Evolution of Massive Stars

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1. Introduction

The term *massive star* is not very precise, and in the following we shall use it for stars with zero age main sequence (ZAMS) masses M_{ZAMS} above approximately $15\,M_\odot$. Note, however, that these abjects may achieve actual masses well below $15\,M_\odot$ during their evolution, as a consequence of mass loss due to stellar winds, pulsations, or other processes. $M_{ZAMS} \simeq 15\,M_\odot$ is a critical initial mass concerning several features. Only stars initially more massive develop superadiabatic layers above the convective hydrogen burning core, which turns already the core hydrogen burning phase to be difficult and uncertain. Only for stars above $M_{ZAMS} \simeq 15\,M_\odot$, mass loss due to stellar wind is important on the main sequence. Stars of lower initial mass always turn to the Hayashi-line after core hydrogen exhaustion, while for massive stars the post main sequence behaviour depends sensitively on physical details. This critical mass of $\sim 15\,M_\odot$ is not to be thought of as a strict limit. It depends especially on the stellar metallicity, and $15\,M_\odot$ may be a good number for Population I stars. It should be sufficiently high, anyway, in order to guarantee a nondegenerate carbon ignition, which ensures that the final evolutionary state of those objects is not a White Dwarf.

Massive stars, though they are relatively rare, deserve much attention due to their extreme properties. They are the most luminous individual objects and thereby rather easy to identify even in external galaxies. Their lifetime is very short ($\lesssim 10^7\,yr$), and so they are excellent tracers of active star formation. Their surface temperature is very high during most of their evolution, turning them into very powerful sources of high energy photons, which may consequently ionize the gas in a large system around them. They are also powerful sources of kinetic energy due to both, high velocity stellar winds ($\sim 10^{51}\,erg$) and the final supernova explosion ($\sim 10^{51}\,erg$). And finally they are the major site of cosmic nucleosynthesis, due to hydrostatic and explosive burning processes. Thereby, they are mainly responsible for the chemical evolution of galaxies.

It is beyond the scope of this paper to discuss all the items mentioned above in detail, rather we concentrate our discussion on structure and evolution of massive stars in phases, which are directly accessible to observations. More specifically, this concerns the hydrostatic evolution up to central helium ex-

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haustion (which accounts for $\sim$ 99% of the stellar lifetime), and the supernova explosion, which is a very short phase, but so luminous as to improve the observational statistic sufficiently.

The aim of the present work is to report on the current status of theoretical evolutionary computations for massive stars in the mentioned phases, and to discuss our knowledge and ignorance concerning abserved luminous stars which may (or may not) be identified with those computer models. Furthermore, we restrict ourselves to the case of spherically symmetric, non-rotating, non-magnetic massive single stars, which — as we show below — is not necessarily a simple case. However, there is some evidence that such stars exist in nature, i.e. that the above restrictions do not necessarily imply oversimplifications (cf. discussion on SN 1987a in Sections 6 and 7).

2. Main sequence evolution

Previously we already mentioned that the modelling of the main sequence evolution of massive stars encounters two main problems: the first is stellar mass loss, the second convection theory or, more specifically, internal mixing processes. Both processes are very difficult theoretical problems involved in stellar evolution calculations in general. However, it is just that for massive stars they are important from the beginning of the evolution, which renders even the main sequence phase as problematic.

Massive main sequence stars suffer mass loss due to a stellar wind which is driven by radiation pressure in absorption lines. Corresponding theories (see Castor et al., 1975) are meanwhile in a state which allows quantitative predictions of mass loss rates and terminal wind velocities within an accuracy of 10-20% (Kudritzki, 1988; Pauldrach et al., 1989). However, all published evolutionary calculations for massive main sequence stars used mass loss rates from fits to observational data (e.g. Lamers, 1981; de Jager et al., 1986). Those empirical mass loss rates have an accuracy of a factor of 2 in general. Especially for very massive stars, where observational data is rare, the error may be even larger. Furthermore, those formulae do not account for the dependence of the mass loss rate on the stellar metallicity, which is predicted from the wind theory and observationally confirmed in Local Group galaxies (cf. Kudritzki et al., 1987). Recently (Langer and El Eid, in prep.) the first stellar evolution calculations using theoretical mass loss rates have been performed by using the analytical solutions for wind models of Kudritzki et al. (1989), which approximate full non-LTE hydrodynamic wind models to high precision. Sequences for stars in the mass range $20\,M_\odot - 200\,M_\odot$ and for four different metallicities ($Z = 0.03, 0.02, 0.05, 0.002$) have been performed. The amount of mass lost during central hydrogen burning was found to be considerably less compared to computations which used empirical mass loss relations. E.g. a $40\,M_\odot$ star with 2% metallicity looses only $\Delta M = 2.5\,M_\odot$ according to our new calculations, while Maeder and Meynet (1987) found a total amount of $\Delta M = 7.5\,M_\odot$ to be lost during hydrogen burning using the mass loss formula of Jager et al. (1986).

This difference reflects mainly differences in the mass loss rates, since the duration of the hydrogen burning phase was comparable in both cases ($4.52\,10^6\,yr$ and $4.80\,10^6\,yr$). For a $100\,M_\odot$ sequence, Langer and El Eid (1986) found, by using the Lamers (1981) formula, $\Delta M = 24.2\,M_\odot$, while the new calculations yield $\Delta M = 11.5\,M_\odot$. These results demonstrate that theoretical mass loss rates are distinctively smaller than those obtained by current empirical mass loss relations. Since Kudritzki and co-worker compared the theoretical wind models with observations in great detail (e.g. not only the mass loss rate and wind velocity, but also spectral line profiles) and found very good agreement in most cases (cf. e.g. Kudritzki, 1988) we tend to favour the theoretical mass loss rates from observational fits, which, anyway, yield quite different results depending on which one is used (cf. discussion in Chiosi and Maeder, 1986).

