Wolf-Rayet Stars
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Wolf-Rayet stars as an evolved stage of stellar life

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Wolf-Rayet (WR) stars, as they are advanced stages of the life of massive stars, provide a good test for various physical processes involved in the modelling of massive stars, such as rotation and mass loss. In this paper, we show the outputs of the latest grids of single massive stars computed with the Geneva stellar evolution code, and compare them with some observations. We present a short discussion on the shortcomings of single stars models and we also briefly discuss the impact of binarity on the WR populations.

1 Introduction

Wolf-Rayet (WR) stars are known to be the very advanced stages of the life of massive stars (Conti 1976). These stars exhibit at their surface signs of hydrogen burning products through CNO cycle (for the WN stars) or even of helium burning products (Crowther 2007). To explain the existence of such objects, elements that are produced in the centre of a massive stars have to appear at the surface. This can be achieve by two different ways: a) internal mixing inside that star, allowing for transporting chemical elements from the place where they are produced to the surface, b) mass loss, that progressively remove the external layer of the star, and can ultimately uncover deep regions of the star, where nuclear burning previously occurred.

Internal mixing can be induced by the convective movements of matter in the convective regions, or by any other kind of mixing process in the radiative regions, such as rotational mixing (e.g. Zahn 1992). Mass loss can be due either by stellar winds, or by mass transfer in close binaries.

In this paper, we present preliminary results showing what are the expected WR stars population in the single massive star scenario, at different metallicities. The assumptions made in our computations and the chosen prescriptions are shortly reminded in section 2. Then, the various mass limits and number ratio of WR subtypes are presented in section 3. Finally, we briefly discuss the interesting challenges that need to be resolved to make progresses in that field.

2 Ingredients of the stellar models

The results presented in this paper were obtained by analysing the models from Ekström et al. (2012), Georgy et al. (2013), and Eggenberger et al. (in prep.). The computations were performed using the Geneva stellar evolution code (Eggenberger et al. 2008). Here is a brief summary of the assumed physical ingredients and prescriptions we used.

Convective zones are determined with the Schwarzschild criterion. For hydrogen and helium burning cores, a penetrative overshoot is assumed, which extends over a fraction $d_{\rm over}$ of the pressure scale height at the formal edge of the convective core. Inside the convective zones, the mixing is assumed to be instantaneous. In the inner regions, convection is assumed to be adiabatic, while in the external envelope, the thermal gradient is computed in the framework of the mixing-length theory (MLT Böhm-Vitense 1958). The free parameter $d_{\rm over}$ is calibrated at solar metallicity, by reproducing the width of the main sequence (MS) at around $1.7\,M_\odot$ (Ekström et al. 2012). The value of the α parameter appearing in the MLT is calibrated on a solar model.

Rotation is included in the framework of the "shellular" rotation approximation (Zahn 1992; Meynet & Maeder 1997; Maeder & Zahn 1998). The transport of angular momentum is computed with both the advective and diffusive term (Zahn 1992), while the transport of chemical elements is a purely diffusive process (Chaboyer & Zahn 1992). In this context, two diffusion coefficients are required. In our works, we use $D_{\rm h}$ from Zahn (1992) and $D_{\rm shear}$ from Maeder (1997). This choice best reproduces the presence of Cepheid loops at solar metallicity. The free parameter appearing in the formulation of $D_{\rm shear}$ is calibrated in order to reproduce the observed enrichment of stars in the range of 10 to $20\,M_\odot$ at solar metallicity (Ekström et al. 2012).

The mass-loss prescriptions and metallicity dependence are described in Ekström et al. (2012) and Georgy et al. (2013). An enhanced mass-loss rate (by a factor of 3) is used for red supergiant stars (RSG) above $20\,M_\odot$ (see discussion in Georgy 2012; Georgy et al. 2012).

In this work, we use the following criteria to classify the WR stars (Georgy et al. 2012). We consider that a star is a WR stars when its $\log(T_{\rm eff})$ is above 4., and its surface mass fraction is smaller than 0.3. A WR star with more than 10^{-5} as surface H mass fraction is a WNL star. If the surface hydrogen abundances drops below 10^{-5}, we have a WNE star if the surface nitrogen abundance is bigger than the carbon one, and a WC star otherwise. These are obviously rough criteria, but they have the advantage that they can be computed with standard outputs from stellar evolution models. A more

