STRUCTURE AND EVOLUTION OF MASSIVE SINGLE STARS AND THEIR RELEVANCE FOR CLOSE BINARY SYSTEMS

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Abstract. Differences in the evolution of massive single stars and components of massive close binary systems are investigated. While for stars above the red supergiant luminosity limit, single star and case B primary evolution merge into a single scenario, large differences for less massive stars are demonstrated to occur at the example of $M_{ZAMS} = 40\mathrm{M}_\odot$, concerning the various WR subtypes, the nucleosynthesis yields, and the supernova stage.

Key words: stars: Wolf-Rayet – massive stars – evolution – binary evolution

1. Introduction

Here, we want to investigate to which extent the stellar evolution models for massive single stars can be reliably used to describe the components of massive close binary (MCB) systems. Since MCB evolution is quite complex (*cf.* Podsiadlowski *et al.* 1992; De Greve, these proceedings) we need to restrict our discussion to the most frequent type of interacting binary system, namely the so called case B systems (Kippenhahn & Weigert 1967) which have periods in a range such that the primary component experiences Roche-lobe overflow after core hydrogen exhaustion, due to the expansion towards the supergiant stage.

The secondary component, which accretes a (basically unknown) fraction of the mass lost by the primary, may perform what is called "rejuvenation" in the literature. This means, it may transform its structure during and shortly after the end of the accretion phase into that of a single star of its new, larger mass (*cf.* Hellings 1983); in this case it needs no further discussion here. However, depending on assumptions on convection, the accreting star may also *not* rejuvenate, but rather obtain a chemical structure unlike that of any single star (Braun & Langer 1994a). In that case, also its further evolution differs from that of single stars; however, though this topic is extremely interesting, it has to be discussed elsewhere (*cf.* Braun & Langer 1995). More relevant to the main topic of this conference is the evolution of the primary component, since it more likely evolves into a Wolf-Rayet (WR) type star. Thus, here we focus on primaries of case B MCBs.

This paper is organized as follows. In Sect. 2, we briefly summarize some basic features of single star WR models. In Sect. 3 it is argued that for stars above a certain mass limit binarity makes basically no differences, while for less massive stars the mass convergence is shown to break down which induces large differences (Sect. 4). Effects of binarity on the nucleosynthesis

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yields are discussed in Sect. 5, and on the supernova explosion in Sect. 6.

2. Single star WR models

From theoretical studies of (single) WR stars, one could be optimistic that these models would be applicable also to WR components in binary systems: Maeder (1983) has found that WR stars obey a tight mass-luminosity relation (*cf.* also Vanbeveren & Packet 1979). In Langer (1989a) it was shown that the thermal and mechanical structure of hydrogen-free WR models is almost independent of the internal chemical composition profiles. This explains the existence of the WR mass-luminosity relation, but also of relations of basically any global quantity with the WR mass (*cf.* also Schaerer & Maeder 1992). As outlined in Langer (1989a), the consequence is that the thermal or mechanical properties of a H-free WR star are independent of its progenitor history, but depend only on the actual mass.

In Langer (1989b) it was argued that also the mass loss rate of H-free WR stars depends (in first approximation) *only* on the WR mass, and it was shown that as consequence of this, WR stars of largely different initial mass end up at identical final mass at the end of their evolution ("mass convergence"). From this behavior, which is also reflected in grids of realistic model sequences (*cf. e.g.,* Schaller *et al.* 1992; Meynet *et al.* 1994), one might be tempted to conclude that, since the main features of WR stars depend on their mass and the masses evolve to the same final value independent of whether the initial WR mass was large (*e.g.,* in a single star) or small (*e.g.,* in a MCB), the final outcome of single and binary WR models is the same. However, though this is partly true, we will spend the rest of this article to identify the cases where differences of both types of evolution are to be expected.

3. Stars above the RSG luminosity limit: single stars *versus* binaries?

The observed upper luminosity limit of RSGs at $\log L/L_{\odot} \simeq 5.7$ (Humphreys & Davidson 1979) strongly indicates that stars above a certain initial mass do not evolve into RSGs. Instead, their radius remains essentially limited by the so called Humphreys-Davidson (HD) limit in the HR diagram, which obviously can be crossed only by the unstable Luminous Blue Variables (LBVs) for a short time (see *e.g.,* Maeder 1989).