The effect of mass loss during core hydrogen burning on the evolution of massive stars has been widely discussed in the literature (e.g. de Loore, 1980; Chiosi and Maeder, 1986) and will not be repeated here. We want to point out the aspect that low mass loss rates favour the occurrence of semiconvection in intermediate layers during core hydrogen burning which may have a large influence on the hydrogen profile and thereby on the post main sequence evolution (cf. discussion of Langer et al., 1985).

Massive main sequence stars are basically composed of a convective core and a radiative envelope. Both parts, however, are not unproblematic. For the convective core, there has been a long debate in the literature, whether its extension can be determined by the Schwarzschild criterion, i.e. $\nabla > \nabla_{ad}$ (where $\nabla = d\ln T/d\ln P$, and $\nabla_{ad} = (d\ln T/d\ln P)_{ad}$), or whether it is larger due to the so called convective overshooting. Current convection theories don't give a unique answer to this problem (cf. e.g. Langer, 1986; Renzini, 1987), and also a comparison of stellar tracks with observations does not yield really strict constraints (cf. Doom, 1985; Mermilliod and Maeder, 1986; Langer and El Eid, 1986). The consequences of an extended convective core for the evolution of a massive star are considerable, not only for the main sequence phase itself, which is prolongated and leads the star to cooler effective temperatures (see e.g. Stothers and Chin, 1985), but also for the post main sequence evolution (cf. Sect. 3), which makes a solution of the overshooting problem very desirable. In this context we refer to Sect. 6, where we include a discussion of the progenitor evolution of SN 1987a, which may bring us somewhat closer to such a solution. The difficulty which may occur in the radiative envelope of massive main sequence stars is the semiconvection. Semiconvection is a process which develops in layers where the temperature gradient is superadiabatic (i.e. the Schwarzschild criterion is fulfilled) but where also a molecular weight gradient is present, which prevents the onset of convection according to the Ledoux criterion (Ledoux, 1941). Instead of convection, which would act on a dynamic timescale, an overstability develops (Kato, 1966), which leads to a mixing process on a thermal time scale (Langer et al., 1983). In massive main sequence stars, the convective core mass decreases with time, leaving behind an extended, chemically inhomogeneous zone. The high contribution of radiation pressure to the total pressure favours the occurrence of superadiabaticity in these layers, which then leads to the onset of semiconvection.

In the main sequence phase, the evolutionary timescale (and therefore the timestep in numerical calculations) is large compared to the thermal timescale. However, one may not assume a complete mixing (i.e. homogenisation) in semiconvective layers during this phase, since the radiative diffusion coefficient is linked to the hydrogen abundance via the opacity (electron scattering dominates). Complete mixing may therefore lead to subadiabatic temperature gradients (cf. Chiosi and Summa, 1970), i.e. to a completely stable situation, which is a contradiction to the assumption that mixing may occur. Iben (1974) realized that a very fine spatial zoning avoids this contradiction. However, in post main sequence phases it is no longer guaranteed that the numerical timestep exceeds the thermal timescale, and the semiconvective mixing has to be treated as timedependent, e.g. by solution of a diffusion equation (Langer et al., 1983). Both mass loss and convective core overshooting tend to choke off the occurrence of semiconvection in massive main sequence stars. This is visible in Fig 1, where the internal convective structure of a star of initially $30\,M_\odot$ is plotted as a function of time. Note that in the computations, the mass loss rate of Lamers (1981) has been used for the main sequence phase, which drastically reduces semiconvection compared to the case of no mass loss (cf. Fig. 10 of Langer et al., 1985). In computations including mass loss and convective overshooting, practically no superadiabaticities occur outside the convective core of the $30\,M_\odot$ sequence during central hydrogen burning.

We argued above that the mass loss rates of massive main sequence stars may have been somewhat overestimated in the past. In Sect. 6 we will see that probably efficient overshooting would have prevented the SN 1987a progenitor to evolve towards high effective temperture before exploding. Therefore, it seems likely that semiconvection actually occurs in the main sequence phase of massive stars. Since energy transport due to semiconvection is negligible (Langer et al., 1985), its effect is just a modification of the intermediate chemical profile. However, this has a large influence on the post main sequence evolution of massive stars (see below, and cf. Fig. 1).

3. The supergiant phase

A supergiant is usually classified as such from spectroscopic criteria, which indicate an extended atmosphere, i.e. a large stellar radius. The ignition of the hydrogen burning shell after core hydrogen exhaustion leads to a strong expansion of the overlying stellar envelope in massive stars, increasing thereby considerably their radius and reducing their surface temperature. Therefore, models of massive post main sequence stars may certainly be identified as supergiants (as long as they still possess a sufficiently massive envelope; cf. Sect. 5). Whether the reverse is true is not certain: towards the end of core hydrogen burning, the radius of a massive star may be much larger compared to its radius on the zero age main sequence (ZAMS). E.g. a $100\,M_\odot$ star increases

