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Massive single star evolution: a comparison with observations
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MASSIVE SINGLE STAR EVOLUTION: A COMPARISON WITH OBSERVATIONS

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Abstract. We firstly examine the critical model assumptions for massive stars, in particular regarding mixing, mass loss and metallicity. The comparisons of models and observations for main sequence stars reveal some interesting problems, such as the lack of O-stars close to the zero-age sequence, the so-called helium and mass discrepancies. We emphasize that this last discrepancy was probably due to the unstable atmosphere modelling used by spectroscopists. The comparisons for supergiants enlighten a number of most interesting problems: the He and CNO abundances in blue supergiants, the distribution of supergiants in the HR diagram and above all the variations of the blue to red number ratios with metallicity. Then, we examine the properties and chemistry of WR stars and the observations and interpretations concerning the great changes of WR numbers in galaxies of different metallicities. Finally, we emphasize the main WR filiations.

Key words: Stars: evolution of - supergiant - Wolf-Rayet - Galaxies: stellar content of

1. Introduction

Massive stars are at the crossroads of many most important astrophysical problems. Due to their high luminosities, massive stars are visible at large distances in the Galaxy and also in the Universe thanks to their distinct features in the integrated spectrum of galaxies. They offer thus a powerful tool for studying stellar populations and star formation in highly redshifted galaxies. Also, they are essential for our understanding of nucleosynthesis and of the precursors of supernovae.

In this review, we examine, in full agreement with the title of this meeting, the most critical model assumptions and the way the models compare with the observations. This leads us to notice the many points of agreement, but also to enlighten the points of disagreement which need further development and represent the germs of future progresses in our understanding of massive star evolution.

2. Short Review of Some Critical Model Assumptions for Massive Stars

Some basic physical model ingredients, like opacities and nuclear reactions rates, still show some embarrassing uncertainties. Particularly, the molecular opacities for red supergiants are insufficient, and the uncertainties on some nuclear rates such as $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ remain rather large. The mass loss rates

are of overwhelming importance in massive star evolution, since all model outputs are heavily influenced by mass loss. The rates generally used are those by de Jager et al. (1988); they are probably not too uncertain close to the main sequence, but for the supergiants of all colours the uncertainties can be quite large, in particular for the red supergiants.

The treatment of convection and mixing in stellar interiors is still a major problem for massive stars, more especially as supergiants are often so close to a neutral state between a blue and a red location, that any changes in the inner structure of the models may have produced a shift from blue to red and vice versa. We may identify the following different assumptions regarding convection and mixing in massive star models:

- Schwarzschild's criterion
- Schwarzschild's criterion and core overshooting
- Overshooting below the convective envelope
- Ledoux criterion
- Semiconvection or semiconvective diffusion
- Turbulent diffusion or other forms of rotational mixing

All these kinds of models are claimed by their authors to well fit the observations and the debate has been very vivid over recent years (Chiosi and Maeder 1986; Maeder and Meynet 1989; Brocato et al. 1990; Stothers 1991ab; Stothers and Chin 1990, 1991, 1992ab). There is at present no definite theoretical or observational proof in favour of any model. However a few useful indications on the limits and possibilities of the various models must be mentioned.

Overshooting has been very much discussed in recent years and many claims have been made in favour of a large overshooting from convective cores with respect to what is predicted by Schwarzschild's criterion. However it seems now clear that the overshooting distance is limited to about (0.2-0.4) H_p , where H_p is the pressure scale height (Maeder and Meynet 1989; Stothers and Chin 1991; Napiwotzki et al. 1993; Meynet et al. 1993b). Some recent comparisons with observations favour Ledoux' rather than Schwarzschild's criterion for convection (Stothers and Chin 1992ab). The result may depend on the adopted mass loss rates, also recent theoretical works (Grossman et al. 1993) show that Ledoux' criterion has no bearing at all in a stratified stellar medium. Thus, both at the theoretical and observational levels, the situation still remains uncertain about convective criteria.

