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The problem of the blue-to-red supergiant ratio in galaxies

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Abstract. By summarizing the available observations, we investigate and confirm the trend that the number ratio of blue-to-red supergiants appears to be an increasing function of the metallicity. Furthermore, we outline that virtually no assumption on stellar model physics explored so far is able to cope with this trend. We present new stellar models in the mass range $15 - 40\,M_{\odot}$, and find that the Ledoux criterion for convection plus semiconvection yields satisfying results at low Z ($Z = 0.002$), but readily fails at high Z ($Z = 0.02$). We discuss the dependence of the theoretical B/R-ratio, especially as function of the treatment of internal convective mixing, and point out the leakage of appropriate convection models. We conclude that a mixing efficiency in between the Schwarzschild and the Ledoux criterion might be most appropriate to explain the B/R-trend with Z, but argue that rotational mixing may have some contribution as well.

Key words: stars: evolution – stars: supergiants – convection – Magellanic Clouds

1. Introduction

The ratio B/R of the blue to red supergiants is a major characteristics of the luminous star population in galaxies. It is one of the stellar properties observable at large distance in the universe. Also it significantly influences the integrated spectrum of galaxies. The B/R ratio was one of the first stellar properties shown to vary through galaxies (van den Bergh 1968). This early work was followed by several others (Humphreys & Davidson 1979; Meylan & Maeder 1982; Humphreys 1983; Humphreys & McElroy 1984; Freedman 1985; Brunish et al. 1986; Maeder & Conti 1994). The main result is that for a given luminosity range, B/R steeply increases with increasing metallicity Z, by a factor of about 10 between the SMC and inner galactic regions.

Over recent years, the problem of the B/R ratio has been a bit occulted by the question of the blue progenitor of SN 1987A, to which many theoretical investigations have been devoted. However, there remains an essential and unsolved problem with B/R. It is true that most models of massive stars are able to more or less fit one value of B/R for one given specific case, i.e. at high or low metallicity, but never for both. Specifically, most models are unable to correctly reproduce the changes of B/R with metallicity, from solar to SMC value.

The B/R ratio is a very sensitive test. Supergiants are often close to a neutral state between a blue and a red location in the HR diagram (Tuchman & Wheeler 1989, 1990). Thus, even small changes in mass loss, in convection or other mixing processes greatly affect the evolution and the balance between the red and the blue. Paradoxically, the situation seems more uncertain for supergiants than for Wolf-Rayet (WR) stars, because WR stars are largely dominated by the effects of mass loss which erase most effects due to uncertain hydrodynamical processes (cf. Langer 1994).

In Sect. 2, we summarize the observational constraints on the B/R ratio. Section 3 examines the situation of the various existing sets of models with respect to the B/R ratio in galaxies. In Sect. 4, we present the results of new calculations of models with semiconvective diffusion for the case of low metallicity and compare them to the observations. Our results are discussed in Sect. 5, and conclusions are given in Sect. 6.

2. Recall about the observational constraints on B/R

2.1. Results of general surveys

Table 1 summarizes the data on the ratio B/R of blue to red supergiants in the SMC, the LMC, the outer Milky Way (MW) regions, the solar neighborhood (SN) closer than 3 kpc and the inner MW regions according to surveys by Humphreys & Davidson (1979), Humphreys (1983), Humphreys & McElroy (1984). It is important to mention that the "B-stars" in these data include the O, B and A stars and even a fraction of main-sequence stars are counted according to the magnitude limit considered. Here, only stars brighter than $M_{\mathrm{bol}} = -7\overset{m}{.}5$ are considered, which corresponds to masses larger than $15\,M_{\odot}$ for red supergiants. An average metallicity Z is also indicated for these zones as in a similar study of Wolf-Rayet stars (Maeder 1991). These data

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Table 1. The B/ R ratio in galaxies. Unless specified B means O, B and A stars

		SMC	LMC	outer MW	SN	inner MW
Z		.002	.006	.013	.02	.03
Stars,	$M_{\rm bol} < -7^{m}\!.5^{\dagger}$	4	10	14	28	48:
Associations,	$M_{\rm bol} < -7^{m}\!.5^{\dagger}$	4	10	14	30	89:
Clusters,	$M_{\rm V} < -2^{m}\!.5^{\ddagger}$	2.5	6.7	7.7		20
counting only B supergiants						
NGC 330		0.5 ... 0.8				
Young clusters					3.6	

† Humphreys & McElroy (1984)

‡ Meylan & Maeder (1982)

clearly show an increase of B/R by a factor of ten over the range of increasing metallicities considered.