This LBV-scenario for the evolution of very massive single stars (*cf.* Langer *et al.* 1994, for a recent discussion including pulsationally induced WR-type mass outflow) has a striking similarity to the case B mass transfer scenario of MCBs: while in the single star case the growth of the stellar radius is limited by the onset of the LBV-instability when the star crosses the HD-limit, it is the Roche-radius (Paczynski 1971) which can not be overcome by the primary component in the binary case. The physical process which prevents the growth of the radius is, in both cases, mass loss. The LBV- or Roche-lobe overflow mass loss only stops when a sufficient part of the H-rich envelope has been lost such that the *intrinsic* direction of evolution in the HR diagram has changed from redwards to bluewards.

It is important to note here that the exact value of the critical stellar radius for the onset of the strong mass loss is not relevant to the structure of the star at the end of this mass loss episode, as long as the mass loss time scale is short compared to the time scale of nuclear evolution. However, the mass loss time scale is determined by the expansion time scale of the envelope, *i.e.*, basically the star's Kelvin-Helmholtz time scale ($\sim 10^4$ yr), which is always short compared to the time scale of core helium burning.

Thus, the (surprising?) result is that for stars above the RSG luminosity limit, there is *no* difference to be expected when a single star is compared to a primary of a MCB with the same initial mass and chemical composition (*cf.* also Vanbeveren 1994). This result is confirmed by detailed numerical computations of a 50 + 45 $M_\odot$ case B binary system and a 50 $M_\odot$ single star calculation (*cf.* Braun and Langer, these proceedings): though the details of the Roche/LBV-mass loss phase were different, the resulting "WNL"-stars were identical.

Let us finally note that the conclusion that very massive single stars and case B primaries evolve identically will hold only as long as effects of angular momentum and internal rotation on the evolution are negligible. For this issue, *cf.* Fliegner & Langer (these proceedings).

4. Stars below the RSG luminosity limit: single stars *versus* binaries!

For red supergiants, it is generally not $\tau_{\dot{M}} \ll \tau_{He}$. Thus, for stars in the mass range where a RSG phase is encountered, differences between single stars and case B primaries have to be expected.

As an example, we have computed the evolution of a 40 $M_\odot$ single star — which is close to the RSG luminosity limit — at $Z = 2\%$ (with OPAL opacities and input physics otherwise as in Langer 1991) with two different assumptions about the mass loss rate. In the first case (sequence "40RSG") the star was allowed to move to the RSG branch, where it spent about 50% of its helium burning life time. We applied three times the mass loss rate of Nieuwenhuijzen & de Jager (1990) on the RSG branch, which made the star turn into the WR regime at a central helium content of $Y_c = 0.50$. At this time it had a remaining mass of 16 $M_\odot$.

In the second case (sequence "40BIN"), we adopt an LBV mass loss phase (*cf.* Langer 1989c), which is appropriate to simulate a case B mass transfer as outlined above. The strong mass loss phase had a duration of $1.8\,10^4$ yr and produced a WR star of 14.5 $M_\odot$.

In Fig. 1 we compare the luminosity as a function of time for the post-MS phases of both sequences, and several striking differences can be seen. The sequence 40RSG spends the post-MS time at *much* higher luminosity (note the logarithmic luminosity scale) than the sequence 40BIN. During the RSG phase, which lasts until $t = 4.32\,10^6$ yr, the stellar mass drops from 38.7 to 16.0 $M_\odot$, but for red supergiants the luminosity is almost independent of the actual mass (it rather depends on the *initial* mass), and thus remains very large ($\log L/L_\odot \simeq 5.7$). During the RSG phase, the H-shell burning adds mass to the helium core, which thus grows to 14.65 $M_\odot$, while its maximum size in sequence 40BIN was 12.8 $M_\odot$. Therefore, the H-rich WN phase ("WNL") extends down to $\log L/L_\odot = 5.38$ in sequence 40BIN, while the minimum "WNL" luminosity is $\log L/L_\odot = 5.52$ in the post-RSG track. This transforms also to the minimum luminosities in the H-free WN phase ("WNE") as $\log L/L_\odot = 5.20$ and 5.36.

