Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Evolution and explosion of Wolf-Rayet stars

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Abstract. We investigate the pre-supernova evolution of Wolf-Rayet stars. We discuss whether the separation of hydrogen-free, core collapse supernovae into Type Ic and Type Ib supernovae is related to the occurrence of 'Case BB mass transfer' in massive close binaries, especially since the new, smaller WR mass loss rates do not favor helium-poor progenitor models from massive single stars. We also discuss the influence of rotation on the formation, evolution and explosion of WR stars using new models for rotating massive stars that have been computed from zero age to core collapse. We compute the spin-down of (non-magnetic) WR stars due to their strong mass loss, and compare pulsar spin rates with our predictions. Finally, we discuss implications of our results for the rotation rate of Type Ib/c supernova progenitors in general, and for SN 1998bw and the 'collapsar' model for γ-ray bursts in particular.

1. Introduction

Up to one fourth of all supernovae are of Type Ib or Ic (Cappellaro *et al.* 1997), *i.e.*, are powered by the iron core collapse in a hydrogen-free star. The key to removing the hydrogen from the surface of these stars during their progenitor evolution is certainly mass loss — although internal mixing may be relevant in some cases (*cf.* Sect. 3). The mass loss can occur either due to a stellar wind, which may allow single stars of solar metallicity to transform into WR stars if their initial mass is above 20–40 $M_\odot$ (*e.g.*, Meynet *et al.* 1994), or due to mass transfer in a close binary system (*e.g.*, Podsiadlowski *et al.* 1992).

2. Binaries

The majority of Type Ib/c supernovae occur in post-mass transfer close binaries, since primary (*i.e.*, initially more massive) components as small as $\sim 10\ M_\odot$ may evolve to core collapse, while the initial mass limit for WR formation in single stars is much higher (Sect. 1). Why then, is the observed population of Galactic

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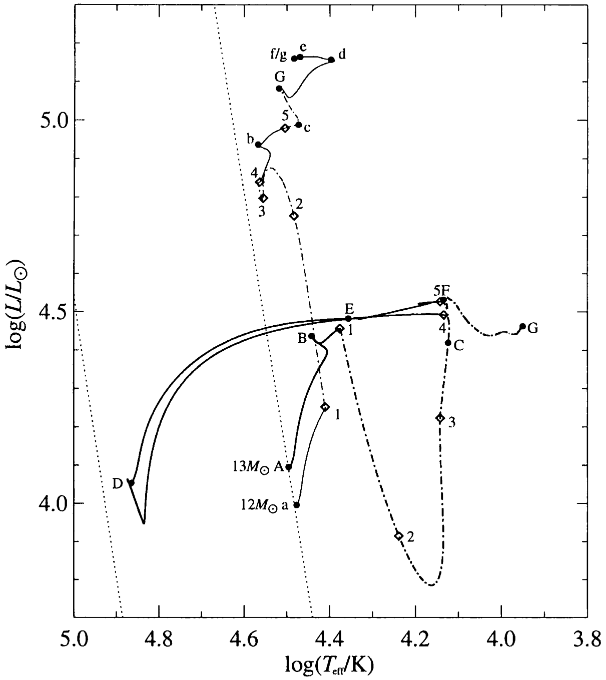

Figure 1. Evolutionary tracks in the HR diagram of the components of a 13+12 $M_\odot$ Case B close binary system with a metallicity of $Z_\odot/4$ and an initial period of 3.1 days. The path of the primary component (initial mass 13 $M_\odot$) is marked by the thick line and upper case letters, that of the secondary by the thin line and lower case letters. Mass transfer stages correspond to the dot-dashed parts of the lines. The thin dotted lines designate the zero age main sequence and the location of pure helium stars (helium main sequence). The letters designate beginning and end of nuclear burning stages, *i.e.*, core hydrogen burning (a/A – b/B), core helium burning (c/C – d/D), core carbon burning (e/E – f/F). g/G marks the beginning of core neon burning. Numbers designate mass transfer events for both stars. 1: beginning of Case B mass transfer, 2: maximum of mass transfer rate, 3: start of slow phase of Case B mass transfer, 4: end of Case B mass transfer, 5: start of Case BB mass transfer. The final masses of the primary and secondary are 1.6 and 22 $M_\odot$, respectively. The primary will explode as a Type Ic supernova, the secondary as a SN 1987A-like event. See Braun & Langer (1999) for more details.