It is not always so clear whether the various authors speaking about semiconvection consider exactly the same physical process. Semiconvection occurs in zones which are convectively unstable according to Schwarzschild's criterion, but would not be so according to Ledoux'. Semiconvection may produce some mixing in zones with a gradient of the mean molecular weight. Various treatments of the problem have been made (Chiosi and Maeder 1986; Langer et al. 1989; Arnett 1991; Chiosi et al. 1992). Langer et al.

(1985) propose a diffusion treatment which is equivalent to Schwarzschild's criterion when the mixing timescale is short compared to the evolutionary timescale and to Ledoux' criterion in the opposite case. These models have a great interest regarding the discussion about the blue progenitor of SN 1987 A (Langer 1991ac) as well as about the evolutionary status of blue supergiants.

Rotational mixing may have large consequences for massive star evolution. The basic reason is that the radiative viscosity is so large that dissipative processes (which are related to radiative viscosity) may have a timescale comparable to the evolutionary timescales of massive stars (Maeder 1987b). Mixing can produce homogeneous or nearly homogeneous evolution on the main sequence and thus directly lead to the formation of WR stars. As emphasized by Langer (1993), rotational mixing may also solve several problems: the existence of the WN+WC stars (Langer 1991b), the origin of N enhancement in OB supergiants and the alleged mass discrepancy for OB main sequence stars, and the blue progenitor of SN 1987 A. Interestingly enough, the claims in favour of semiconvection mean less mixing in convective zones with varying mean molecular weight, while the claims in favour of turbulent mixing mean more mixing in radiative zones. Whether both these claims are true is a major question. In this context, one must notice that both semiconvection and rotational mixing depend mainly on the radiative diffusivity. Thus, rather than advocating two different processes, one for explaining SN 1987 A and another one for the properties of OB stars, it seems advisable to examine whether a single physical process can account for the various constraints. It is likely that in future, rotation will be an unavoidable property in star models. The same is probably true for binarity, which can induce tidal mixing and mass transfer.

How does massive star evolution depend on metallicity Z is a major question. Indeed, Z can enter evolution through four possible doors. 1) The nuclear production: metallicity may influence the nuclear rates, a good example is the CNO cycle. In general, a very slight contraction or expansion to a new equilibrium state may strongly compensate the changed rate. 2) Opacity effects: in the interiors of massive stars, electron scattering is the main opacity source, which is independent on metallicity. Thus, contrarily to the case of low and intermediate mass stars, metallicity through opacity has no great direct effect on the inner structure of massive stars. 3) Stellar winds: only in the very external layers, metallicity Z may strongly influence the opacity and thus the atmospheres and winds. Wind models for O-stars by Abbott (1982) suggested a Z -dependence of the mass loss rates $\dot{M}$ of the form $\dot{M} \sim Z^\alpha$, with $\alpha = 1.0$. Models by Kudritzki et al. (1987) and by Leitherer and Langer (1991) gave a value α between 0.5 and 0.7. It is likely that this is the main effect by which metallicity may influence massive star evolution (Maeder, 1991). For yellow and red supergiants, there is however no model

giving reliable enough mass loss rates and $\dot{M}$ vs. Z relation. This is a major uncertainty in post-MS evolution. 4) There is a ratio $\Delta Y/\Delta Z$ between the relative enrichments in helium and heavy elements of the order of 5 as established from low Z HII regions (Pagel et al. 1992). Thus, changes in Z imply large changes in Y , which have a direct effect on the models.

Binary mass transfer by Roche lobe overflow (RLOF), which is an extreme case of tidal interaction, drastically modifies the course of stellar evolution. It may thus significantly influence the comparison between observations and models (Vanbeveren 1991; Vanbeveren and de Loore 1993; see also Vanbeveren in this meeting). Estimating the exact importance of that effect is of major importance for most comparisons between models and observations. The fraction of all stars (single and binaries) undergoing RLOF is estimated to be 20 to 40% (Podlaskowski et al. 1992). In section 6 below, we also discuss the value of this fraction. We may remark that this percentage does not account for the fact that some close binaries could be mixed by tidal interactions and would thus evolve homogeneously, without large increase of their radius and thus without RLOF. Indeed, the true importance of RLOF in many problems is still uncertain and complete simulations of star populations with binaries remain to be done.