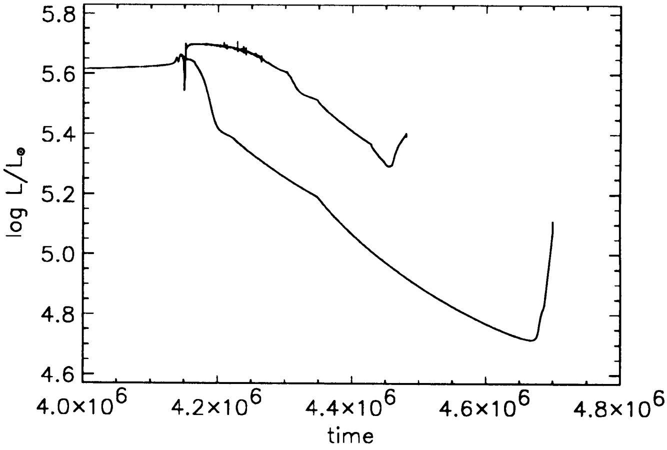

Fig. 1. Stellar luminosity versus time (in yr) for the post-MS phases of two 40 $M_\odot$ sequences, 40RSG (upper curve) and 40BIN, comparing single star and case B primary evolution (see text). The final luminosity increase marks the end of core helium burning, and the tracks end at their pre-supernova positions.

However, the RSG phase did not only produce a larger helium core compared to the 40BIN track, but it shifted the WR stage to a much later phase of core helium burning (i.e. $Y_c \leq 0.50$). Since the evolutionary speed (i.e. dY_c/dt) of core helium burning depends basically on the helium core mass, which firstly is larger than in the 40BIN case and secondly can decrease only very late during core helium burning ($Y_c \lesssim 0.3$) due to the WR mass loss, the sequence 40RSG reaches the end of core helium burning (and thus the pre-SN stage) already $\sim 3.1\,10^5$ yr after core hydrogen exhaustion, while the helium burning life time of sequence 40BIN is more than 50% longer (*cf.* Fig. 1). This is also reflected in the final masses of both sequences, which are 9.26 $M_\odot$ for 40RSG, and 4.75 $M_\odot$ for 40BIN. While, at the time of core collapse, the post-RSG star is still in the WN/WC transition phase (*cf.* Langer 1991b), sequence 40BIN has an extended WC stage and dies as a star which is extremely carbon- and oxygen-rich at the stellar surface; the final surface mass fractions are $Y = 0.26$, $C = 0.53$, and $O = 0.19$.

Altogether we see that at 40 $M_\odot$, there are already huge differences between single star and case B primary evolution. Note that 40 $M_\odot$ is rather close to the upper RSG luminosity limit, and the discussed differences certainly increase for decreasing initial mass. *E.g.*, at 25 $M_\odot$, a single star probably does not reach the WR stage at all (*cf.* Schaller *et al.* 1992; Meynet *et al.* 1994), while a case B primary certainly does (Podsiadlowski *et al.* 1992; De Greve & de Loore 1992; Vanbeveren & de Loore 1994).

In particular, we have to conclude that there is a minimum luminosity for "WNL" stars from single stars, which is basically the luminosity of the helium core in a star with an initial mass equal to the minimum mass for WR formation M_{WR}. If we adopt (somewhat arbitrarily) $M_{WR} = 30 M_\odot$, we obtain an initial mass of the helium core of roughly 9 $M_\odot$, which transforms to approximately $\log L/L_\odot = 5.0$ with the WR mass-luminosity relation (Langer 1989a). Thus, hydrogen-rich WR stars as WR152, WR128, WR10, and WR49, which have luminosities of about $\log L/L_\odot = 4.4, 4.7, 4.85$, and 4.9, respectively, (*cf.* Hamann *et al.* 1993, Hamann these proceedings), are possibly post-Roche lobe overflow objects.