A study limited to a sample of the best studied young clusters in these various areas, in order to avoid problems related to the possible incompleteness of the data, confirms the growing frequency of red supergiants at lower Z as in the SMC (cf. Meylan & Maeder 1982). Table 1 also shows the results for stars brighter than a magnitude limit $M_{\rm V} = -2^{m}\!.5$ in clusters. Different cutoffs of course lead to different values of the B/R ratio, because different numbers of main sequence stars are counted in each case. But, the same kind of gradient, with a range of about a factor of 10 over the range of Z considered, is present for different choice of the limits. These various studies also suggest that there is an excess of B and A supergiants, as if the main sequence band were more extended than given by theoretical predictions.

2.2. *Recent results from cluster analyses*

More recent studies of young SMC and LMC clusters well confirm the high number of red supergiants at low Z. A photometric and spectroscopic study of NGC 330 in the SMC by Carney et al. (1985) confirms the high number of red supergiants. It gives a B/R ratio of 9/15, when B represents only blue supergiants. The age of this cluster is about 12 million years. A CCD study of the same cluster by Cayrel et al.(1988) shows the same kind of result with a B/R ratio which can be estimated to be 7/13. CCD photometry with uvby colors was performed by Grebel & Richtler (1992), these authors find a B/R ratio equal to 12/15 for NGC 330, also counting in B only the blue supergiants. Similarly, Brocato & Castellani (1993) give a ratio equal to 9/15. The overall result is that, when strictly B and red supergiants are counted, a result for B/R of about 60% is found in this young SMC cluster. Let us note that the very young SMC cluster NGC 346 shows 5 red and 2 B supergiants along the track of a 15 $M_{\odot}$ star, however sequential star formation took place in this cluster and makes comparison difficult (Massey et al. 1989).

In the LMC, the young cluster NGC 2004 has been very much observed (Bencivenni et al. 1991; Sagar et al. 1991). It shows 11 red supergiants, but the presence of blue supergiants is more controversial. Bencivenni et al. say there is none, while their color-magnitude suggests one or two. Other young LMC clusters (Sagar et al. 1991) show many stars with a location in the HR diagram corresponding to that of blue supergiants, this in agreement with the overall results by Humphreys & McElroy (1984).

We have also searched in the data basis of Mermilliod (1994) for galactic clusters, the young clusters in the solar neighborhood with log age between 7.0 and 7.1. These are NGC 3293, 3766, 4755, 5606, 6193, 6871 and IC 2944. Estimating the number ratio of blue to red supergiants (strictly speaking), we find a ratio B/R = 3.6, while it is 0.60 in the SMC.

The chemical abundances in main sequence stars and supergiants have been reviewed by Maeder & Conti (1994). For supergiants, it appears that most galactic O, B and A supergiants show N and He enhancements (cf. Herrero et al. 1992; Gies & Lambert 1992; Venn 1993). This supports an early suggestion of Walborn (1976, 1988) that ordinary supergiants are enriched in N and depleted in C as a result of CNO processing. There are however exceptions, the so called OBC stars as well as B-supergiants (Dufton & Lennon 1989) showing normal N and C. The B supergiants in the Magellanic Clouds also generally show N and He enhancements (Reitermann et al. 1990; Kudritzki et al. 1991; Lennon et al. 1991), but some F and K supergiants surprisingly show normal CNO ratios (Spite et al. 1991; Barbuy et al. 1991). Thus, the correct models have also to account for the observed He and N enrichments.

3. The existing models and the B/R ratio

The necessity of accounting for the observed B/R ratios in galaxies of various metallicities Z is a very constraining requirement. It means that a correct sharing of the He-burning phase between the blue and the red part of the HR diagram has to be realized at all possible Z. The most difficult point to explain is generally the presence of red supergiants in the SMC. Let us examine several of the recent sets of models with respect to this constraint.

Models with Schwarzschild's criterion: Such models without overshooting and semiconvection were computed with and without mass loss for 4 values of Z by Brunish & Truran (1982ab). Brunish et al. (1986) show that an acceptable agreement is realized with the observed B/R in the solar neighborhood. However, we notice that these models predict an increasing B/R ratio with decreasing Z in contradiction with the observed trend. Independently of the exact slope of B/R ratio with Z, a severe problem of these models is that they predict no or very few red supergiants for the SMC. These difficulties are confirmed by more recent models with Schwarzschild's criterion by Stothers & Chin (1992), who show that Ledoux criterion is better supported by SMC data.