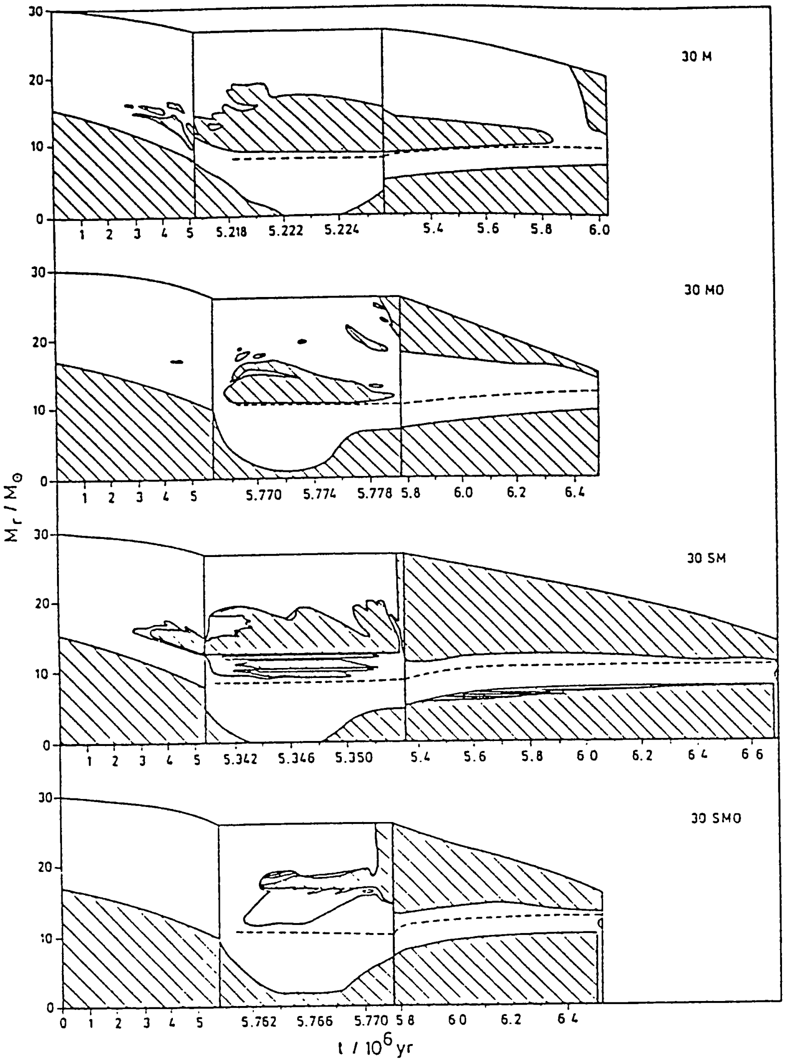

Fig. 1: Internal structure as function of time for a star of 30 $M_\odot$ initial mass with 4 different assumptions on convection: 1. Schwarzschild criterion for convection (30M); 2. Schwarzschild criterion with overshooting of 0.2 pressure scale heights (30MO); 3. Semiconvection (efficiency parameter $\alpha = 0.1$) and without overshooting (30SM); and 4. Semiconvection ($\alpha = 0.1$) and overshooting (30SMO). Hatched areas indicate convection, surrounded white areas semiconvection. The time scale breaks twice, separating the three phases core hydrogen burning, contraction phase towards helium ignition, and core helium burning. The dashed line indicates the position of the H-burning shell. The upper borderline of the figures shows the total mass as a function of time. All sequences have been computed with Lamers (1981) mass loss rate for effective temperatures above 6 500 K and Reimers (1975) for lower values. For central He-burning, a convective envelope means that the star is in the Red Supergiant stage, while otherwise it is a Blue Supergiant. A detailed description of these sequences can be found in Langer (1986a).

its radius from 13 $R_\odot$ at H-ignition to 53 $R_\odot$ at core hydrogen exhaustion. In the following, anyway, we refer to post main sequence phases when we use the expression "supergiant".

The effective temperture, at which models of massive stars perform core helium burning depends sensitively on the input physics used in the model computation, and has been subject to many studies in recent years. Mass loss and convective overshooting, which both diminish the envelope mass of the star, tend to push the star towards the Hayashi line, i.e. towards the Red Supergiant stage (cf. Stothers and Chin, 1979; Maeder, 1981; Maeder and Meynet, 1987). Semiconvection also favours core helium ignition as a Red Supergiant due to a limitation of the hydrogen content at the position of the H-burning shell (cf. Fig. 1). However, when the H-shell propagates outwards with time it may eventually reach layers with high hydrogen concentration and reactivate, leading to a "blue loop" in the Hertzsprung-Russell diagram, i.e. to hotter effective temperatures (cf. Langer et al., 1985). However since the efficiency of all three processes is somewhat uncertain, reliable post main sequence tracks are hard to predict. In this context the supernova 1987a is a very useful event, since it helps constrain these uncertainties considerably (cf. Sect. 6). From the computations of Maeder and Meynet (1987) we can say that moderate overshooting and current standard mass loss rates yield almost no Blue Supergiants at all for "massive" stars (i.e. $M_{ZAMS} \gtrsim 15\,M_\odot$). Therefore, one or both of these processes should have a reduced efficiency compared to that adopted by Maeder and Meynet.

New computations for 20 and 40 $M_\odot$ stars with galactic metallicity performed with the Schwarzschild criterion for convection (Langer and El Eid, in prep.) indicate a movement on the nuclear timescale from hot effective temperatures to the Red Supergiant stage in the HR diagram during central helium burning. This appears to be more consistent with the distribution of Supergiants in the HR diagram (see Humphreys and McElroy, 1984).

Stars more luminous than $\sim 10^{5.7}\,L_\odot$ (corresponding to $M_{ZAMS} \gtrsim 50\,M_\odot$), are known to have no observed Red Supergiant counterparts in the HR diagram (Humphreys and McElroy, 1984; Humphreys, 1984). In order to avoid that a very massive star evolves to low effective temperatures after core hydrogen exhaustion, its envelope mass has to be drastically reduced, which can be achieved either by adopting an extremely high mass loss rate after core hydrogen exhaustion, or by assuming convective overshooting to be very efficient during core hydrogen burning (cf. Langer and El Eid, 1986; Maeder and Meynet, 1987), or a combination of both. The question which of this two processes is the dominant one is enlightened by an analysis of the so called Luminous Blue Variables (LBVs), which is the subject of the next Section.