WR stars (*e.g.*, K.A. van der Hucht, these Proceedings) dominated by single stars?

One has to wonder whether the He-core of, *e.g.*, a 10 $M_\odot$ star, once it is uncovered by mass transfer, should be designated as a WR star. Such stars may not have a strong wind and their spectra may not be dominated by emission lines. The problem is that those objects are almost unobservable, as demonstrated in Fig. 1. While the 'WR'-component of the system has, during most of its life time, a luminosity of ~ 10^4 $L_\odot$, the companion, *i.e.*, the mass gainer, is roughly a factor of 10 more luminous. Thus, although the supernova statistics clearly tells us that there must be many more 'WR'+OB pairs than single WR stars, we don't see them.

Fig. 1 also elucidates why there may be two distinctly different classes of hydrogen free core collapse supernovae, Type Ib which clearly show helium lines, and Type Ic which generally do not show helium — although small amounts of helium may also be present in Type Ic events (Filippenko *et al.* 1995). Helium stars below $\sim 3\,\mathrm{M}_\odot$ expand to red giant dimensions after core helium exhaustion (Trimble & Paczyński 1973; see also Woosley *et al.* 1995). Even though the system displayed in Fig. 1 has a period of ~ 40 days after the first mass transfer, the helium star can initiate a second (so called case BB) mass transfer which removes $\sim 80\%$ of its helium-rich layers. It seems conceivable that the post-BB mass transfer stars correspond to Type Ic supernovae (*cf.* Nomoto *et al.* 1994, Woosley *et al.* 1995) while primaries with initial masses above 12–15 $\mathrm{M}_\odot$ develop helium or 'WR' stars which are too massive to become a red giant and thus keep most of their helium envelope until the supernova stage.

However, Woosley & Eastman (1995) argued that the amount of helium seen in a Type Ib/c supernova (*i.e.*, the helium-line strengths) may not only depend on the amount of helium which is present but also on the amount of radioactive ^{56}Ni which is mixed close to or into the helium layer during the explosion and which can thus excite the helium line. Since Hachisu *et al.* (1991) have shown that more mixing is expected in the explosions of lower mass helium stars, it might be stronger in the post-BB mass-transfer stars.

We note that the latest downward correction of the empirical WR mass loss rates due to clumping effects by a factor of ~ 3 (Hamann & Koesterke 1998) makes it unlikely that the more massive helium stars, or WR stars formed in single stars, can lose enough mass to a wind to end up with as little helium as the post-BB mass transfer stars (Woosley *et al.* 1995; Wellstein & Langer 1999). Consequently, the case BB mass transfer introduces a dichotomy to the structure of the hydrogen-free core collapse supernovae which may well be related to the distinction of Type Ib and Type Ic supernovae.

3. Rotation

While the effect of rotationally induced mixing on the formation of WR stars has been investigated for some time (Maeder 1987; Langer 1992; Fliegner & Langer 1994; see also A. Maeder and G. Meynet, these Proceedings), predictions for the time-dependent rotation rate of WR stars became available only recently. Langer (1998) showed that mass loss combined with efficient internal angular momentum transport leads to a (non-magnetic) spin-down even for O stars (*cf.* also Heger & Langer 1998). Fliegner & Langer (1994) found that nevertheless WR stars formed through rotationally induced mixing during core hydrogen burning — *i.e.*, in particular H-rich WN stars — can maintain rapid rotation for some 10^5 yr (*cf.* Fig. 2). In fact, applying the Bjorkman-Cassinelli model according to Ignace *et al.* (1996) to those rapidly rotating WNL stars leads to the prediction of very aspherical photospheric shapes (Fig. 3). We may speculate that this relates to those ~10% of the WR stars which show strong polarization — which in fact are primarily of WN-type (A.J. Willis, these Proceedings).

