

Massive stars in advanced evolutionary stages, and the progenitor of GW150914

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Abstract. The recent discovery of a gravitational wave from the merging of two black holes of about 30 solar masses each challenges our incomplete understanding of massive stars and their evolution. Critical ingredients comprise mass-loss, rotation, magnetic fields, internal mixing, and mass transfer in close binary systems. The imperfect knowledge of these factors implies large uncertainties for models of stellar populations and their feedback. In this contribution we summarize our empirical studies of Wolf-Rayet populations at different metallicities by means of modern non-LTE stellar atmosphere models, and confront these results with the predictions of stellar evolution models. At the metallicity of our Galaxy, stellar winds are probably too strong to leave remnant masses as high as $\sim 30 M_{\odot}$, but given the still poor agreement between evolutionary tracks and observation even this conclusion is debatable. At the low metallicity of the Small Magellanic Cloud, all WN stars which are (at least now) single are consistent with evolving quasi-homogeneously. O and B-type stars, in contrast, seem to comply with standard evolutionary models without strong internal mixing. Close binaries which avoided early merging could evolve quasi-homogeneously and lead to close compact remnants of relatively high masses that merge within a Hubble time.

Keywords. stars: atmospheres, stars: early-type, stars: evolution, stars: fundamental parameters, Hertzsprung–Russell diagram, stars: mass loss, stars: winds, outflows, stars: Wolf-Rayet

1. Introduction

At the 14th of September 2015, the advanced LIGO detectors registered for the first time a gravitational wave (Abbott *et al.* 2016). According to the analysis of the waveform, this wave testified the event of two merging black holes (BHs) of $36^{+5}_{-4} M_{\odot}$ and $29^{+4}_{-4} M_{\odot}$ at a distance of about 400 Mpc. The immediate conclusion, and even the prediction prior to the measurement, was that such heavy BHs can only form by stellar evolution at low metallicity, where the mass-loss due to stellar winds is low and hence the stellar remnants can be more massive (Belczynski *et al.* 2016). Still heavily debated is whether such BHs form separately in dense clusters and then combine into a close pair by dynamical interactions, or whether they evolve as close binaries all the time. Since both scenarios have their problems, a primordial origin has also been suggested (see Postnov, these proceedings).

2. Galactic Wolf-Rayet stars

Massive stars may end their life in a gravitational collapse while being in the red-supergiant (RGS) phase or as Wolf-Rayet (WR) stars. The sample of putatively single and optically un-obscured Galactic WR stars has been comprehensively analyzed with increasing sophistication (cf. Fig. 1). It became clear that the WN stars (i.e. the WR stars of the nitrogen sequence) actually form two distinct groups. The very luminous WNs with $\log L/L_{\odot} > 6$ are slightly cooler than the zero-age main sequence and typically still

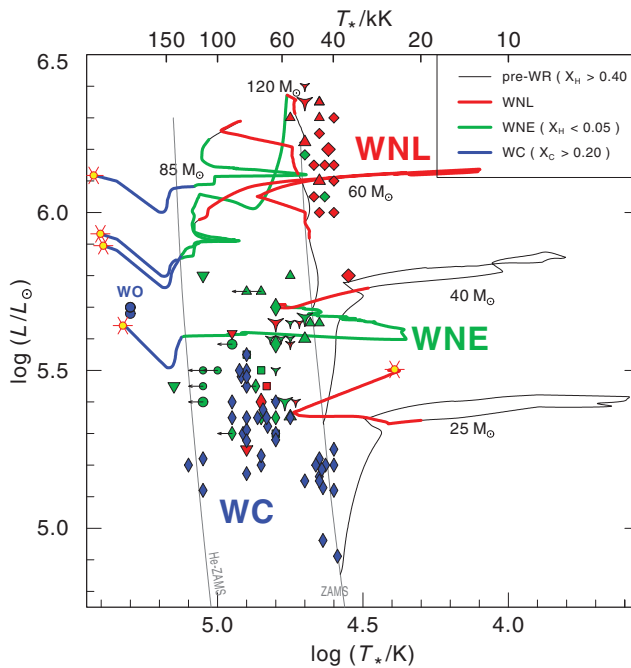


Figure 1. HRD of single WR stars in the Galaxy. The discrete symbols represent analyzed stars (Hamann *et al.* 2006, Sander *et al.* 2012), while the tracks are from the Geneva group accounting for rotationally induced mixing (Georgy *et al.* 2012).

contain hydrogen in their atmosphere (often termed WNL for “late”). In contrast, the less luminous WNE stars are hotter (“early” WN subtypes) and typically hydrogen free. The WR stars of the carbon sequence (WC) are composed of helium-burning products and share their location in the Hertzsprung-Russell diagram (HRD) with the WNE stars.

From this empirical HRD one can deduce the evolutionary scenario (Sander *et al.* 2012). The WNL stars evolve directly from O stars of very high initial mass ($> 40 M_{\odot}$). In the mass range $20 - 40 M_{\odot}$ the O stars first become RSGs and then WNE stars and finally WCs. Stars with initially less than $\approx 20 M_{\odot}$ become RSGs and explode there as type II supernova before having lost their hydrogen envelope.

