and “old” solar metallicity; and $Z = 0.04$, double “old” solar. To clarify the selection regarding solar metallicity, we have utilised the solar abundance determinations from Grevesse & Sauval (1998) (“old” solar) and Asplund et al. (2009) (“new” solar). A comparison of evolution between models of “old” and “new” solar compositions shows very little difference, and in light of this, we prefer “old” solar abundances for use in our models. Our preference for using “old” solar abundance agrees with the nearby cosmic abundance standard from Nieva & Przybilla (2012).

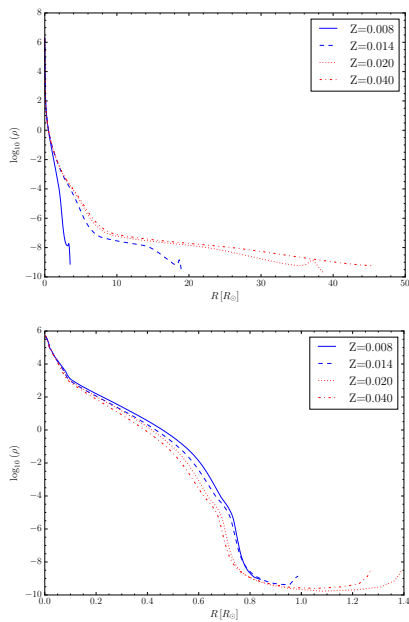


Fig. 1: Density profile of a 3 and 15 M_{\odot} helium star (top and bottom, respectively) at the end of shell-helium burning for different metallicities.

2 Computational method

2.1 Construction of the Models

To investigate the evolution of helium stars, we have constructed a grid of hydrogen-free models. We make use of the Cambridge STARS evolutionary code. Originally developed by Eggleton (1971), it has been

2.2 Mass-loss Scheme

We employ a mass-loss scheme, outlined in Eldridge & Vink (2006), which is derived from Nugis & Lamers (2000):

$$\dot{M}_Z \propto \dot{M} \beta \left(\frac{Z}{Z_{\odot}} \right)^{\frac{1}{2}}, \quad (1)$$

where \dot{M} is taken from Eldridge & Vink (2006), Z is the metallicity of the model, and Z_{\odot} is solar metallicity. To test the effect of varying the mass-loss rate on the evolution of a model, we introduce a parameter, β . We may use this parameter to estimate the evolution of the helium star model if, before the hydrogen envelope were removed, more helium burning had occurred. For example in the case of $\beta = 1$, the hydrogen envelope is removed before the beginning of helium burning, so the tracks represent the greatest possible effect of mass loss on the models. Thus, more helium mass would be lost from the WR stars. However for $\beta = 0$, the evolution towards the end of the track represents how the star would appear if the hydrogen envelope were removed near the end of helium burning.

3 Results

We may divide our helium star models into two categories: low mass (“helium-giant type”), and high mass (“Wolf–Rayet type”).

3.1 Low-mass helium stars

Low-mass ($< 8M_{\odot}$) helium star models evolve as “helium giants”. A helium giant has a stellar structure that is analogous to that of a red-giant star: a dense core region with an expansive envelope (see top panel of Fig. 1).

3.2 High-mass helium stars

High-mass ($> 8M_{\odot}$) helium star models evolve as “traditional” Wolf–Rayet stars, having characteristic high temperatures due to strong mass loss (Crowther 2007). The structure of a high-mass helium star differs from that of a low-mass helium star by the properties of its envelope: an extended region of near-constant density with a large density inversion at the surface (see bottom panel of Fig. 1). The density inversion sits atop the extended envelope structure of the high-mass helium star models, and due to the stellar interior reaching the phase space of the iron-opacity peak (Gräfener et al. 2012), is affected by metallicity.

4 Populations of helium stars

In Figure 2 we present our models compared to observed WR stars on the Hertzsprung–Russell diagram. Observational data is taken from Hamann et al. (2006); Sander et al. (2012), for Galactic WN and WC stars; Hainich et al. (2014), for Large Magellanic Cloud (LMC) WN stars; and Tramper et al. (2013, 2015), for WO stars. In our work, we attempt to reproduce the observed locations of WR stars.