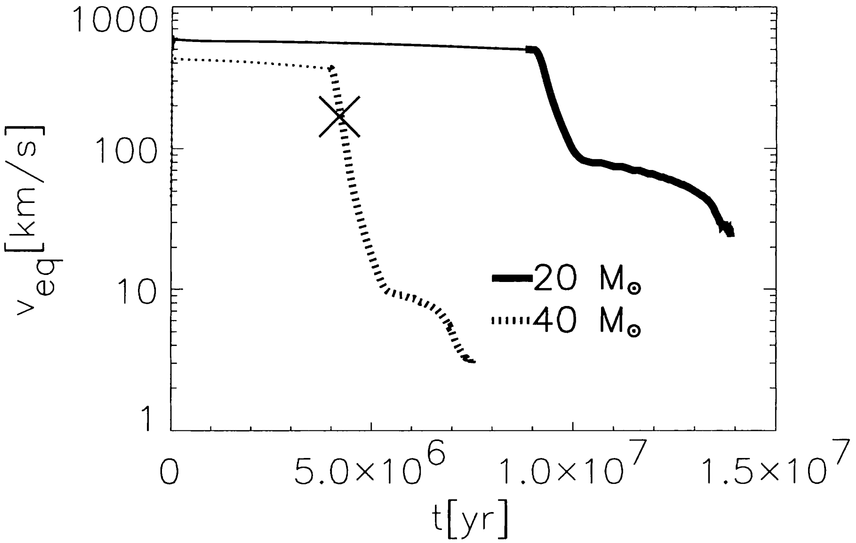

Figure 2. Evolution of the equatorial rotation velocity of rapidly rotating 20 M$_\odot$ and 40 M$_\odot$ models during core hydrogen burning, assuming efficient rotational mixing (Fliegner & Langer 1994). Rapid rotation is maintained until a spin-down occurs when the WR stage is reached, which is marked by the thick drawn parts of the lines. The cross on the 40 M$_\odot$ track marks the model for which the photospheric shape is displayed in Fig. 3.

In any case, the majority of the WR stars are expected to rotate slowly. It is clear from Fig. 2 that WR stars formed during core H-burning lose most of their angular momentum already before core helium ignition. Fig. 4 shows the evolution of the internal specific angular momentum profile for a 25 M$_\odot$ sequence which forms a WR star after a red supergiant phase. Also this model is, during its WR stage, a slow rotator with an equatorial surface velocity of $\sim$1 km s^{-1}.

For the core collapse mechanism in general and for γ-ray burst progenitor models in particular it is important to know the specific angular momentum, j, in the iron core at the time of collapse. Heger (1998) has computed a whole grid of massive star models in the mass range 10–25 M$_\odot$ from zero age to core collapse, including the effects of the centrifugal force on the stellar structure and relevant rotationally induced instabilities (see also Heger *et al.* 1999). He obtained iron core specific angular momenta of the order of $j = 10^{16}$ cm^{2}s^{-1}. These rather large values, which can be compared with values derived from pulsar spin rates (Langer *et al.* 1997; Heger 1998; Heger *et al.* 1999), predict the centrifugal force to play a non-negligible role during core collapse and bounce (Table 1).