3. Comparisons between Models and Observations on the Main Sequence

Several grids of models taking into account some of these effects have been made over recent years (Brunish and Truran 1982ab; Maeder 1990; Schaller et al. 1992; Alongi et al. 1993; Schaerer et al. 1993; Charbonnel et al. 1993; Meynet et al. 1993a; de Loore et Vanbeveren 1993). A general comparison of cluster sequences and evolutionary tracks has been made (Meynet et al. 1993b), which shows a very good general agreement. However, in the case of massive stars some specific problems are known to exist.

There is an apparent lack of O-stars close to the zero-age sequence (Garmany et al. 1982). The point is also quite clear from recent gravity and T_{eff} determinations by Herrero et al. (1992). Chiosi et al. (1992) suggest that this is due to the fact that about 20% of the O-stars are still embedded in molecular clouds. Alternatively there may be no true ZAMS for O-stars, because nuclear reactions ignite early during the contraction phase (Appenzeller 1980) and may thus make stars inhomogeneous before the end of the contraction phase. Also for massive stars, the accretion timescale of the protostellar cloud is longer than the Kelvin-Helmoltz timescale. The consequence is that no pre-MS star should be visible (Palla et al. 1993), a fact which could contribute to hidden stars close to the ZAMS.

Another possible problem is the so-called mass discrepancy for O-stars. Spectroscopic masses derived from gravity and terminal velocity determi-

nations were claimed to be smaller than those predicted by stellar models (Herrero et al. 1992 and ref. therein; Kudritzki et al. 1992). In other words, spectroscopy suggests that O-stars are overluminous for their masses and the discrepancy amounts to about 50%. An interpretation by Langer (1993) is that the overluminosity of O-stars is the sign of some rotational or tidal mixing enlarging the helium core. The reality of the mass discrepancy has been questioned recently by Lamers and Leitherer (1993). They show that there exist large discrepancies between theoretical and observed mass loss rates, the same being true for the terminal velocities; they also show that the discrepancies cannot be solved by adopting smaller masses for O-stars. According to Schaerer and Schmutz (1993), the use of plane-parallel models for O-stars may lead to significant errors for spectroscopic gravities, masses and He abundances. It is likely that the claims about the mass discrepancy are due to previous unsafe modelling of stellar atmospheres or to mixing in the interiors. A recent study by Pauldrach (this meeting) tends to support this view.

The surface abundances in He and CNO elements offer a powerful test of stellar evolution. Evidences of CN processing are provided by He and N enhancements together with C depletion, while O-depletion only occurs for advanced stages of processing. The abundances may cover the range from solar values ($C/N = 4$, $O/N = 10$) to CNO equilibrium values in the extreme case which is reached in WN stars ($C/N = 0.02$, $O/N = 0.1$; Maeder 1983, 1987a). Models with mass loss but no extra-mixing predict He and N-enrichment in MS stars only for initial masses larger than about 50 $M_{\odot}$ depending on the mass loss rates. Models with rotational mixing may lead to an early appearance of the products of the CNO cycle (cf. Maeder 1987b). The observations of 25 OB stars by Herrero et al. (1992) show that most MS stars have normal abundances. Fast rotators are an exception and they present He and N enhancements. Among exceptions, the group of ON stars, i.e. O-stars with N-enrichments (Walborn 1976, 1988) contains at least 50% of short-period binaries (Bolton and Rogers 1978). An analysis of the association Per OB1 suggests (Maeder 1987b) that there is a bifurcation in stellar evolution: while most stars follow the tracks of inhomogeneous evolution, a fraction of about 15%, mainly composed of fast rotators and binaries, may evolve homogeneously and become ON blue stragglers. Herrero et al. (1992) spoke about an He discrepancy in connexion with the alleged mass discrepancy of O-stars. Clearly there is not so much of an He discrepancy on the main sequence, except for the case of fast rotators or close binaries. The He discrepancy however seems to be generally present in supergiants.