Models with Schwarzschild's criterion and overshooting: As shown by Maeder & Meynet (1989), by Chin & Stothers (1991) and by Stothers & Chin (1991b), the overshooting from cores cannot be too large, otherwise the models meet severe difficulties in the comparison with observations. This clearly excludes models with large overshooting, in particular the blue loops tend to disappear. Let us examine the Geneva models at various Z and with a moderate overshooting from convective cores (Schaller et al. 1992; Charbonnel et al. 1993; Schaerer et al. 1993ab; Meynet et al. 1994). The last paper shows the same models of massive stars at different Z, but with increased mass loss rates. According to Meynet (1992), the number of blue to red giants and supergiants is quite correctly predicted for clusters in the solar neighborhood. Simultaneously, a very good fit of the sequences in the HR diagram for galactic clusters of all ages was achieved by these models (Meynet et al. 1993). Thus, the situation is rather satisfactory at solar Z.

However, at $Z = 0.004$, or smaller, the models with current mass loss rates do not predict red supergiants for $M > 12\,M_{\odot}$, while as shown above many are observed. Changes of the mass loss rates may considerably modify the B/R ratio (Maeder 1981). As shown by Meynet (1992), it is possible to account for the observed red supergiants in the SMC by increasing the mass loss rates by about a factor of 2.2. Nevertheless, it seems difficult to get the correct gradient of B/R with Z, if one adopts the relation between mass loss rates and Z predicted by stellar wind models (cf. Kudritzki et al. 1987).

Models with core overshooting have also been made by Fagotto et al. (1994) at $Z = 0.004$, by Alongi et al. (1993) at $Z = 0.008$ and by Bressan et al. (1993) at $Z = 0.020$. They include the same amount of core overshooting as mentioned above and also some overshooting below the convective envelope. This last effect is uncertain, because the choice of the overshooting parameter $l/H_{\rm p}$ in the envelope from fitting on the observed $T_{\rm eff}$ of red giants already determines the depth of the convective zone. As shown by Chin & Stothers (1991) (see also Stothers & Chin, 1991a) and by Alongi et al. (1993), the overshooting below the envelope favors the blue loops. At $Z = 0.02$, the 20 $M_{\odot}$ model by Bressan et al. (1993) spends the whole core He-burning phase as a red supergiant star. As stated by these authors, these new models at $Z = 0.020$ are less able (compared to models with old opacities) to explain the observations of supergiants in the Milky Way and LMC, even considering for this latter a lower metallicity. These authors suggest an increase of the opacities (cf. Bertelli et al. 1984). Interestingly enough, new models at $Z = 0.004$ by Fagotto et al. (1994) predict both blue and red supergiants. Thus, the agreement seems better at low than at high Z for this set of models. Finally we note that the above mentioned models by Chin & Stothers (1991) at $Z = 0.021$, with overshooting, also produce only red supergiants.

Models with the Ledoux criterion: Models with Ledoux criterion by Brocato & Castellani (1993) are interesting in the sense that they predict at $Z = 0.003$ both blue and red supergiants, with a B/R ratio of 3 at 16 $M_{\odot}$ and of about 1 at 20 $M_{\odot}$. This is a satisfactory feature in view of the cluster NGC 330 in the SMC, even if the predicted ratio is not exactly the observed one.

There is nevertheless a problem with these models in the sense that for Z larger than 0.006, there are mostly or only red supergiants predicted. This is in contradiction with the observations by Humphreys & McElroy (1984) of LMC and Milky Way, and also with the observations of clusters in the Milky Way and LMC. Thus, the models predict a trend of B/R with Z opposite to the observed one.

Models with Ledoux criterion by Stothers & Chin (1992) show the same as those by Brocato & Castellani (1993), in particular they give a good fit for B/R in NGC 330. However, we notice that for the 15 $M_{\odot}$ model the ratio B/R is larger at $Z = 0.002$ than at $Z = 0.004$, which over that small range is opposite to the observed trend. The existence of this difficulty is confirmed by the models at $Z = 0.02$ with Ledoux criterion (Chin & Stothers 1990), which predict that all the He- burning phase is spent in the red supergiant stage. Another problem is that when mass loss is included there are no blue supergiants predicted at 15 $M_{\odot}$ for $Z = 0.004$, in contradiction with the observations.