4. Luminous Blue Variables

As mentioned above, there are no observed stars in the upper right corner of the HR diagram (see Humphreys and Davidson, 1979; Humphreys and McElroy, 1984). The borderline between this empty region and the rest of the HR diagram, the so called Humphreys-Davidson (HD) limit, depends only weakly on the effective temperature for values lower than $\sim 15\,000\,K$, lies at $\log L/L_\odot \simeq 5.7$, and corresponds to the absence of very luminous Red Supergiants mentioned in the previous Section. For surface temperatures in excess of $15\,000\,K$, the luminosity at the HD-limit increases with increasing temperature.

From observations it is known that the mass loss rate due to stellar wind increases quite drastically for stars closer to the HD-limit (de Jager et al., 1986). Furthermore, many — if not all — stars close to the HD-limit show irregular variability, and on timescales of decades some (e.g. P Cygni, η Carina) show real outbursts, which have to be interpreted as shell ejections (Lamers, 1989). Humphreys (1989) has tried to give a definition of the Luminous Blue Variables (LBVs), which is a collective designation for the variable stars close to the HD-limit, and which comprises the P Cygni type stars, the S Doradus variables, and the Hubble-Sandage variables. According to Humphreys, besides their variability, LBVs have the following properties: they show emission- and/or P Cygni-lines in their spectra, show a surface temperature variation in the range $25\,000\,K - 8\,000\,K$, have high luminosities, very high mass loss rates, and show evidence for circumstellar ejecta by e.g. an infrared excess. Quantitative analysis of the ejecta, such as in η Car, and the atmospheres and circumstellar envelopes of these stars show that they are nitrogen and helium rich (Davidson et al., 1982, 1986; Allen et al., 1985). This supports the idea of a reduced envelope mass due to mass loss and/or mixing in post H-burning very massive stars (cf. Sect. 3), which leads to H-burning products at the stellar surface.

Lamers (1989) has analysed the mass loss rate of several LBVs in different galaxies. It ranges from values, which can possibly explained by the radiation driven wind theory, i.e. $\sim 10^{-5}\ M_\odot\ yr^{-1}$, corresponding to quiescent phases, up to values of $10^{-2} - 10^{0}\,M_\odot$ in one violent outburst. Lamers estimates the time averaged mass loss rate to be of the order of $10^{-4}\ M_\odot\ yr^{-1}$, but the uncertainty is large. Depending on the recurrence time of violent outbursts and on the average ejected mass it could also be higher. Adopting a value of $10\,M_\odot$ as the order of magnitude of the mass which a massive star has to loose in the LBV stage in order to avoid an evolution to cool effective temperatures, a time average mass loss rate of $10^{-4}\ M_\odot\ yr^{-1}$ would result in a duration of the LBV phase of $\sim 10^{5}\,yr$. This value seems too large regarding the small number of LBVs as compared to the number of Wolf-Rayet stars, the probable LBV descendants with lifetimes of some $10^{5}\,yr$ (cf. Sect. 5).

Another way of estimating the duration of the LBV phase for massive stars comes from evolutionary considerations. Consider a star close to the HD-limit, moving towards cool surface temperatures. In a certain (small) time interval

Δt the star increases its radius by ΔR. In order to stop the redwards motion, the star has to loose an amount of mass ΔM which leads to a radius decrease of ΔR (see Heisler and Alcock, 1986). Thus, the condition $R(t) = const.$ yields a critical mass loss rate $\Delta M/\Delta t$. In stellar evolution calculations, this critical rate can be found by adopting a mass loss formula of the form $\dot{M} = \dot{M}_0(T_{eff,0}/T_{eff})^{\alpha}$ with large α (say $\alpha = 5$). Using standard mass loss rates for $\dot{M}_0$, e.g. those predicted by the radiation driven wind theory, and for $T_{eff,0}$ a value close to the HD-limit, ensures a continuous but drastic increase of the mass loss rate at the HD limit, and the star will establish the condition $R(t) = const.$ Langer and El Eid (in prep.) performed computations of this type and found $\dot{M}(\dot{R} = 0) \simeq 5\,10^{-3}\, M_{\odot}\, yr^{-1}$ for a sequence with $M_{ZAMS} = 100\, M_{\odot}$, which leads to a duration of the LBV phase of $8\,10^3\, yr$.

However, we note that the radius increase per time at the HD-limit, i.e. the speed of the redwards evolution close to the HD-limit, may depend much on the previous evolution of the star, i.e. on the adopted input physics of the computations, especially concerning convection/semiconvection and main sequence mass loss rate. E.g. very massive stars without mass loss and overshooting evolve redwards only on a nuclear timescale rather than on a thermal timescale (cf. Stothers and Chin, 1976). In this case, the LBV phase would last considerably longer and would proceed at much smaller mass loss rates.

In this context it is especially interesting to point out that a lower main sequence mass loss rate may prolongate the LBV phase for two reasons: it leaves more mass to get rid of in this phase, and it reduces the speed of redwards evolution after central H-exhaustion, thereby reducing the LBV mass loss rate. Therefore, since the main sequence mass loss rates in the Magellanic Clouds are known to be smaller compared to those in the Milky Way (Kudritzki et al, 1987), this may explain the relatively large number of LBVs in the LMC. Preliminary computations for a $100\, M_{\odot}$ star of LMC composition and main sequence mass loss according to Kudritzki (1987, 1989) indicate $\dot{M}(\dot{R} = 0) \simeq 10^{-3}\, M_{\odot}\, yr^{-1}$.