Evolutionary tracks still partly fail to reproduce this empirical HRD quantitatively, despite of all efforts, e.g. with including rotationally induced mixing. The WNE and WC stars are observed to be much cooler than predicted; this is probably due to the effect of “envelope inflation” (Gräfenner *et al.* 2012). Moreover, the mass (and luminosity) range of WNE and WC stars is not covered by the post-RSG tracks. Evolutionary calculations depend sensitively on the mass-loss rates \dot{M} that are adopted as input parameters. Empirical \dot{M} suffer from uncertainties caused by wind inhomogeneities: when clumping on small scales (“microclumping”) is taken into account, lower values for \dot{M} are derived from observed emission-line spectra. Large-scale inhomogeneities (“macroclumping”), on the other hand, can lead to underestimating mass-loss rates (Osinkova *et al.* 2007).

Due to the open questions of mixing and the true \dot{M} , it is still uncertain which is the highest BH mass that can be produced from single-star evolution at Galactic metallicity. For instance, the luminosities of the two WO stars included in Fig. 1 would correspond to masses as high as $\approx 20 M_{\odot}$ if they were chemically homogeneous, while the displayed evolutionary track for initially $40 M_{\odot}$ ends with only $12 M_{\odot}$ at core collapse.

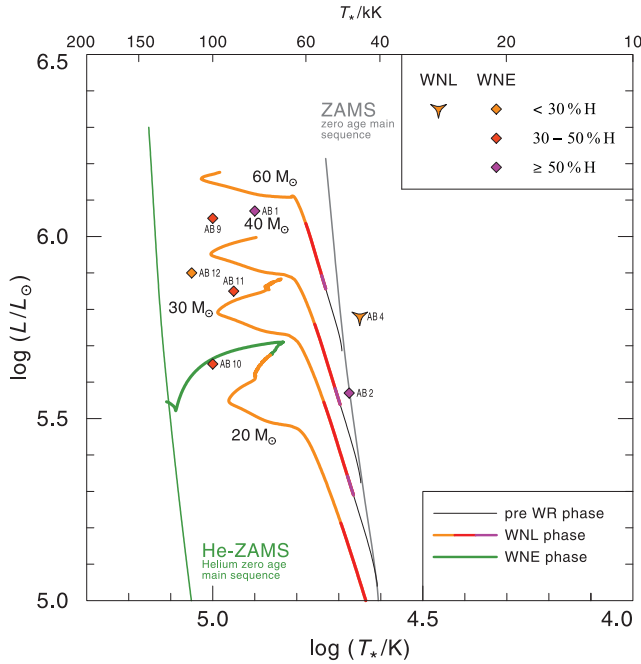


Figure 2. WN stars in the SMC; the discrete symbols are from the analyses of the stars as labeled, while the tracks from Brott *et al.* (2011) adopt very strong rotational mixing (initial $v_{\text{rot}} > 500 \text{ km/s}$). Colors code in both cases for the hydrogen mass fraction (see inlet). From Hainich *et al.* (2015)

3. Massive stars at low metallicity

The population of massive stars depends critically on their metallicity Z . This becomes obvious, e.g., from the WR stars in the Small Magellanic Cloud (SMC) where Z is only about 1/7 of the solar value. In contrast to the Galaxy, *all* putatively single WN stars in the SMC show a significant fraction of hydrogen in their atmosphere and wind, like the Galactic WNL stars. However, the WN stars in the SMC are all hot and compact, located in the HRD (Fig. 2) between the zero age main sequence for helium stars (He-ZAMS) and the H-ZAMS (or at least, in two cases, close the latter). Such parameters cannot be explained with standard evolutionary tracks, unless very strong internal mixing is assumed which makes the stars nearly chemically homogeneous. Corresponding tracks are included in Fig. 2. Quantitatively, they still do not reproduce the observed hydrogen mass fractions.

Stellar winds from hot massive stars are driven by radiation pressure intercepted by spectral lines. The literally millions of lines from iron and iron-group elements, located in the extreme UV where the stellar flux is highest, play a dominant role. Hence a metallicity dependence is theoretically expected. For O stars, such Z dependence is empirically established (e.g. Mokiem *et al.* 2007). For WN stars, Hainich *et al.* (2015) found a surprisingly steep dependence, probably due to the multiple-scattering effect (see also Hainich, these proceedings).