Models with semiconvection: Models with semiconvection by Arnett (1991) at $Z = 0.007$ are shown to be able to relatively well fit the distribution of supergiants in the LMC by Fitzpatrick & Garmany (1990), taking also into account the red supergiants by Rebeirot et al.(1983). However, at lower Z values of 0.005 and 0.002, such models predict a rapidly growing ratio B/R in contradiction with the observations. Specifically, these models only predict blue supergiants at low Z, and a dominance of red supergiants at $Z = 0.01$ or higher. This trend is just opposite to the observed one.

Summary of the comparisons: There is no set of models correctly predicting the observed trend of decreasing B/R with decreasing Z. They all do the opposite. In general, the models with Schwarzschild's criterion (with or without overshooting) can reproduce the B/R ratio at solar composition, but they fail to do it at lower Z. At the opposite, models with Ledoux criterion and models with semiconvection correctly reproduce B/R at the metallicities of the SMC or LMC, but they fail at higher Z.

In other words, the restricted scheme for convection (Ledoux) looks better at low Z, while the extensive convection with overshooting is better at solar Z. (We notice that the pres-

Table 2. Characteristic quantities of the computed sequences

#	M_{ZAMS} $M_{\odot}$	α_{sc}	α_{over}	M_{f} $M_{\odot}$	τ_{H} 10^6 yr	τ_{He} 10^6 yr	$\mathrm{B/R}^{\dagger}$
1	15	0.04	0.	14.8	11.1	0.97	2.48
2	20	0.04	0.	19.1	7.9	0.60	0.05
3	25	0.04	0.	23.4	6.3	0.42	0.27
4	40	0.04	0.	36.8	4.3	0.32	0.52
5	20	∞	0.25	19.4	9.1	0.89	4.70
6	20	0.04	0.25	–	9.1	–	–
7	20	0.04	0.50	–	10.1	–	–
8*)	15	0.04	0.	13.6	10.2	1.12	0.02
9*)	$15^{1)}$	0.04	0.	13.9	10.2	1.12	0.54
10*)	$15^{2)}$	0.04	0.	14.8	10.2	1.13	0.30

† includes C-burning evolution
*) $Z = 0.02$
1) mixing length parameter $\alpha = 2.0$
2) no post main sequence mass loss

ence of envelope overshooting, in addition to core overshooting, may lead to better results at low than at high Z). These various results are undoubtedly the sign of something inadequate or missing in the present treatment of mixing in massive stars.

4. New models with semiconvective diffusion

4.1. Model assumptions and results

In focussing on the impact of the treatment of convection in the presence of molecular weight gradients on the B/R-ratio — an effect which persists at very small metallicity, in contrast to mass loss or opacity effects — we thought it worthwhile to somewhat explore the case of (semiconvective) mixing at a rate intermediate between the Schwarzschild and the Ledoux case. In earlier papers (Langer et al. 1989, Langer 1991) it has been shown that a semiconvective mixing speed described by a parameter α_{sc} can be found which yields massive star models at $Z = 0.005$ which produce quite well the B/R-ratio observed in the LMC. Since the largest problem with matching observed B/R-ratios occurs usually at small metallicity, we investigate in the following the properties of stellar models adopting the same semiconvective mixing speed as in Langer (1991) but at $Z = 0.002$.

We have computed model sequences with initial masses of 15, 20, 25, and 40 $M_{\odot}$, including mass loss according to Nieuwenhuijzen & de Jager (1990), but multiplied by $(Z/Z_{\odot})^{0.65} = 0.224$ in order to account for the metallicity dependence of the stellar winds (Kudritzki et al. 1987; Leitherer & Langer 1991). The nuclear burning has been followed in detail using nuclear reaction networks. We have utilized the OPAL opacities of Iglesias et al. (1992). Convective/semiconvective mixing has been performed as in Langer (1991). In particular, semiconvective mixing is computed by solving a diffusion equation, with a diffusion coefficient being proportional to a parameter α_{sc}, where $\alpha_{\mathrm{sc}} = 0$ is equivalent to adopting the Ledoux criterion for convection, $\alpha_{\mathrm{sc}} \gg 1$ to adopting the Schwarzschild criterion. In accordance with earlier work we used $\alpha_{\mathrm{sc}} = 0.04$ in the present paper. In general, we have computed the models from the ZAMS to core carbon exhaustion. A mixing length parameter of $\alpha = 1.5$ has been used.