We should note here, that the LBV phase does not necessarily proceed always in the same way for all stars, rather that qualitative differences may occur for stars of different ZAMS mass or actual mass. Langer (1989a) proposed that the behaviour of stars in the LBV phase may be determined by the internal hydrogen profile, which (for a fixed convection theory) is a function of the stellar mass. He argues that LBVs of very high mass will produce late WN stars as descendants, while those of smaller mass will produce early WN stars (cf. Sect. 5). Furthermore, he discusses the possibility of a post-Red Supergiant LBV phase as well as a post-LBV Red Supergiant phase. Neither are prohibited by observations for a narrow mass range corresponding to the luminosities of the most luminous Red Supergiants, i.e. there exist LBVs of similar bolometric brightnes.

Nothing has been said up to now about the physical mechanism of the LBV mass loss, which in reality is not continuosly varying but rather erratic. At a recent IAU meeting (Davidson and Moffat, 1989) several mechanisms for the diversity of unstable behaviours of LBVs have been proposed (cf. review of Walborn, 1989), e.g. radiation pressure (cf. Lamers and Fitzpatrick, 1988; but also Pauldrach and Puls, 1989), internal density inversion and related super-Eddington luminosity (Maeder, 1989) or convectively initiated turbulent pressure (Kiriakidis, 1987). Which of these proposed mechanisms really act in LBVs is yet unclear. It is worth pointing out, however, that they are all related to the recombination of hydrogen at temperatures of $\sim 15\,000\,K$. This changes drastically the opacity and the mean molecular wheight, which has effects on radiation transport, convection and equation of state.

5. Wolf-Rayet stars

Wolf-Rayet (WR) stars are supposed to be the descendants of massive stars which have lost all or the main part of their hydrogen rich envelope (cf. Chiosi and Maeder, 1986), and therefore the WR stage is probably succeeding the LBV phase. However, not all single WR stars are necessarily formed via the LBV scenario. Some may be direct descendants of Red Supergiants, while others could perhaps be formed already during the main sequence evolution., e.g. due to rotationally induced mixing (cf. Maedér, 1987). We should mention also that some WR stars might have formed through mass exchange in a close binary system, but that this is not the dominant WR formation scenario (cf. Chiosi and Maeder, 1986, and references therein).

WR stars exist, and independently of how they might have been formed one may consider their internal structure and evolution. For that we want to divide the WR stars into two classes, those which still contain some hydrogen in their envelope — let us call them late WN or WNL stars here — and those which do not contain any hydrogen, which we will designate as (true) WR stars. Our definition of WNL stars is roughly consistent with that derived from spectroscopic criteria (cf. Willis, 1982). We regard the WNL stars as a separate class, since there is evidence from both observation and theory that they have very different properties compared to the other WR stars. WNL stars are known to be much more massive (Niemela, 1983; Moffat, 1982) and luminous (cf. e.g. Smith and Maeder, 1989) than other WR subtypes. Furthermore, they are much less compact, i.e. have much larger radii, which may be provoked by the presence of hydrogen: hydrogen raises the opacity, lowers the mean molecular wheight, and — probably most important — allows the presence of a second nuclear burning region besides the He-burning center, i.e. sets up a hydrogen burning shell. These structural differences may result in the occurrence of absorbtion lines in WNL spectra (van der Hucht et al., 1988; see below), and may be related to spectroscopic similarities of WNL and Of stars (cf. Bahannan and Walborn, 1989).

Hydrogenless WR stars, in contrast, which appear either as early WN stars or as WC/WO stars, are compact, much dimmer and less massive than WNL stars. Since they do not contain hydrogen, their only nuclear energy source is the helium burning center. This makes their internal structure relatively simple, and results e.g. in a narrow mass luminosity relation (cf. Maeder, 1983). Langer (1989b) constructed a grid of WR models and investigated the dependence of observable quantities as function of the WR mass, composition, and convective structure. He found that due to the dominance of radiation pressure all over the star except in a tiny mass fraction close to the stellar surface, WR mass and surface chemical composition alone determine all observable quantities. He could derive e.g. the theoretically allowed areas for WR stars in the L-M, R-M, and L-T diagrams (see Figs. 2 and 3), where R and T correspond to radius and surface temperature of the hydrostatic WR core. He also derived estimates for the optical thickness τ of the WR wind zone, which may hide