4. Comparisons Between Models and Observations for Supergiants

Many problems and controversies remain about supergiants. These stars are often close to a neutral state between a blue and a red location in the HR diagram (Tuchmann and Wheeler 1989, 1990). There, even minor changes in convection and mixing processes may greatly affect the evolution. Let us examine some critical problems.

4.1 HE AND CNO ABUNDANCES IN BLUE SUPERGIANTS

A lot of new observations have been made in recent years, which well support Walborn's hypothesis (1976, 1988) that ordinary OB supergiants are enriched in helium and nitrogen and depleted in carbon, as a result of CNO processed elements present at the stellar surface. According to Walborn, the particular case may be the small group of OBC supergiants, which just have cosmic abundances. This hypothesis is supported in particular by the results of Herrero et al. (1992) who showed that supergiants of type Ia, Iab and Of stars present He-enrichments. Like for all rules, there are exceptions: some B-supergiants do not exhibit He and N excesses. These authors also show that fast rotators of all luminosities present evidences of CNO processing. Similar enhancements of nitrogen and helium abundances have also been found for several post-MS B-type stars by Gies and Lambert (1992). Abundances determinations have also been made for B-supergiants in the LMC and SMC, which is particularly interesting in relation with studies on the status of the progenitor of SN 1987 A (Kudritzki 1990; Lamson et al. 1991). From these results it is clear that B-type supergiants in the Galaxy, the LMC and the SMC generally show evidences of CNO processing.

The above observations place severe constraints on stellar models. Most of them do not predict He and N-enrichments in blue supergiants at solar composition. This may be called an He discrepancy (Herrero et al. 1992). Blue loops, with the associated He and N-enrichments (as a result of dredge-up in red supergiants) only occur for $M < 20 M_{\odot}$. This is the case for models with Schwarzschild's criterion and overshooting (Schaller et al. 1992), and with Ledoux criterion (Stothers and Chin 1992ab; Brocato and Castellani 1993). Models with semiconvection (Arnett 1991) have the same difficulty: at solar composition, the evolution goes straight to the red supergiants and there are no enriched blue supergiants. At lower metallicity like that of the LMC, most of the models have some blue loops and are thus in better position to explain the observed enrichments. Only complete comparisons in clusters at various Z will show the exact points of agreement or disagreement.

4.2 DISTRIBUTIONS OF THE SUPERGIANTS IN THE HR DIAGRAM

There seem to be relatively more stars out of the formal MS band than is predicted (see Meylan and Maeder 1982). The problem appears particularly serious at low metallicities as in the SMC and LMC. Instead of 10% of stars out of the MS, this fraction seems to be about 40%. In the Milky Way, excesses of A-type supergiants have also been suggested (Stothers and Chin 1977; Chiosi et al. 1978). The observed and theoretical numbers could be brought into an agreement if the MS would also include the B and A-type supergiants. This discrepancy is related to the so-called blue Hertzsprung gap (BHG), which is predicted by most models to occur at the end of the MS and which is not observed; instead, the true star distribution appears to be continuous from the MS to the A-type supergiants (Nasi and Forteri 1990; Fitzpatrick and Garmany 1990; Chiosi et al. 1992).

Various explanations have been proposed for the lack of BHG. Opacity effects may produce a paunch on the MS as shown above, but with present opacities (Iglesias et al. 1992) and mass loss rates, the paunch is located at too high luminosities to account for the observations (Schaller et al. 1992). Extended atmospheres and/or binaries (Tuchmann and Wheeler 1989, 1990) have been advocated. Mixing was shown to reduce but not to suppress the gap (Langer 1991c). The temperature scale may also be a problem. Indeed, a gap between $T_{\text{eff}} = 35'000$ K and $20'000$ K corresponds only to a difference of 0.04 in (B-V) colour, which is quite small and may be blurred by several effects. Only the adjustment of individual isochrones on star clusters, together with a mapping of He and CNO abundances, will properly inform us about the reality of the gap problem and on the exact status of blue supergiants.

We also have to consider the red side of the distribution of the blue and yellow supergiants in the HR diagram. A net decrease appears in the distribution of LMC supergiants in the HR diagram to the left of an oblique line between $\log T_{\text{eff}} = 4.2$ and 3.9 (Fitzpatrick and Garmany 1990). This feature is called the ledge. Two kinds of models are able to produce a high number of blue supergiants and give rise to a ledge: a) models with low mass loss, b) models with blue loops.