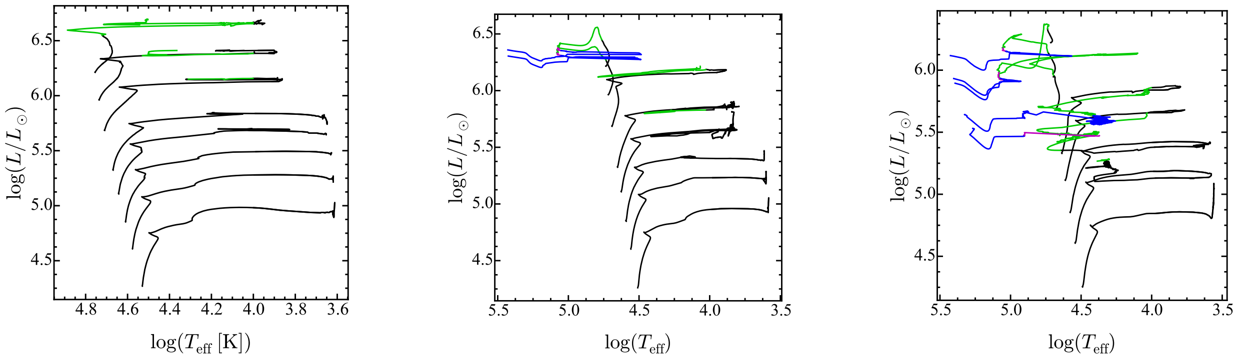

Fig. 1: HRD of rotating massive star models: $Z = 0.002$ (SMC, *left panel*), $Z = 0.006$ (LMC, *middle panel*), and $Z = 0.014$ (solar, *right pannel*). In each panel, models from $15\,M_\odot$ (bottom track) to $120\,M_\odot$ (top track) are shown. The different WR stages are indicated in colour: WNL (green), WNE (purple) and WC (blue). The initial rotation velocity is 40% of the critical one. Models are taken from Georgy et al. (2012) for $Z = 0.002$, Eggenberger et al. (in prep.) for $Z = 0.006$ and Ekström et al. (2012) for $Z = 0.014$.

detailed classification would require the modelling of the emergent spectrum (taking into account the winds), and this is so far not possible during the computation runtime. Such spectrum modelling in a post-processing approach has shown that a classification based on the aspect of the spectrum leads to significant differences (Groh et al. 2014).

3 Wolf-Rayet stars from single star models

Figure 1 shows the Hertzsprung-Russell diagram (HRD) for our latest models of massive stars, for 15, 20, 25, 32, 40, 60, 85, and $120\,M_\odot$, at three metallicities: $Z = 0.002$ (*left panel*), corresponding to the metallicity of the Small Magellanic Cloud, $Z = 0.006$ (*middle panel*), corresponding to the Large Magellanic Cloud one, and finally solar metallicity $Z = 0.014$ (*right panel*). The successive WR stages are highlighted with different colours: the WNL phase is shown in green, the WNE one in purple, and the WC one in blue.

A direct consequence of the weakness of the stellar winds at lower metallicity (Vink et al. 2001; Eldridge & Vink 2006) is that it becomes more and more difficult to produce WR stars when metallicity is decreasing. Moreover, at solar metallicity, our models spend a longer time in the RSG phase, allowing them to lose a lot of mass, and helping them to cross the HRD towards the WR phase at lower mass (around $20\,M_\odot$, see also Vanbeveren et al. 1998).

The minimal masses to enter into a given WR phase are given in Table 1. At solar and LMC metallicities, all WR types are accessible to single star models. Note however that the WC subtype occurs only for very massive stars at the LMC metallicity, while at solar Z, models more massive that about $27\,M_\odot$ are able to reach this stage. Moreover, these stars are found at luminosities higher than $\log(L) \sim 5.3$ at $Z_\odot$ and $\log(L) \sim 6.2$ at $Z_{\rm LMC}$. At the metallicity of the SMC, the radiative stellar winds are too weak to produce stars more evolved than the WNL phase, and no stars without hydrogen at the surface are expected from our models. The minimal mass to produce a WR star progressively shift from about $20\,M_\odot$ at $Z_\odot$ to more than $50\,M_\odot$ at the SMC metallicity. Above these masses, the endpoint of the evolution of our models are thus WR stars from our simple classification scheme (see however Groh et al. 2013b,c). It is not yet clear what would be the final fate of this kind of stars in terms of supernova explosion (type Ibc, failed supernova, direct collapse? See Heger et al. 2003; Dessart et al. 2011; Groh et al. 2013a; Bersten et al. 2014).

	O-star	WNL	WNE	WC
Solar	$15.8\,M_\odot$	$20.0\,M_\odot$	$25.3\,M_\odot$	$27.0\,M_\odot$
LMC	$14.2\,M_\odot$	$32.1\,M_\odot$	$60.8\,M_\odot$	$63.1\,M_\odot$
SMC	$12.6\,M_\odot$	$53.5\,M_\odot$	–	–

Tab. 1: Minimal mass to enter into a given phase. Results at $Z_\odot$ are taken from Georgy et al. (2012).