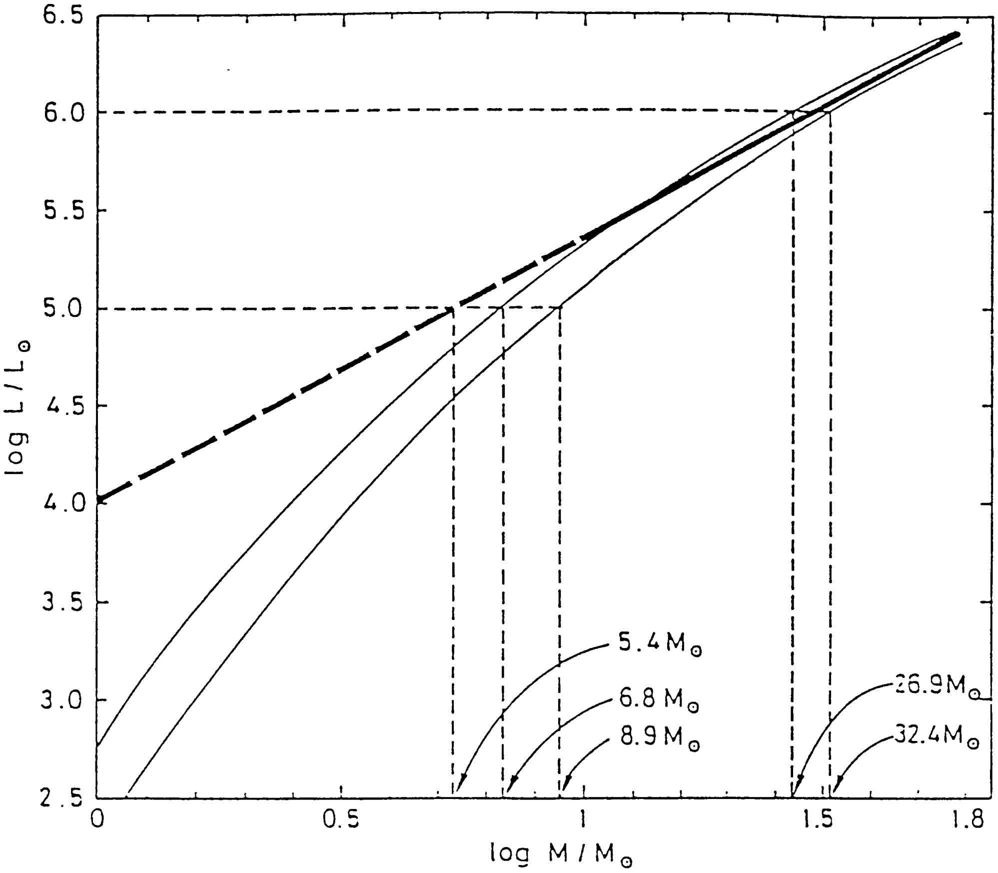

Fig. 2: Mass-luminosity relation for Wolf-Rayet stars. The theoretically allowed area in the $\log M - \log L$ diagram for hydrogenless WR stars is the area in between the two continous lines. The thick continuous line corresponds to the $M - L$ relation of Maeder and Meynet (1987) and is extrapolated towards lower masses (dashed part). Two examples of a mass determination for a given luminosity are indicated.

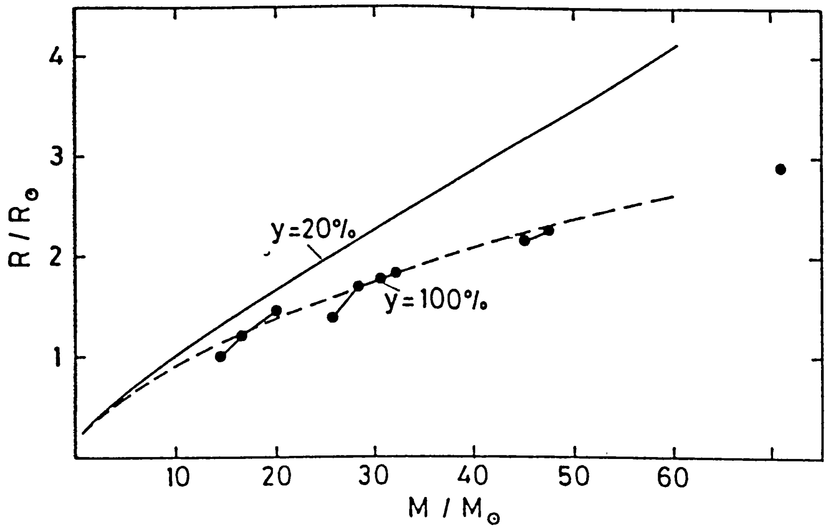

Fig. 3: Mass-radius relation for Wolf-Rayet stars. The allowed area in the $R-M$ diagram for hydrogenless WR stars is bounded by the two curves, which correspond to extreme cases of surface chemical composition, i.e. a helium mass fraction of 20 and 100%. The dots correspond to models from the evolution computations of Maeder and Meynet (1987); cf. Langer (1989b). Note that R stands for the hydrostatic core radius of WR stars (see text).

the hydrostatic WR core from observations, and showed that $\tau \sim \dot{M}/R$. This means that absorbtion lines can be expected in WR spectra only for stars with relatively small mass loss rates ($\dot{M} < 10^{-5}$ $M_\odot$ yr^{-1}) or large hydrostatic core radii (which applies to WNL stars; see above).

Stellar evolution calculations for massive stars, which lead through the WR phase, are rather rare in the literature (e.g. Maeder, 1983; Doom et al., 1986; Langer and El Eid, 1986; Prantzos et al., 1986; Maeder and Meynet, 1987; Langer et al., 1988). A comparison of observationally derived positions of WR stars in the HR diagram (e.g. Lundström and Stenholm, 1984; Schmutz et al., 1988) with those tracks — though it is very difficult to perform; cf Langer (1989b) — indicates a basic discrepancy, which is that the observed luminosities (and therefore the masses) are too low to compare with theoretical computations. This discrepancy is confirmed by simplified WR evolution calculations of Langer (1989c), who computed IMF-averaged WR properties and compared with the complete WR sample of van der Hucht et al. (1988). He also showed that this discrepancy can be removed by adopting the concept of mass dependent mass loss rates for WR stars, which is motivated by the models of Langer (1989b), and which has already been suggested by Abbott et al. (1986) from observational data. Langer finds that a mass loss law of the form $\dot{M}_{WR} \simeq (0.6 - 1.0)10^{-7}(M_{WR}/M_\odot)^{2.5}$ [$M_\odot$ yr^{-1}] yields good agreement of theory and observations in many respects. This concerns IMF-averages of WR masses and luminosities, WR progenitor ZAMS masses, WR subtype ratios, and WR lifetimes. Also the final WR masses, i.e. the masses of the supernova configurations resulting from massive stars which evolve into WRs, is much smaller adopting mass dependent WR mass loss rates rather than keeping the WR mass loss rate constant with time (as usually done), which may have important implications for the explanation of the newly identified class of type Ib supernovae, as will be discussed in the next Section.