Clearly, models with low mass loss (Brunish and Truran 1982ab; Schaller et al. 1992) predict that most of the He-phase is spent in the blue supergiant phase directly after the MS. This may give a ledge. However such models do not make red supergiants, which is in disagreement with observations in the LMC and SMC. Models with blue loops also enhance the number of blue supergiants, and are simultaneously able to account for the He and N-enrichments in blue supergiants. This is the case of most models with overshooting, Ledoux criterion or semiconvection and masses smaller than about $20 M_{\odot}$. For example, models with overshooting at $Z \leq 0.008$ have

well developed blue phases at all masses (Schaefer et al. 1993). As shown by Meynet (1993), the number ratio B/R of blue to red supergiants for young clusters in the Galaxy are well accounted for by these models. It is however not certain whether the loops are correctly predicted for stars with initial masses larger than $20 M_{\odot}$.

4.3 THE STATISTICS OF BLUE AND RED SUPERGIANTS AND ITS VARIATION WITH METALLICITY

The number ratio B/R of blue to red supergiants was among the first stellar properties shown to vary through the Galaxy and to exhibit differences between the Galaxy and the Magellanic Clouds (van den Bergh 1968; Meylan and Maeder 1983; Humphreys and McElroy 1984; Brunish et al. 1986). The main trend is that B/R increases steeply with metallicity: for M_{bol} between -7.5 and -8.5 , B/R is up to 40 or more in inner galactic regions and only about 4 in the SMC (Humphreys and McElroy 1984). A difference by an order of magnitude between the Galaxy and the SMC was also found on the basis of well selected clusters (Meylan and Maeder 1982).

The various star models are generally able to account for the occurrence of blue supergiants, with B/R ratios in relatively good agreement with the observations (Brunish et al. 1986). One of the reasons is of course the flexibility offered by the uncertain mass loss rates. Indeed, B/R may change from infinity in case of no mass loss to about 0 for very high mass loss rates. Thus the real difficulty is not to account for an average observed B/R ratio, but to account also for the change of B/R with metallicity. The models with Schwarzschild's criterion and overshooting (Schaller et al. 1992; Alongi et al. 1993), the models with Ledoux criterion (Brocato and Castellani 1993) and the models with semiconvection (Arnett 1991), even if they are able to fit the average B/R ratio in the LMC or in the Galaxy, appear all to predict higher B/R ratios at lower Z in contradiction with the observations. This is a major problem, which is not solved in any grids of models. We do not yet know what models with turbulent diffusion or rotational mixing are predicting at various Z, since grids of such models are not yet available.

5. Properties and Chemistry of Wolf-Rayet Stars

WR stars are nowadays considered as bare cores resulting mainly from the peeling-off by stellar winds of stars initially more massive than about 25 to $40 M_{\odot}$. The main arguments are (Abbott and Conti 1987; Conti 1988; Lamers et al. 1991):

1. The low H/He ratio in WR stars, rarely larger than 3 in late WN stars and mostly 0 in other subtypes.
2. The CNO ratios show equilibrium values in WN stars.
3. The continuity of the abundances in the sequence of types

O, Of, WNL, WNE, WCL, WCE and WO

well corresponds to a progression in the peeling off the stars.

4. The observed mass loss rates in O-stars and in supergiants are high enough to remove the stellar envelopes during the stellar lifetimes, as well as the average mass loss rates in WR stars are sufficient to accomplish the further peeling off.
5. The low average masses between 5 and 10 $M_{\odot}$ of WR stars and their fitting to a mass-luminosity relation (Smith and Maeder 1991).
6. The presence of WR stars in young clusters and associations with ages smaller than $6 \cdot 10^5$ yr (Humphreys and McElroy, 1984).
7. The existence of transition objects Of/WN between Of and WR stars and between LBV and WN stars.
8. The presence of He and N-rich shells around some WR stars (Esteban and Vilchez 1992).
9. The WR/O and WN/WC number ratios are consistent with theoretical expectations and with their predicted variations according to the metallicity of galaxies (Maeder 1991).
10. The consistency of the T_{eff} of WR stars with that of He-rich bare cores when optically thick winds are accounted for (cf. Schaller et al. 1992; Schaerer and Maeder 1992).