Heger (1998) found that the angular momentum transport (for non-magnetic models) was self-regulating in the sense that the final specific angular momentum of the iron core depended only weakly on the initial rotation rate. More rapid rotators undergo a stronger rotationally induced mixing during the early

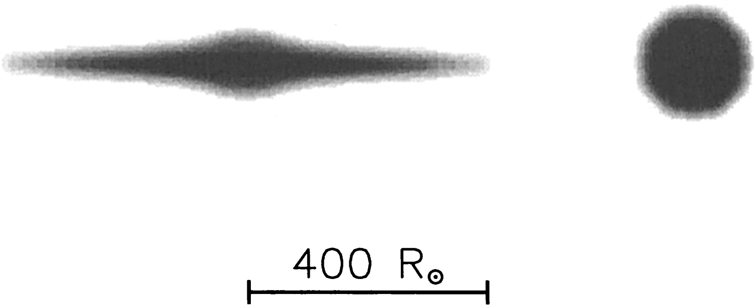

Figure 3. The apparent shape of a rapidly rotating WR model taken from a $40\,M_\odot$ sequence (*cf.* Fig. 2) applying the wind compression effect of Ignace *et al.* (1996) with a $\beta = 3$ velocity law and a constant wind opacity of $0.4\,\mathrm{cm}^2\mathrm{g}^{-1}$, viewed from within the equatorial plane (*left*), and pole-on (*right*). The photospheric radius of this model would be only $42\,R_\odot$ were the mass loss spherically symmetric.

evolutionary phases and therefore transport angular momentum more efficiently out of the core into the envelope. Fig. 5 gives an example of this by comparing the time evolution of the angular momentum profiles in two $15\,M_\odot$ stars with very different initial rotation rates.

If one compares the observed rotational rates of even young pulsars with the predictions above (Table 1), the predictions (~ 1 ms) are about one order of magnitude faster. This apparent discrepancy might be resolved by the recent proposition of a pulsational instability and accompanying gravitational wave radiation and corresponding angular momentum loss in hot neutron stars (Lindblom *et al.* 1998), or it may indicate that magnetic effects in the transport should not have been neglected (Spruit & Phinney 1998).

Woosley (1993) and MacFadyen & Woosley (1999) have recently proposed that massive helium cores which promptly form black holes at the end of their evolution might produce cosmological γ-ray bursts lasting several seconds or more. The 'collapsar' model requires specific angular momentum in the stellar mantle in the range $3\text{–}20 \times 10^{16}\,\mathrm{cm}^2\mathrm{s}^{-1}$ just prior to collapse. These values are a little larger than those predicted by Heger (1998), but nevertheless possible, especially for low metallicity Z. The reduced main sequence mass loss accompanying lower Z results in a more massive presupernova (helium) star and faster rotation; both benefit the model. However, since the γ-ray burst progenitor needs to be a compact star (MacFadyen & Woosley 1999) — *i.e.*, a

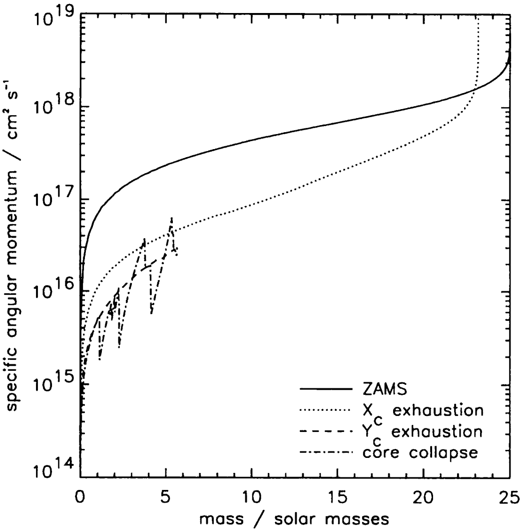

Figure 4. Specific angular momentum as function of the mass coordinate for various evolutionary stages of a 25 M$_\odot$ sequence which evolves as O star → RSG → WR star. See Heger (1998) and Heger *et al.* (1999) for details.