6. Supernovae from massive stars

Massive stars up to $M_{ZAMS} \simeq 100\,M_\odot$ are supposed to proceed hydrostatic nucleosynthesis up to silicon burning, thereby forming a degenerate Fe/Ni-core. The ensuing core collapse is thought to give rise to the standard scenario of supernovae (SNe) from massive stars (Woosley and Weaver, 1986). Note that stars initially more massive than $\sim 100\,M_\odot$ explode through the $e^\pm$-pair creation scenario by explosive oxygen burning (cf. again Woosley and Weaver, 1986), potentially as very massive WR stars of type WNL (El Eid and Langer, 1986; Langer, 1987a,b). Possible observational counterparts of such pair creation SNe could be the peculiar SN 1961v (Langer,1987c), or the SN remnant Cas A (El Eid and Langer, 1986). The optical display of such supernovae depends greatly on the presence of hydrogen in the envelope and the amount of radioactive nickel produced by the explosive burning (Woosley and Weaver, 1982; Herzig, 1988; Ensman and Woosley, 1989; Herzig et al., in prep.).

The presupernova configuration of a star with initial mass in the range $15\,M_\odot \lesssim M_{ZAMS} \lesssim 100\,M_\odot$ is either a Supergiant or a Wolf-Rayet star. Since most of the WR stars do not contain hydrogen in their envelope, such objects would be classified as type I SNe when exploding. The usual type I SNe, also designated as type Ia, are probably related to low mass binary stars (cf. Woosley and Weaver, 1986). The recently identified class of type Ib SNe (cf. Branch, 1986), however, shows a distinct preference to occur in regions of active star formation and should therefore be related to more massive stars. Ensman and Woosley (1988) performed lightcurve computations for WR stars exploding due to the core collapse mechanism and concluded that most type Ibs could not originate from WR stars, since the theoretical lightcurves are only consistent with observed ones when very low WR masses ($M_{WR} \lesssim 8\,M_\odot$) are adopted for the computations, which they found to be inconsistent with existing stellar evolution calculations (cf. Sect. 5). However, as mentioned above, the concept of mass dependent mass loss rates for WR stars naturally leads to such small final WR masses (Langer, 1989c) for all WR stars (except WNLs), independent of their initial mass. Therefore, the idea of WR stars as type Ib SN progenitors may be realistic.

The usual type II SN explosions are thought of as being relatively well understood in general. The standard model is that of an exploding Red Supergiant which blows up due to the core collapse mechanism (cf. Woosley and Weaver, 1986), and the SN 1987a in the Large Magellanic Cloud (LMC) confirmed the general picture. An unexpected peculiarity of SN 1987a was, however, that its progenitor star was a Blue rather than a Red Supergiant.

Several reasons have been suggested in order to explain why a Blue Supergiant may explode and why nobody though about that before it happened. First, the SN 1987a is the only observed SN in an irregular dwarf galaxy, which are generally low metallicity systems. The metallicity of the LMC is $\sim 1/4$ of that in the Milky Way, and this circumstance was first thought of as explaining the Blue Supergiant explosion (cf. e.g. Hillebrandt et al.,1987). However, soon it became evident that the SN 1987a progenitor must have been a Red Supergiant several $10^4\,yr$ before the explosion (Fransson et al., 1989). Woo6ley (1988) found that massive low metallicity stars may return from the Hayashi track to hotter surface temperatures during the contraction phase towards central carbon burning (i.e. at the right time), when the Ledoux criterion for convection is used instead of the usual Schwarzschild criterion. Also Weiss (1989) performed evolutionary computations and got a Blue Supergiant SN progenitor with the Ledoux criterion, but in his case the so called blue loop occurred during central helium burning (i.e. too early). Recent evolutionary computations of Langer , El Eid, and Baraffe (1990), who used the semiconvection theory suggested by Langer et al. (1983), indicate the following results for a $20\,M_\odot$ star with LMC composition (cf. also Fig. 4): Blue Supergiant explosions are obtained for values of the semiconvective efficiency parameter α of $0.05 \leq \alpha \leq 0.008$, while red explosions occur for larger or smaller values. Note that $\alpha = 0$ corresponds to the Ledoux criterion for convection, while $\alpha = \infty$ recovers the Schwarzschild criterion. The value recommended by Langer et al. (1983, 1985) for theoretical reasons was $\alpha \simeq 0.1$. For the blue explosions, the effective temperature at the time of explosion was found to be in the range $21\,000\,K \gtrsim T_{eff,expl} \gtrsim 13\,000\,K$, depending on α. Some sequences performed a blue loop during central helium burning, most of them returning to the Hayashi line at central helium exhaustion. These results turned out to be insensitive to changes in the adopted mass loss rates. Note that for $\alpha = 0.01$ but galactic metallicity ($Z = 2\%$) we obtained a Red Supergiant SN progenitor structure.

These results indicate that probably molecular weight barriers in the stellar interior cannot be overcome by convection instantaneously, which is implicitly assumed by adopting the Schwarzschild criterion for convection, rather that mixing in chemically inhomogeneous and superadiabatic regions is performed on a thermal timescale. Also convective overshooting should have a limited efficiency, at least as long as the molecular weight within the convective zone and the adjacent radiative layers is different. If this picture will be confirmed, it would mean that most stellar evolution calculations performed yet for massive stars contain a basic oversimplification. Note that e.g. the mass of the C/O-core at central He-exhaustion obtained for a $20\,M_\odot$ sequence with semiconvection and an efficiency parameter in the range which yields a blue explosion is of the order of $2\,M_\odot$, while adopting the Schwarzschild criterion results in a C/O-core mass of $\sim 4\,M_\odot$. Also the central carbon mass fraction at core helium exhaus-