There are two main groups of Wolf-Rayet stars, those of types WN and those of types WC. WN stars show the products of the CNO cycle. The late WN of types WN6–WN9, noted shortly WNL, generally still contain hydrogen with H/He ratios between 0 and 3 (Conti et al. 1983; Hamann et al. 1993; Willis 1991). The early WN stars of types WN2–WN6, noted WNE, generally show no hydrogen in their spectra, but there are a few cases with H/He ratios between 0 and 0.5. A correlation of the H-content with the T_{eff} of WN stars, rather than with their subtypes, has been found by Hamann et al. (1993): the coolest WN stars show hydrogen and the hottest ones have none. One may remark however that the coolest group is mainly formed by WNL stars while the hottest group consists of WNE stars. Thus, both pictures are essentially consistent. We may conjecture that the presence or absence of hydrogen is a key physical factor strongly influencing the structure of the outer layers. The above observed abundance ratios well correspond to the equilibrium values of the CNO cycle (cf. Maeder 1983, 1987a), i.e. the C/N and O/N ratios are two orders of a magnitude smaller with respect to solar abundances. Interestingly enough, such abundances are rather independent on the various model assumptions and they mainly depend on the nuclear cross-sections. The good agreement with model predictions is very important; it indicates the general correctness of our understanding of the CNO cycle and of the relevant nuclear data.

WC stars contain no hydrogen and are mainly He, C and O-stars (Smith and Hummer 1988; Willis 1991; Nugis 1991). A most interesting finding is

that by Smith and Hummer, who showed that the C/He ratio is increasing for earlier WC subtypes. Smith and Maeder (1991) emphasized that the (C+O)/He ratio is to be preferred to the C/He ratio which goes up and down during the He processing and to the O/C ratio which may give confusing results in galaxies of different metallicities. They propose the following calibration (in number ratios):

	(C+O)/He
WC9	0.03–0.06
WC8	0.1
WC7	0.2
WC6	0.3
WC5	0.55
WC4	0.7–1.0
WO	> 1

The sequence WC9 to WO appears to be a progression in the exposition of the products of He-burning and the rare WO types introduced by Barlow and Hummer (1982) just appear as the most extreme type in this sequence. Comparisons of observations and model predictions show a generally good agreement (Willis 1991, 1993). The above connection between WC subtypes and the (C+O)/He ratios is the key for understanding the differences in the distribution of WC stars in galaxies of different metallicities.

Evolutionary models also predict M–L– $\dot{M}$ –R– T_{eff} relations for WR stars without hydrogen (WNE, WC). Such He–C–O cores have a rather simple internal structure with little composition difference between the center and the surface, so that the above relations are mostly independent on the way the WR stars have been formed. Models (Maeder 1991; Schaerer and Maeder 1992) show that the differences due to the metallicity of the parent galaxy concern mainly the lifetimes and the domain of the M–L– $\dot{M}$ –R– T_{eff} relations occupied by WR stars. The basic connection is the mass–luminosity relation (Vanbeveren & Packer 1979; Maeder 1983; Langer 1989a; Schaerer and Maeder 1992):

$$\log L/L_{\odot} = 3.03 + 2.695 \log M/M_{\odot} - 0.461 (\log M/M_{\odot})^2$$

For $M > 10 M_{\odot}$, a linear relation may well fit. On the observational side, a mass–luminosity relation has been demonstrated (Smith and Maeder 1989; Smith et al. 1993); it implies a constant bolometric correction of 4.5.

6. The Relative Number Frequencies of WR Stars in Galaxies

WR stars are observed in several nearby galaxies, which gives statistical data on their relative frequencies at various metallicities. Data for nearby galax-

ies have been collected by Smith (1988) and Maeder (1991), who showed a strong increase of the number ratios WR/O and WC/WN with the metallicity of the parent galaxies.