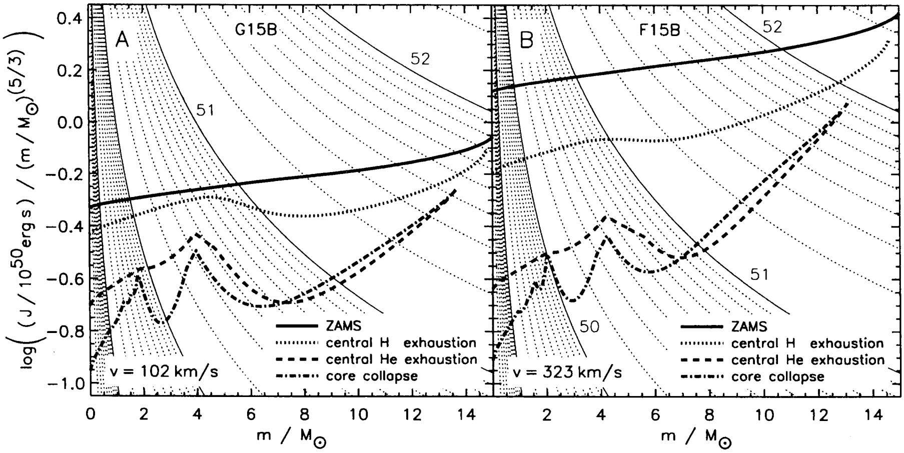

Figure 5. The logarithm of $J(m)/m^{5/3}$ (where $J(m)$ is the angular momentum contained in a sphere with the mass coordinate m) as function of the mass coordinate (thick lines) for various evolutionary stages (as indicated) of two 15 M$_\odot$ sequences with different initial rotation rates, 102 km s^{-1} in the left and 323 km s^{-1} in the right diagram. The thin lines give a logarithmic scale of levels of constant J, labeled with log(J/erg s). See Heger (1998) for more details.

Table 1. Properties of a $20\,\mathrm{M}_\odot$ star at the mass coordinate $M_r = 1.7\,\mathrm{M}_\odot$ (the mass of the iron core) at various times during the evolution (*cf.* Heger *et al.* 1998).

evolutionary stage	j ($\mathrm{cm^2\,s^{-1}}$)	r (cm)	ρ ($\mathrm{g\,cm^{-3}}$)	ω ($\mathrm{s^{-1}}$)	ω/ω_c
ZAMS	10^{17}	$4\,10^{10}$	3.4	$7\,10^{-5}$	0.03
H-exhaustion	$2\,10^{16}$	$3\,10^{10}$	8.0	$2\,10^{-5}$	0.008
He-exhaustion	10^{16}	$3\,10^{9}$	$8\,10^{3}$	10^{-3}	0.01
collapse	10^{16}	$6\,10^{7}$	10^{9}	3	0.08
neutron star	(10^{16})	10^{6}	$4\,10^{14}$	10^{4}	0.7

WR star — the WR mass loss rate would also need to be significantly reduced at low Z. The connection between γ-ray bursts and Type Ic supernovae has recently been demonstrated by a γ-ray burst (GRB 980425) associated with the Type Ic SN 1998bw which appeared to originate from a massive hydrogen-free star (Woosley, Eastman & Schmidt 1999; Iwamoto *et al.* 1998). Thus, the question of the γ-ray burst progenitors adds to the importance of the still unsolved question of the metallicity dependence on the WR mass loss rate.

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Discussion

Vanbeveren: The treatment of rotation by the Geneva group is quite different from the one in your group. The Geneva treatment predicts a convective core during core hydrogen burning that is spinning-up whereas in your models, the cores spin down. Could you comment on this?

Langer: Even through the details of the treatment of rotationally induced transport processes in the Geneva models and our models differ, both consider the same relevant physical instabilities (*e.g.*, Eddington-Sweet circulations, shear mixing, baroclinic instability) to operate on certain time-scales which are very similar in both codes. The way the centrifugal force is treated in the stellar structure equations is also the same in both codes. Whether or not the stellar core can spin up or down during core hydrogen burning is then also depending on the angular momentum loss which is coupled to the stellar mass loss (*e.g.*, Langer 1998). However, compared to the span in rotation rates during the final burning stages — which can easily be 10 orders of magnitude, and where the core is always dramatically spun-up — the degree of differential rotation on the main sequence is anyway small.