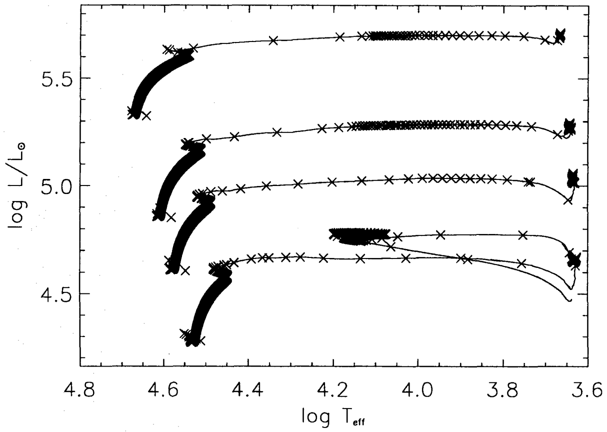

Fig. 1. Evolutionary tracks in the HR diagram of stars with initial masses of 15, 20, 25, and 40 $M_{\odot}$ and $Z = 0.002$, computed with semiconvection (cf. sequence # 1-4 in Table 2). The distance in time between two successive crosses on the tracks is 5000 yr

Figure 1 shows the resulting tracks in the HR diagram, while the upper part of Table 2 gives some additional informations. We find that in general the considered models spend a significant time of their post main sequence evolution in the hot part of the HR diagram, but also a significant time as RSGs at the Hayashi line. Table 2 lists the ratio B/R of the core helium burning time spent at effective temperatures above 10 000 K to the time spent at cooler temperatures. Note that the 15 $M_{\odot}$ sequence spends a long time as a RSG before its extended BSG phase, with the consequence of a weak dredge–up of helium and nitrogen (the surface helium mass fraction rises from 0.244 to 0.246, that of nitrogen from $1.03\,10^{-4}$ to $2.76\,10^{-4}$, while ^{12}C is depleted from $3.48\,10^{-4}$ to $2.12\,10^{-4}$ and ^{16}O being almost unaltered). For the higher masses, the BSG stage occurs prior to the RSG stage, i.e. the surface abundances in the BSG stage are unaltered. The time evolution of the surface temperature of the four sequences during core helium burning is displayed in Fig. 2.

In order to demonstrate the influence of convection, we have computed a 20 $M_{\odot}$ sequence with the Schwarzschild criterion and a moderate convective core overshooting of 0.25 pressure scale heights (sequence # 5 in Table 2), i.e. very similar to the parameters in the calculations of Schaller et al. (1992). The resulting track, which is compared with the 20 $M_{\odot}$ track obtained with semiconvection (# 2) in Fig. 3, is in fact very similar to the results at 20 $M_{\odot}$ of Schaller et al. (for $Z = 0.001$) and of Charbonnel et al. (1993; $Z = 0.004$); namely, the Hayashi line is only reached at the very end of core helium burning, and very few red supergiants are predicted. Note that this result shows

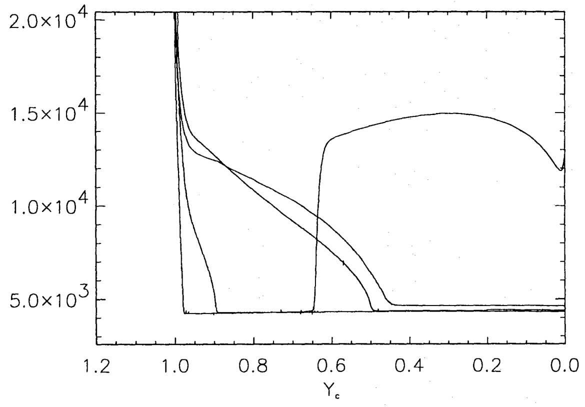

Fig. 2. Effective temperature as function of the central helium mass fraction Y_c for the tracks shown in Fig. 1 (seq. # 1-4)

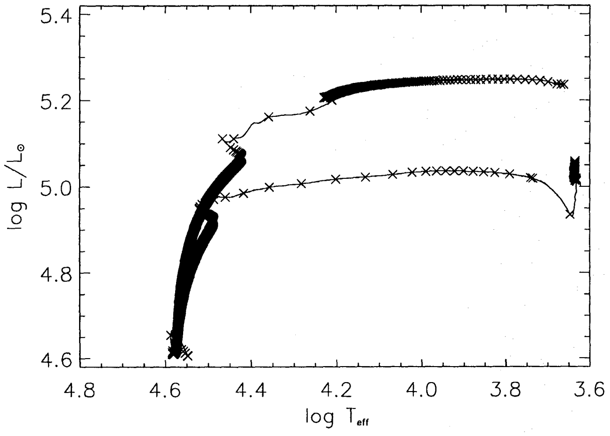

Fig. 3. Evolutionary tracks in the HR diagram for two 20 $M_\odot$ stars. The lower track is computed with semiconvection (cf. Fig. 1, and seq. # 2 in Table 2), the upper track with the Schwarzschild criterion for convection and with convective core overshooting (seq. # 5). The distance in time between two successive crosses on the tracks is 5000 yr

also the consistency of the presently used computer code and the Geneva stellar evolution program.