The origin of the observed variations of the relative number of WR stars in the Galaxy, the LMC and SMC was a very debated subject. Originally, these variations were attributed to metallicity by Smith (1973) and Maeder et al. (1980), who suggested that high Z favours mass loss, which in turn favours the formation of WR stars. The dependence on metallicity was criticized by several authors, who attributed the differences in the WR populations mainly to changes in the IMF and SFR (Bertelli and Chiosi 1982; Garmany et al. 1982; Massey and Arnandorff 1991). However, these claims are unlikely because no systematic difference of the IMF slope has been found between the Galaxy, the LMC and SMC (Humphreys and MacEroy 1984; Mateo 1988; Massey et al. 1989; Parker et al. 1992). Also, the galactic gradient of the WR number is much steeper than that of O-stars (Meylan and Maeder 1982; van der Hucht et al. 1988). Thus, IMF and SFR differences do not seem to be the key factor here, while it may be very important in starburst regions. Thirdly, a problem of the explanation based on metallicity was that regions of similar Z, as the LMC and the outer galactic regions, have differences in their WR populations (Massey and Arnandorff 1991). The explanation is likely that in a given ring in the Galaxy there is a scatter in Z and that the average WR population is heavily weighted towards properties typical of higher Z (Smith and Maeder 1991).

In order to clarify the debate, let us make the following considerations. WR properties and statistics depend on many parameters: metallicity Z, star formation rate SFR, initial mass function IMF, age in bursts, duration of the bursts, binary frequency, etc. Thus, it is essential to distinguish: a) Regions in galaxies where the assumption of an average constant star formation rate over, say, the last $2 \cdot 10^7$ yr is valid, b) Regions or galaxies where a recent burst has occurred so that the assumption of a constant SFR does not apply. The first case concerns for example large rings in the Milky Way and galaxies, where the SFR and ages play no role. There the metallicity effects on stellar evolution seem to be a dominant factor. This case is examined in this review, its proper understanding is a prerequisite for the studies of the second group. Indeed, case b) involves all possible parameters and concerns HII regions, blue compact galaxies, WR galaxies and starbursts. Some model properties for this case b) are discussed by Meynet (this meeting).

The WR/O, WC/WR (and WC/WN) ratios strongly increase with the metallicity of the parent galaxy (cf. Maeder et al. 1980; Smith 1988, 1991). The general trend of growing WR/O ratios is also confirmed by the studies of the integrated properties of HII galaxies (Arnault et al. 1989; Conti 1991; Smith 1991; Vacca and Conti 1992; Mas Hesse and Kunth 1991; Mas Hesse 1992). In stellar models a growth of these ratios with Z is predicted (Maeder

1991; Maeder and Meynet 1994). The growth of WR/O results from the lowering of the minimum initial mass for forming WR stars and from the increase of the lifetimes with increasing Z (and mass loss). With Salpeter's IMF and standard mass loss rates, the models predict a WR/O ratio equal to 0.08 at $Z = 0.04$ and 0.28 for mass loss rates twice as large. This illustrates well the great influence of the mass loss rates on the values of the number ratios. At $Z = 0.002$, the WR/O ratios are in both cases 0.006, which is negligible. This is in agreement with the low fraction of WR stars in metal deficient galaxies. Also the study of the integrated spectrum and HeII 4686 feature in dwarf galaxies shows a total absence of WR contribution at Z lower than about 0.002 (Arnault et al. 1989; Smith 1991). The models show growth of WC/WN which results from the higher mass loss rates which lead to an earlier visibility of the products of He-burning. Interestingly enough, for increased mass loss rates, the WC/WN ratios go down again for $Z \geq 0.02$ instead of further increasing as expected. This results from the fact that the WN phase of the most massive stars may already be entered during the main sequence phase and is therefore much longer. Whether this is the right explanation for the apparently larger number of WN stars in starbursts (Vacca and Conti 1992) is still unknown.