Hence, the lower mass-loss for massive O stars in the SMC, compared to the Galaxy, might reduce the angular-momentum loss and thus maintain the rapid rotation which causes the mixing and quasi-homogeneous evolution to the WR regime. Alternatively, one might speculate that the low \dot{M} in the SMC is insufficient to remove the hydrogen envelope, and thus prevents the formation of single WR stars. This would imply that

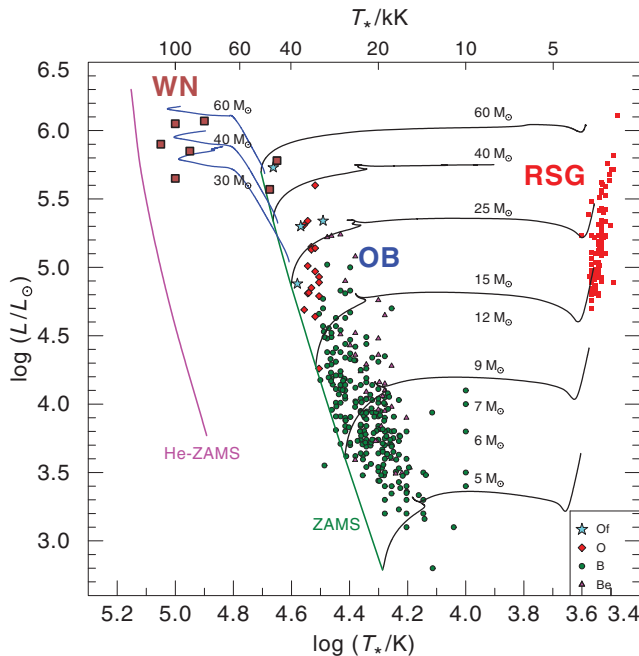


Figure 3. Massive stars in the SMC. The discrete symbols are from our analyses of about 300 O and B type stars (Ramachandran *et al.* in prep.), and the red supergiants are from Massey *et al.* (2003). The WN stars are the same as in Fig. 2, as are the quasi-homogeneous evolutionary tracks. The “normal” tracks are also from Brott *et al.* (2011) but with slower initial rotation ($v_{\text{rot}} = 300$ km/s).

the observed single WNs have all formed through the binary channel, possibly as merger products.

But what happens with SMC stars of slightly lower mass? We have analyzed about 300 OB stars in the region of the supergiant shell SGS 1 (Ramachandran *et al.* in prep.). Their HRD positions are included in Fig. 3, together with “normal” tracks with less rotational mixing. As the comparison shows, the O and B-type stars with initial masses below $30 M_{\odot}$ are consistent with “normal” evolution to the RSG stage. Only the more massive Of stars might also be consistent with quasi-homogenous evolution, as are the WN stars discussed above.

4. Massive binaries

In their majority, massive stars are born in binary systems. Marchant *et al.* (2016) suggested a scenario of “massive overcontact binary (MOB) evolution” that could lead to a tight pair of massive black holes as observed in the GW events. Two massive stars which are born as tight binary would evolve fully mixed due to their tidally induced fast spin and interaction. They would swap mass several times, making their masses about equal, but under lucky circumstances they might avoid early merging.

Figure 4 shows two such evolutionary tracks from Marchant (priv. comm.). In both examples, the tracks end at core collapse with a pair of $34 + 34 M_{\odot}$ objects. We have calculated synthetic spectra for representative points along the evolutionary tracks (marked by asterisks in Fig. 4) and found that such spectra would look unspectacular if observed; in the advanced stages, the stars would appear as WN-type (with hydrogen, like those in

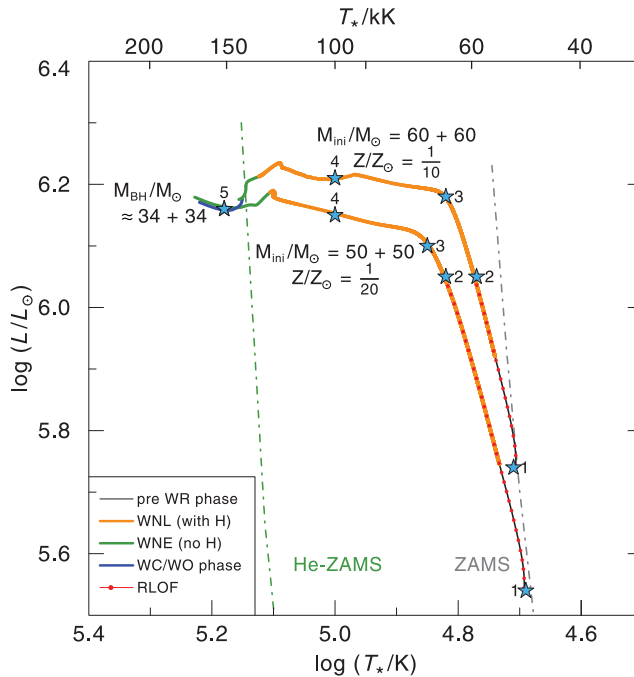


Figure 4. Tracks for “massive overcontact binary evolution (MOB)” (from Marchant, priv. comm.). Due to the mass exchange, both binary components have equal masses and therefore evolve identically. One of the two tracks shown is for a binary of initially $50 + 50 M_{\odot}$ and metallicity of $1/20$ solar, and the another one for $60 + 60 M_{\odot}$ and metallicity of $1/10$ solar. The asterisks mark positions for which we calculated representative synthetic spectra (Hainich *et al.* in prep.).

the SMC discussed above) or, towards the end of the track for $60 M_{\odot}$, as a hot WC type, always with otherwise weak metal lines due to the low abundances. The only characteristic differences compared to single stars would be the doubled luminosity and, if the orbital inclination is favorable, the radial-velocity variation in the double-lined spectrum with short period.

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