Thus, we note that semiconvection induces, like mass loss, a tendency of the models to reach the RSG stage well before core helium exhaustion and would predict a considerable number of RSGs for a low Z galaxy as the SMC, in contrast to models which adopt the Schwarzschild criterion and moderate core overshooting. In order to investigate whether semiconvection can also drive the models early to the Hayashi line when some convective core overshooting is assumed, we computed two further 20 $M_\odot$ sequences with semiconvection (α_{sc} = 0.04) and with convective core overshooting during core hydrogen burning, namely with α_{over} = 0.25 and α_{over} = 0.50 (sequences 6 and 7 in Table 2).

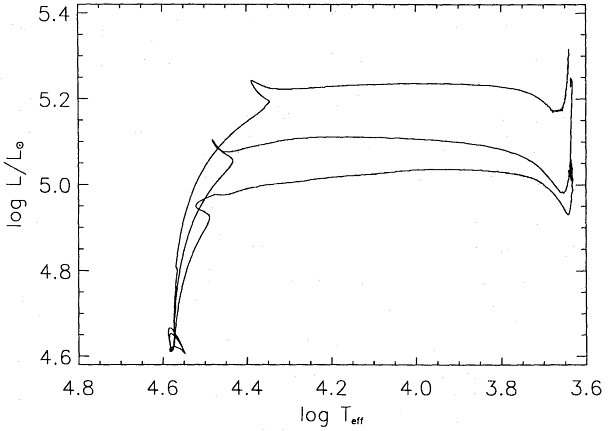

Fig. 4. Evolutionary tracks in the HR diagram for three 20 $M_\odot$ stars computed with semiconvection and with different assumptions on convective core overshooting. This was neglected in the lowest track (seq. # 2), while the middle and upper tracks include an overshooting of 0.25 and 0.5 pressure scale heights, respectively (seq. # 6 and 7). The two tracks with overshooting are computed only up to early core helium burning stages

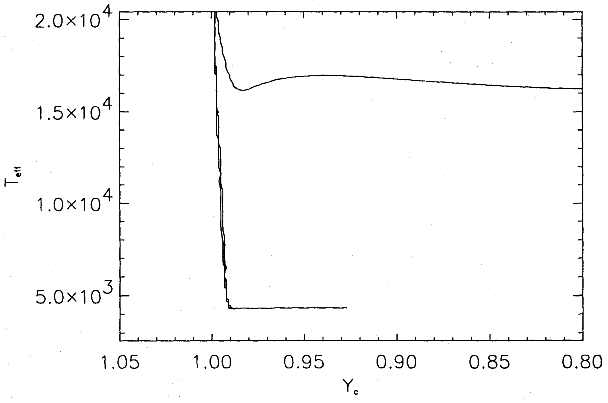

Fig. 5. Same as Fig. 2 but for the sequences# 5, 6 and 7. The lines for sequences 6 and 7, which extend to the lower temperatures, are almost identical

As the applied concept of semiconvection accounts for the influence of molecular weight barriers on (superadiabatic) convection, it would be a misconcept not to consider their effect on convective overshooting in sequences 6 and 7. However, a theoretical description of this effect is not available (cf. Langer 1991). Note that during core hydrogen burning, such situations are not encountered, but since the convective core during central helium burning tends to grow the problem is met in this evolutionary phase. Therefore, we stopped the calculations of sequences 6 and 7 during early core helium burning.

Figure 4 compares the evolutionary tracks of sequences 6 and 7 with that of sequence 2. It shows that, independent of the assumption on convective core overshooting, all 20 $M_\odot$ models with semiconvection tend to move to the Hayashi line early during core helium burning. Apparently, convective overshooting even accelerates this trend. Thus, the effects of semiconvection and overshooting to move the star to the Hayashi line add up and act together rather than compensating each other.