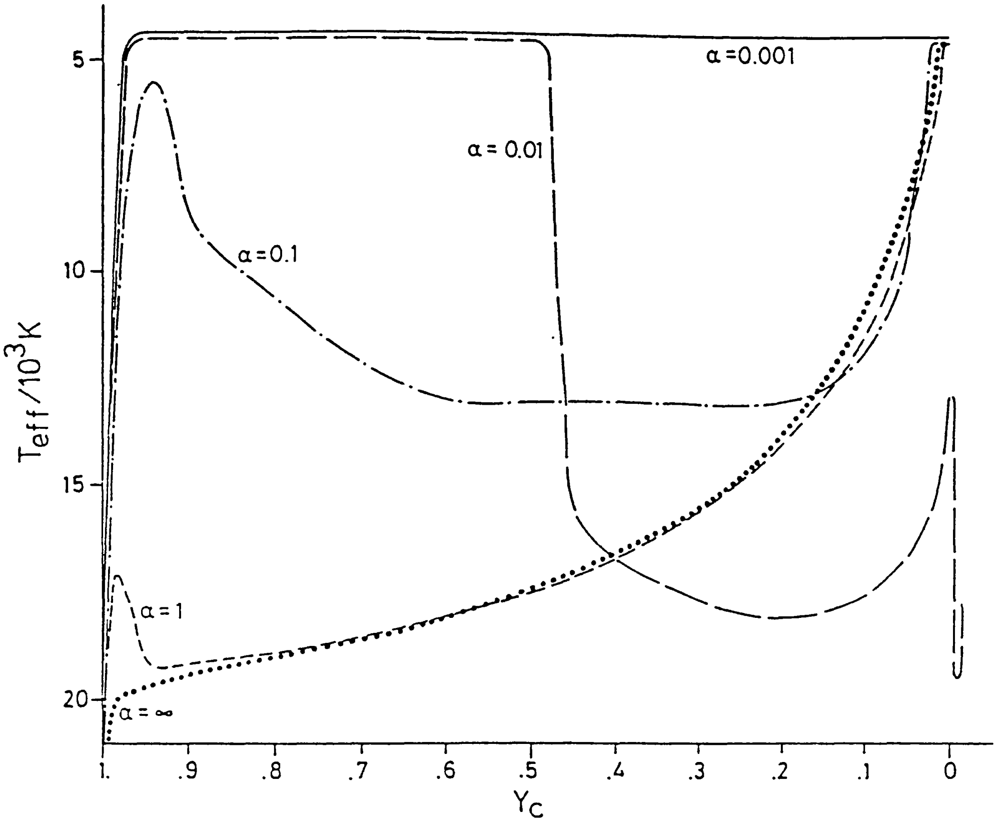

Fig. 4: Surface temperature during central helium burning as function of the central helium content for 20 $M_\odot$ sequences of LMC composition computed with mass loss and semiconvection for varying semiconvective efficiency parameter α. Tracks for $\alpha = 0.001, 0.01, 0.1$, and 1.0 are shown, as well as that of a sequence computed with the Schwarzschild criterion, which corresponds to $\alpha = \infty$. The sequences with $\alpha = 0.001$, 0.1, 1.0, and ∞ yield Red Supergiant explosions, while $\alpha = 0.01$ yields a blue explosion at $T_{eff} \simeq 17\,000\,K$. (Note that the computations have been performed up to carbon burning, which ensures that the surface temperature will not change any more.) For α slightly larger than 0.01 we got a track similar to that for $\alpha = 0.01$ but the surface temperature diminished towards central helium exhaustion up to the Hayashi line. For values slightly lower than 0.01 we got a track like that for $\alpha = 0.001$, but with a blue loop to $T_{eff} \simeq 15\,000\,K$ after central helium exhaustion. See Langer, El Eid, and Baraffe (1990) for more details.

tion is greatly influenced, values ranging from $X_C = 0.06$ for the Schwarzschild case up to $X_C = 0.20$ for inefficient semiconvective mixing. Hence it appears that internal mixing during He-burning will have a strong impact on the final stages of massive stars.

7. Summary

In the present work we intended to report on progress and problems in the simulation of the evolution of massive ($M_{ZAMS} \gtrsim 15\,M_\odot$) stars. It could not be our aim to be comprehensive in this respect, rather we selected topics which are controversial at present. We confined ourself to problems concerning the stellar structure and observable evolutionary phases, leaving out late burning stages and the whole item of stellar nucleosynthesis.

We argued that the main sequence phase already bears significant problems. New evolutionary calculations, which relied for the first time on theoretical mass loss rates according to the radiation driven wind theory indicate that main sequence mass loss might have been somewhat overestimated in the past. The consequences thereof and of assumptions on the convection theory on the effective temperature of core helium burning Supergiants as well as on lifetime and mass loss rate of stars in the LBV phase have been discussed. We stressed the importance of the metallicity of the stellar matter for main sequence mass loss, which affects the subsequent surface temperature evolution, and argued that the relatively large number of LBVs in the LMC compared to the Milky Way could be related to that. We motivated that WR stars of type WNL should be considered as a class separately from all other WR subtypes, and showed why they may well have absorbtion features in their spectra. We stressed on the concept of mass dependent WR mass loss rates and outlined the possible relation to the type Ib supernova class. Finally, we presented new evolutionary computations in connection with the progenitor evolution of SN 1987a, and showed that the observational constraint of the blue-red-blue evolution can be recovered by computations using input physics, which — if not standard — was propagated well before the supernova occurred.

Especially the last example demonstrates the strengths and weaknesses of current theoretical stellar models. Certainly, present day stellar evolution theory is yet unable to explain observations like — for example — the irregular and manifold behaviour of LBVs. But if really such a complicated evolution as that of the SN 1987a progenitor can be simulated by completely neglecting e.g. rotation, magnetic fields, and assuming spherical symmetry — which still has to be approved — it means that either stars are simple objects (at least some of them) or our evolution codes are quite good for their designed purpose. On the other hand, the fact that the Blue Supergiant explosion was so surprising shows clearly, that our codes may still be too simple to predict reliably how stars evolve and fade away.

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