4.1 WN stars

Observed early-type WN stars lie near the HeZAMS for massive helium stars and are, generally, in good agreement with helium star models above $\approx 10M_{\odot}$. However, the agreement is not so favourable for observed late-type WN stars. These WN stars have stellar temperatures that are far cooler than temperatures at the HeZAMS, and their locations cannot be reproduced using models with $\beta > 0$.

Without mass loss ($\beta = 0$), we see an interesting result: the higher mass helium star models do, indeed, cross the region of observed (hydrogen-free) late-type WN stars for solar metallicity (“old” and “new”). A small amount of mass loss will remove the outer layers of the envelope and expose the hot interior of the model. Thus, without mass loss, the

model swells due to inflation and the surface temperature decreases.

4.2 WC/WO stars

The expected locations of WC stars (marked in solid blue lines) are in very poor agreement with the positions of observed WC stars. As first suggested by Sander et al. (2012) in their analyses of Galactic WC stars, the Conti scenario (Conti 1975) is insufficient at explaining this discrepancy. We note from Fig. 2 that low-mass helium models can reproduce the observed locations of early- and late-type WC stars.

The observed WO stars in Fig. 2 occupy locations on the HR diagram that are hotter and more luminous than the observed WC stars, implying a higher stellar mass for WO stars. We find the observed WO stars in a region predicted by our high-mass models.

5 Discussion

In light of our work, we can draw some firm conclusions about certain aspects of WR star evolution and speculate about others.

First, WO stars are what we have always considered to be WC stars in stellar models. They are the progeny of the most massive WN stars ($M_{\text{He},i} \gtrsim 10M_{\odot}$) that have suffered significant mass loss and are the hottest WR stars. Due to their significant mass loss, WO stars are likely to explode as Type Ic supernovae at any metallicity. However, these massive stars are also likely to form black holes at core collapse, so it is unknown as to whether they produce visible supernovae (e.g., Smartt 2015).

Second, WC stars evolve from less massive stars ($M_{\text{He},i} \lesssim 10M_{\odot}$). The evolution of these stars could be described either as an inflationary effect occurring towards the end of their lives or as them becoming helium giants. The WC stars experience increased mass loss as they evolve; a consequence of a decrease in surface gravity allowing material on the surface to be removed more efficiently. The expansion of the envelope, whether through inflation or a helium-giant phase, is metallicity dependent. For low metallicities, the stars would retain a small fraction of hydrogen in their envelopes, and would not be identified as WC stars. This is in agreement with the lack of observed WC stars at low metallicity. We note the WC stars are unlikely to be the evolutionary end-points of the typical WN stars observed. They are more likely to arise from lower mass objects that we have yet to find; the recently identified and very faint WN3/O3 stars discovered by Massey et al. (2015) are also possible candidates.

In summary, we have created a series of helium star models at various metallicities and mass-loss rates. The models are available for download on the BPASS website (<http://bpass.auckland.ac.nz>).