We may also wonder about the differences between models having the same overshooting, but different convection criteria (sequence # 5 and 6). The comparison shows that the main sequence phase of both sequences are practically identical, but large differences occur during shell hydrogen burning. The effect of semiconvection on the extent of the convective shell which forms above the helium core during H-shell burning is responsible for the largely different post-main sequence behavior. In Fig. 5 it can be seen that the sequence # 6 turns to the Hayashi line immediately after core hydrogen exhaustion (the same for sequence # 7), while the sequence with the Schwarzschild criterion keeps a hot surface temperature.

Finally, in order to investigate the effect of semiconvection at higher metallicity, we have computed some 15 $M_\odot$ models at Z = 0.02. Sequence # 8 (cf. Table 2) has been computed with an input physics identical to that of sequence # 1. Due to the adopted metallicity dependent mass loss rates, its total lost mass is no longer negligible. This sequence turned to the Hayashi line immediately after core hydrogen exhaustion and remained there during the whole later evolution (cf. Fig. 6). However, at high metallicity, the evolution of massive stars depends more strongly on several input physics parameters than at low metallicity, which makes the problem more complex. To demonstrate this, we have computed two further 15 $M_\odot$ sequences at Z = 0.02 with identical input physics, except that in one case we used a mixing length parameter of 2.0 instead of 1.5 (sequence # 9), and in the second case we omitted post main sequence mass loss (sequence # 10; cf. final masses in Table 2). In both cases, a blue loop developed during core helium burning (cf. Fig. 6).

Note that for initial masses higher than 15 $M_\odot$, the influence of variations in the (uncertain) mass loss rates is expected to be even larger since the relative amounts of mass lost increase with increasing mass.

4.2. Comparison with observations

The models at low metallicity (Z = 0.002) computed with semiconvection (sequences # 1-4) are certainly in qualitative agreement with the observed supergiant distribution in the SMC, in the sense that they account for a sizeable population of blue and red supergiants at the same time (cf. Fig. 1). A more detailed comparison, e.g. with individual clusters, appears not very useful at the present time, due to uncertainties in the observations (cf. Sect. 2) and due to the sensitivity of the model results on the various input parameters as demonstrated above.

At Z = 0.02, the basic model with semiconvection at 15 $M_\odot$(sequence # 8 in Table 2) predicts no blue supergiants, while the observations show many of them. Thus, we find here a situation rather similar to that found for models with Ledoux' criterion (cf. Sect. 3): agreement at low Z and disagreement at high Z, while for models with Schwarzschild's criterion it is the opposite. As shown by Fig. 6, the disagreement can be reduced by changes of the mixing length in the convective envelope or by changes of the mass loss. This illustrates the fact that various uncertainties in basic parameters also intervene in the problem.

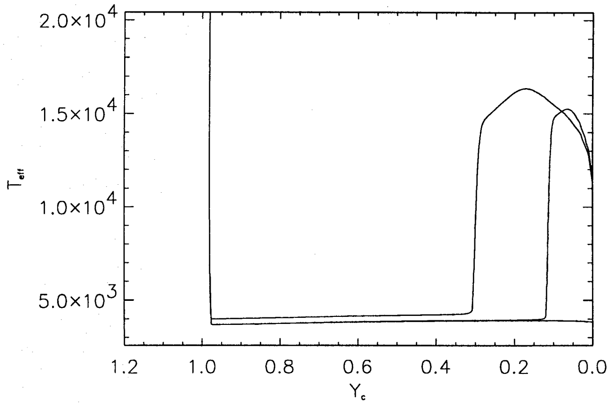

Fig. 6. Same as Fig. 2 but for three 15 $M_\odot$ stars of Z = 0.02 computed with semiconvection (seq. # 8 - 10; cf. Table 2). Sequence #8 remains at the RSG branch during the whole core helium burning phase, while sequences # 9 and 10 perform blue loops at $Y_c \simeq$ 0.30 and 0.12, respectively

5. Discussion

In the previous sections, we have investigated the performance of present day massive star models with respect to the predicted B/R-ratio as function of the metallicity Z. We have seen that presently there is no set of models — and thus no prescription of the interior physics — able to accurately account for the observed dependence of the B/R-ratio on Z. It is one of the main purposes of the present paper to point out this deficiency of the present massive star models.