Indeed, close comparisons between models and observations must account for the various channels of WR formation and in particular the binary RLOF, which seems to improve the comparisons (Vanbeveren 1991; Vanbeveren and de Loore 1993). These analyses, together with the new ones we have performed (Maeder and Meynet 1994), show that the best fit of the observed WR/O and WC/WN ratios is obtained with models having high mass loss rates, but that it is also necessary to assume that a certain fraction of the O-stars becomes WR stars as a result of binary mass transfer. This fraction was estimated to be 35% by Vanbeveren and de Loore (1993), which is in rather good agreement with the results by Podsiadlowski et al. (1992). The new comparisons we make also show that a better agreement is achieved if one takes into account the possibility that some WR stars result from RLOF in binaries. These new comparisons indicate that the fraction of WR stars which truly owe their existence to RLOF is highly variable with the metallicity of the galaxy, being nearly 100% at low Z like in the SMC and going down to values as low as about 10% in the inner regions of the Milky Way. It is important to emphasize that these fractions are not necessarily identical to the fractions of WR binaries.

7. The Distribution of WC Subtypes

The distributions of WC and WO stars in galaxies present a number of very distinct properties:

- 1. It is well known that WC stars are more numerous in inner galactic

regions (cf. van der Hucht 1988). More specifically, the later a WC subclass is, the inner is the limit in galactocentric radius beyond which no star of that subclass is found, (Smith and Maeder, 1991). Indeed, WC9 and WC8 stars are only found in inner galactic regions with higher Z . For metallicity Z as in the LMC, WC stars are mostly of types WC6-WC4. In dwarf galaxies, only WC4 and WO stars are found. Also, the above authors emphasize that at low Z values (lower than for the LMC) the majority of stars in the WC-WO group are WO stars.

-2. In the Milky Way, the luminosity of earlier WC subtypes is lower than for later WC subtypes (Lundström and Stenholm 1984; van der Hucht et al. 1988; Conti 1988).

-3. Stars of a given WC subtype seem brighter at lower Z as suggested by Smith and Maeder (1991), who point out that surprisingly LMC WC4 stars are even brighter than galactic WC5-WC6 stars.

The above facts are well explained on the basis of the relation between WC subtypes and the (C+O)/He ratio as shown by Smith and Maeder (1991). The entry points and lifetimes in the WC9 to WO sequence are highly dependent on mass and Z . At high Z , due to high mass loss the WC stage is entered early during the He-burning phase, so that the surface (C+O)/He ratio is low and thus the WC type is generally later than at lower Z . As evolution goes on, mass and luminosity decline and the ratio (C+O)/He decreases, and thus the sequence of earlier WC types is described. The entry point in the above sequence occurs at lower L and thus earlier WC types for lower stellar masses.

For lower metallicities, the entry in the WC phase occurs with higher (C+O)/He ratios, i.e. earlier WC types, and the evolutionary sequence up to type WO is shorter. This behaviour, illustrated by Figures 10 to 13 in Maeder (1991), explains the above properties (points 1 to 3). We emphasize that the fact that the luminosity for a WC subtype depends on the initial Z may have some consequence for the interpretation of the WC lines in the integrated spectra of galaxies, a fact which should be accounted for in populations synthesis with WR stars.

From the observations of WR stars in clusters and in galaxies, some preferential filiations between WR subtypes can be enlightened (van der Hucht, 1988; see also Moffat et al. 1986):

$R < 8.5$ kpc	WNL $\rightarrow$	WCL
$R > 6.5$ kpc	WNL $\rightarrow$	WCE $\rightarrow$ WO
	WNE $\rightarrow$	no WC stars

R is the galactocentric radius. These filiations are very well supported by the model results (Maeder 1991). The first connection is typical of high M

and Z : a long WNL phase, followed by a negligible WNE phase, emerges on the late and luminous part of the WC sequence. The second connection is typical of large masses with solar Z or lower, while the third one corresponds to lower masses. Thus, we see that the observations and understanding of WR stars in nearby galaxies has brought about the clarification of many problems. This allows us to apply these results for the interpretation of the integrated spectrum of galaxies.

On the whole, we see that in the domain of massive stars there are presently many encouraging points of agreement, but observations also show some difficulties which need to be explored and will require further improvements of the stellar models.

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