However, note that also extremely high *main sequence* mass loss (Meynet *et al.* 1994; *cf.* also Langer *et al.* 1994) or internal mixing due to rapid rotation (Fliegner and Langer 1994) may produce some "WNL" stars below the single star luminosity limit quoted above.

5. Nucleosynthesis

We can only briefly note here that also the nucleosynthesis yields of single stars and case B primaries may be quite different.

First of all, in MCBs there is the effect that some fraction β of the mass lost by the primary is not expelled into the circumstellar medium but is rather accreted by the secondary component. This may not change the total yields very much, since most of the accreted material is probably unprocessed and ejected again with the secondary's stellar wind or supernova explosion (though detailed calculations are still lacking). Thus, for stars above the RSG luminosity limit, there is no major effect of binarity on the nucleosynthesis to be expected. Only in the case of radioactive isotopes — like for ^{26}Al — it may be important, since the corresponding γ-ray line flux depends on whether its decay occurs in the circumstellar medium or inside the secondary star (*cf.* Braun and Langer, these proceedings, for detailed models).

For stars below the RSG luminosity limit, a comparison of the yields of sequences 40RSG and 40BIN (*cf.* Sect. 3) gives an indication of the differences of MCB and single star nucleosynthesis. Most important is that the single star remains much more massive and thus develops larger core masses. Thus — provided that it explodes at all; *cf.* Sect. 6 — its yield of oxygen (3.3 $M_\odot$) and oxygen burning products is much larger compared with that of 40BIN, which ejects only 1.9 $M_\odot$ of ^{16}O. (Note that the models have been computed up to silicon ignition, which allows an accurate prediction of the oxygen yield.) On the other side, due to the rapid mass loss during early helium burning in sequence 40BIN, much more ^{12}C is ejected compared with 40RSG, which transforms most of the ^{12}C into ^{16}O during helium burning. Using the $^{12}C(\alpha,\gamma)^{16}O$ rate recommended by Weaver & Woosley (1993), we obtained a final carbon yield of 1.8 $M_\odot$ for sequence 40RSG, and of 2.4 $M_\odot$ for 40LBV. Note that all quoted yields include contributions from the stellar mass loss and the supernova ejecta.

The ^{26}Al yields of both sequences are discussed by Braun and Langer (these proceedings).

6. Supernova explosion

The striking difference in the final masses of sequences 40RSG (9.3 $M_\odot$) and 40BIN (4.8 $M_\odot$) has certainly consequences for the question of the ensuing supernova explosion.

The smaller star (40BIN) develops smaller mass cores and is thus more likely to perform a supernova explosion at all. Actually, according to comprehensive grids of binary models (*cf.* de Loore & De Greve 1992), it appears that the final mass of case B primaries does never exceed $\sim 5M_\odot$, due to mass convergence. Consequently, massive ($M_{ZAMS} \gtrsim 10\ M_\odot$) case B primaries might *always* explode as supernovae (*cf.* Woosley *et al.* 1994). Whether or not this is compatible with the possibility of black holes in binary systems (*cf.* Cowley 1992) remains to be investigated.

Massive stars below the RSG luminosity limit, on the contrary, develop (at least at solar metallicity) the largest core masses among all massive stars (*cf.* Maeder 1992, Woosley *et al.* 1993). Thus, the possibility of forming a black hole may exist in this case.

7. Conclusion

We have seen that, assuming the major effect of binarity is Roche-lobe overflow mass loss, only case B primaries below the RSG luminosity limit evolve differently from single stars. Since single star post-RSG WRs are formed only rather late during core helium burning, the mass convergence scenario does not apply to them. Thus, their final mass may be very large, compared to case B primaries of any initial mass and to initially more massive single stars, with major consequences for the WR evolution (Sect. 4), nucleosynthesis (Sect. 5), and the supernova explosion (Section 6).

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DISCUSSION:

Lindsey Smith: Now, I get to do a "Dick Thomas". In about 1968 when Paczynski had suggested that WR stars were pure He stars as produced by mass exchange and we believed that WR stars were about $10M_\odot$ - Kippenhahn emphasised that a pure He $10M_\odot$ star is unstable to the ϵ-mechanism. I have always thought this must be significant for WR stars and Andre Maeder has consistently emphasised the point since then.