Walborn: What are the prospects for defining the WR state in the evolutionary models in terms of observed WR envelope/wind parameters, beyond the surface chemical composition? If radiation pressure, effective gravity, mass-loss rates, wind density, or other physical parameters could be tracked and correlated with the surface composition, the correspondence between model and observed stages might become more definite, and the interpretation of both be improved.

Langer: In our models, we have no sharp distinction between WR and non-WR stars. We smoothly increase the mass loss with decreasing surface hydrogen content according to empirical results summarized by Hamann. This seems to have a correspondance in reality beyond the mass loss rate itself, as the 'WR-phenomenon' appears to evolve gradually as well, as we see from the transition spectral types intermediate to O and WN stars. However, I agree that ultimately one should combine models for the interior and the atmosphere of WR stars to get theoretical spectral evolution. To my knowledge, this has never been done yet, partly due to the fact that we don't know anything empirically about the optically thick part of the WR winds, while on the other side we have no theory for the force which drives the winds in this regime.

Schutte-Ladbeck: Now that we have heard all three talks on massive star evolution, I was wondering whether any of you would like to comment on why there is no B[e] supergiant phase in any of the models. B[e] supergiants have two-component winds, are thought to be rotating, are known preferrentially in the MCs, and one is in a binary (R 4) with a ring nebula. What is their relation to WR stars?

Maeder: The correspondence between models and spectroscopic observations is an old and important problem. In the case of B[e] stars, I think the correspondence may rest on better basis, when we shall also include in the models the predictions for the angular variations of the mass loss rates $\dot{M}(\theta)$.

Langer: In a recent paper (Langer, 1998, in: A.M. Hubert & C. Jaschek (eds.), B[e] Stars (Dordrecht: Kluwer), p. 235) I have made detailed suggestions as to the origin of B[e] supergiants in the context of my models. I referred to two different evolutionary stages of massive single stars, where the stars may arrive at critical rotation and thus are perhaps able to produce a slowly outflowing disk wind. Furthermore, in that paper I proposed a detailed scenario for the B[e] phenomenon in that system and simultaneously explain the apparent age discrepancy of the secondary component (an evolved A-type star) and the unusually high L/M ratio of the B[e] component.

Shara: How many grid-points do you need until calculation-stability is reached?

Langer: As in all grid-based numerical calculations, we have to ensure that our results do not change when we (say) double the number of grid-points, or half the time-step. We have been testing this, and about 500 grid-points for the main sequence phase and up to 2500 for the final burning stages turn out to be sufficient.

Maeder: I think this is a point about which most modelists are very careful. We always set the time-steps and the mass shells so that changes by a factor of two (or more) makes no difference in the results.

Bohannan: To follow up on Walborn's comment: Paul Crowther and I have established spectroscopic criteria to distinguish between extreme Of and low excitation WR spectral types. These criteria which include the width of the He II 4686 emission line and the blue-shift of 'photosperic' lines as well as the mass flux in the wind, could be used in an atmosphere on top of stellar interior models to define the presence of the WR phenomenon in stellar evolution.

Langer: This could be done and is perhaps useful for comparing models with observations directly. For the results of massive star evolutionary calculations in general it is important that we adopt the proper mass loss rates, and as the WR phenomenon as such (*i.e.*, the appearance of broad emission lines) appears to be a gradual phenomenon, we turn the WR wind on in a gradual rather than a discrete way (*cf.* my answer to the question of Walborn).

Matteucci: Did you find a significant production of primary ^{14}N in your models with rotation?

Langer: Yes, we do. Particularly so for low metallicity (*e.g.*, see Langer, Heger & García-Segura 1998, Rev. Modern Astron. 11, for a first, preliminary report).