In view of the discussion in Sect. 3 and the results presented in Sect. 4, one may wonder how the current models should be improved. The models with the Ledoux criterion and semiconvective mixing are basically o.k. at low Z, but they produce too many red supergiants at high Z. As outlined in Sect. 4.1, at high Z the models depend on more parameters than at low Z; i.e., in addition to the treatment of convection (which affects the models at any Z) the results are sensitive to mass loss rates and changes in the opacities. Thus, there may still be the possibility that the convective treatment in the models with the Ledoux criterion plus semiconvection is basically correct and that the high Z models can be cured by changing other parameters. However, though this possibility would have the advantage of not altering the agreement of the tracks presented in Fig. 1 with the observations, it may appear more likely that some contribution of convective overshooting in either core or envelope convection zones is required and/or that the semiconvective efficiency parameter needs to be changed.

For the models with the Schwarzschild criterion, on the other side, which — with some overshooting — work well at high Z (cf. Sect. 3), it appears more likely that the convective treatment should be revised. Here, the low Z models need to be cured, and at low Z the treatment of internal mixing appears to be the most effective thing to change the model behavior, since e.g. mass loss rates or opacity uncertainties are rather negligible. Certainly, as has been demonstrated in Sect. 4.1 through sequences # 6 and 7, the consideration of molecular weight barriers in the computation of the extent of convection zones would help to increase the predicted red supergiant population at low Z.

In total, also since the required physics to cure both types of models should converge to the same assumptions, the truth may be somewhere in between the Schwarzschild and the Ledoux criterion, and in between the neglect and incorporation of convective overshooting. However, in view of the many parameters which are still uncertain in stellar modelisation, it appears very complex to find out the right parameter combination by scanning the huge parameter space. It may be worthwhile instead to focus on the development of convection theories which are able to predict the efficiency of convective overshooting and — possibly more important — to model the effect of molecular weight barriers on convection and convective overshooting.

However, let us note that even with such a theory at hand it could not be guaranteed that this would be the end of the B/R-problem. The reason is that there are numerous hints from observations and from theory, that rotation can induce some non-negligible amount of internal mixing (cf. Maeder 1987; Langer 1992; Denissenkov 1994) and thus considerably change the stellar evolution tracks. To determine the order of magnitude of this effect for the evolution of stars of various masses and for the overall distribution of massive stars in the HR diagram is certainly one of the most exciting problems presently persisting in the theory of massive star evolution. The need of accounting for sizeable He- and N-enhancements in a large fraction of B-supergiants gives further support to this possibility.

Finally, note that if one attempts to relate the failure of the models to deficits in the treatment of the internal convection zones (concerning, e.g., the choice of the convection criterion, semiconvection, convective overshooting), it is immediately clear that also the nucleosynthesis predictions of the models are uncertain. However, as shown by Weaver & Woosley (1993), the heavy element yields of massive stars may change only by a factor of 2 as a result of changing from the Schwarzschild to the Ledoux criterion, with rather constant relative ratios for most isotopes (^{18}O being a noticeable exception). Therefore, we note that even if massive star models presently have problems to qualitatively account for the observed B/R-ratios, this does not imply that their further predictions (e.g. lifetimes, nucleosynthetic yields, etc.) are not qualitatively correct, but rather that the B/R-ratio is an extremely sensitive quantity.

6. Conclusions

We have outlined above that observations clearly indicate that the B/R-ratio is an increasing function of the metallicity. Though data on individual objects may not be conclusive, the general trend can be inferred by the comparison of data derived in a defined way at different metallicities.

We have shown furthermore, that basically all present day massive star models have problems in reproducing the observed trend. We have discussed in some detail the effect of the probably most relevant ingredient in stellar models in this respect, namely the treatment of convection. We conclude that models with the Schwarzschild criterion, which fail at low Z, might have to incorporate to some extent the effects of molecular weight gradients on convection. However, models with the Ledoux criterion fail at high Z. Thus, some intermediate solution, possibly with some amount of overshooting, may be most appropriate.

However, we point out that currently no theoretical model for the simultaneous treatment of overshooting and semiconvection (i.e. molecular weight barriers) exists in a form which is readily applicable for stellar evolution calculations. Finally, we note that also rotationally induced mixing may contribute to the B/R-problem, to an extent which is yet unknown.

We have to conclude that massive star models in the considered mass range still lack some significant physical ingredient. However, we want to emphasize that this does not imply that the results of massive star theory have to be questioned altogether. The B/R-ratio is a quantity which is known to depend extremely sensitive on the model parameters. It is thus a welcome amplifier which can (and finally will) be very useful to constrain the model physics very accurately. Most other results of massive star calculations depend far less on the uncertain assumptions and can thus be used with much more confidence.

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