Langer: The "strange mode" instability found by Wolfgang Glatzel and co-workers grows about 10^5 times faster than the ϵ-pulsations. Thus, while the latter might be damped relatively easily, mass outflow must be expected in this case.

Schmutz: You pointed out that there is a difference between the upper limit in luminosity of the WNL and WNE stars. However, since this difference is only a factor of two, you should be careful not to overinterpret this difference. Howarth & Schmutz (1992, A&A 261, 503) have pointed out that the luminosities derived from spectroscopic analyses are likely to be systematically too low by a factor of two. Moreover, based on the work I have presented in my talk, I suspect that the systematic effect is larger for WNE stars.

Langer: Concerning the luminosities of WR stars, I have to rely on the work of people like you, and when you revise your previous results, I certainly have to take this into account. What I want to say is that an observed upper luminosity limit for hydrogen-free WN stars can be directly transformed into an upper mass limit for the helium cores formed by massive core hydrogen burning stars, whatever the precise actual value of the limiting luminosity is.

van Kerkwijk: Is your prediction that binaries do not produce BHs, not contradicted by the existence of Cyg X-1 & LMC X-3?

Langer: Certainly, black holes in massive close binary systems may provide a very important constraint for the theory of massive star evolution. However, I have not yet attempted to understand the progenitors evolution of Cyg X-1 and LMC X-3 in detail. If simple binary models fail in this respect, one might also in this case think about additional mixing processes. They might lead to a more compact star and thus prevent or reduce Roche lobe overflow, and the primary may stay more massive as in the standard case.

Meynet: You mentioned in your talk the ^{18}O-rich meteoritic grains whose composition can be the mark of WR-enriched materials. With your models can you reproduce the three constraints on $^{16}O/^{18}O$; $^{12}C/^{13}C$ and $^{14}N/^{15}N$ and if yes is it an effect of your taking into account of semi convection?

Langer: Yes; this has been shown in detail in my paper in A&A 248, 531 (1991). Note, however, that any slow (compared to convection) mixing process might yield a similar result.

Schulte-Ladbeck: I thought pulsations could *initiate* the mass-loss of W-R stars, but could not drive the wind to infinity. Can you tell us more about your pulsationary driven mass-loss mechanism?

Langer: You are completely right. The acceleration of the wind to the very high terminal velocities observed in WR stars must also in this scenario be provided by the radiation force (cf. Lucy and Abbott 1993, Ap.J).

Conti: I like the simple idea that binary RLOF can provide lower luminosity W-R stars, but this makes a simple prediction: namely, all low luminosity W-R are binaries. Is this borne out by observations?

Langer: No. As Wolf-Rainer Hamann showed in his talk, this seems not to be the case. This does of course not mean that the above statement needs to be incorrect (since binarity might be relatively unimportant) but it does mean that especially the low-luminosity hydrogen-rich WN stars are probably formed in a "special" single star scenario, as also pointed out by Andre Maeder in his talk. Rapid roation and correspondingly strong internal mixing is a good candidate (cf. the contribution of Jens Fliegner and myself to this meeting).

Niemela: If there are pulsations which are 10^5 times more powerful, wouldn't you expect them to be observed?

Langer: On first glance: yes. However, the non-linear behaviour of these pulsations is yet hardly explored, and the switch to a stationarily outflowing solution in the highly non-linear regime cannot be excluded.

Pols: If all single stars $\geq 40\ M_\odot$ and all components of binary systems (of any mass) reduce their mass to $\leq 5\ M_\odot$ there may be a problem with the lower mass limit for black-hole progenitors and possibly with the black-hole formation rate, apart from the impossibility to form massive black holes in binaries. How certain are the WR mass-loss rates used in evolutionary calculations?

Langer: The mass loss rates used in current calculations of WR evolution - especially the mass dependent mass loss - are basically constrained by the observed low luminosities and masses of WC stars. These tell you directly that most massive stars end their lives with only few solar masses left.

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