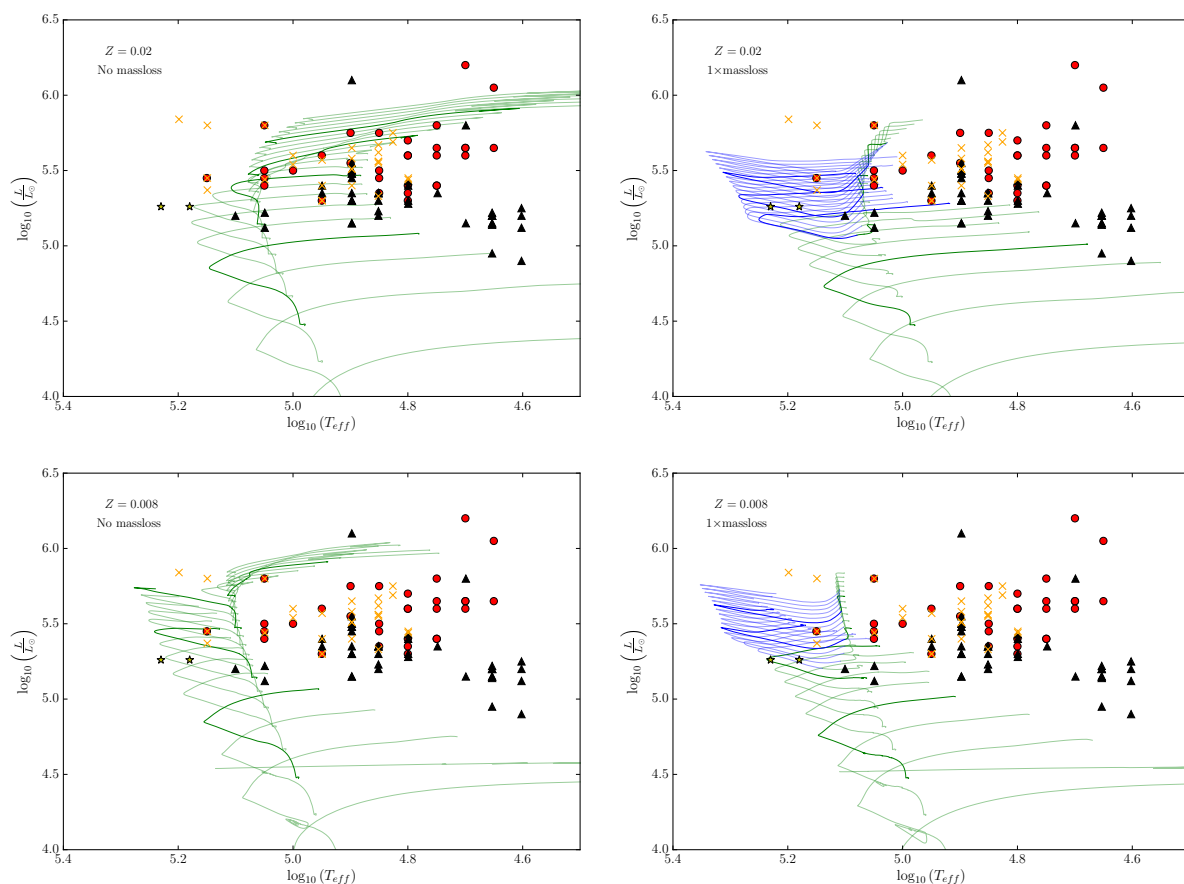


Fig. 2: HR diagram of our evolved models. For clarity, models with initial masses of 5, 10, 15 and 20 M_{\odot} are made thicker. Observed WR star locations are marked as follows: Galactic WN, red circles; Galactic WC, black triangles; WO, yellow stars; and LMC WN, orange saltires. All observed stars are hydrogen-free. The phase of WR mass loss is indicated, WN (solid, green line) and WC (solid, blue line); non-WR mass loss is shown with solid, black lines. Mass-loss rate and metallicity are noted on the plots.

Future areas of research include incorporating the inflation of Gräfenner et al. (2012) into the model evolution, and increasing the resolution of the model grids

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D. John Hillier: (*also to John Eldridge*) Do you expect WCs that arise in binary evolution to be slow rotators? Most WC stars show no evidence for polarization.

John Eldridge: Binary WC stars would be expected to be slow rotators. Especially if they have expanded as, by conservation of momentum, they would also spin down. Although, if they are in binaries, we don't know how strong the tides would be.

Norbert Langer: In your comparison to observations, you should not include the pre-MS He stars or the cool He-giant phase, as they are very short lived.

Liam McClelland: The post-helium-burning lifetime of low-mass helium stars (the He giants) is comparable to the helium-burning lifetime of the more massive stars.

Philip Massey: Is there a problem with the scarcity of WOs and this result?

Liam McClelland: The scarcity of WO stars is consistent with the short lifetime of that phase.



Liam McClelland (l.) listens to the question from Phil Massey