The expected ratio of WR stars to O-type stars, as well as subtype ratios, are shown in Table 2, in the constant star formation context. These numbers confirm that the number of WR stars with respect to O-type stars is decreasing with decreasing metallicity. The fraction of WC star is also expected to decrease at low metallicity, as well as the WC/WN ratio. Comparison with the observation at solar metallicity was presented in Georgy et al. (2012). Our results showed that in order to reproduce the observed ratio, WR stars should originate from a stellar population containing about 50% of

	WR/O-stars	WNL/WR	WNE/WR	WN/WR	WC/WR	WC/WN
Solar	0.066	0.687	0.022	0.709	0.291	0.409
LMC	0.016	0.887	0.005	0.892	0.108	0.121
SMC	0.006	1.000	0.000	0.000	0.000	0.000

Tab. 2: Various type ratios. Values at $Z_{\odot}$ are taken from Georgy et al. (2012).

binaries, in good agreement with results from more elaborated synthetic binary population codes (Vanbeveren et al. 1998; Eldridge et al. 2008). Note also that our WC/WN ratio reproduce reasonably well the observed trend at different metallicities (Neugent et al. 2012).

4 Discussion

Since a few years, it became clear that massive star populations contain a significant fraction of binary stars (e.g. Sana et al. 2012). It is thus important to know what are the physical mechanisms responsible for the appearance of the WR phenomenon (or subtypes), and what is linked to binary evolution or not. Recent observations of Galactic WC stars show a significant number of such kind of stars at surprisingly low luminosities ($\log(L) \sim 5.2$, Sander et al. 2012). These stars are hard to form through single star channel, even with a strong mass-loss rate during the RSG phase (Georgy 2012; Meynet et al. 2015), except if we assume that the strong mass loss continues *after* the RSG phase (Vanbeveren et al. 1998). On the other hand, they are routinely produced through the binary channel (Eldridge et al. 2008, 2013).

The relatively high number of high luminosity WNL stars with a large fraction of hydrogen on their surface (e.g. Hainich et al. 2014) on the other hand points to the need of accounting for a proper treatment of the internal mixing of the star, particularly inside the radiative zones (Georgy et al. 2012). This illustrates the need of a correct treatment of the physics of *single* massive star, that definitely intervenes as well in the modelling of binary evolution.

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Thomas Madura: I was wondering if you could comment on the effect of the LBV phase on your results, e.g., large burst of mass loss.

Cyril Georgy: This could indeed change the results shown here. For example, a massive ejection can help entering the WR phase sooner, or at lower mass. Generally, the numbers I showed are extremely dependent on the various mass-loss rates adopted for the computation, that are sometimes not well known (for example, the RSG or LBV mass-loss rates).

Claus Leitherer: The agreement between observed and predicted WR subtype ratios seems to worsen rather than improve with rotation. Are you concerned about this?

Cyril Georgy: The main point here is that the number of WR in general (not the subtypes) is much better reproduced by rotating than non-rotating models. The results I showed were only for the purpose of presenting what our models are able (or not) to do, knowing that they suffer from a lot of uncertainties (physics of convection/rotation, mass loss, classification into a given type on the basis of surface abundances and not spectrum, and impact of a significant population coming from the binary channel).

Gloria Koenigsberger: Could you comment on the internal velocity structure used for these calculations? How is the Ω-profile chosen?

Cyril Georgy: Our models follow the time evolution of the internal Ω-profile in the framework of the "shellular rotation" (see the contribution by G. Meynet). However, we do not include a strong internal coupling, as it would be for example by considering the effect of an internal Tayler-Spruit dynamo. We have thus differential rotation in the radial direction, producing shear mixing.

The Ω-profile is set to be flat on the zero-age main sequence, and is then evolved self-consistently during the stellar life, under the combined effects of internal transport, and angular momentum removal due to the stellar winds.

Vikram Dwarkadas: Can you use the number of type Ib/c SNe to infer whether rotating or non-rotating stars are more likely to give rise to the Ib/c population. Or at least infer whether single or binary stars are more likely progenitors.

Cyril Georgy: Due to the fact that a significant fraction of these progenitors should come from the binary channel, it is hard to use them to constrain the physics of rotation. The study of the lightcurves, however, can help to infer the mass of the ejecta, and thus, the mass of the progenitor (see the contribution by L. Dessart). As far as I know, current studies indicate that the mass of the ejecta is rather small, favouring binary progenitor.