EVOLUTION OF MASSIVE STARS, SUPERGIANTS AND WOLF-RAYET STARS

André Maeder
Geneva Observatory
Switzerland

1. INTRODUCTION

Massive stars (say $M \gtrsim 9\ M_\odot$) play a major role in Astrophysics. They are the main agents of nucleosynthesis and galactic enrichment and present many interesting properties, like high stellar winds, chemical surface enhancements, instabilities etc. which deserve further investigation. Furthermore, massive stars also are the powering sources of giant H II regions and have important radiative, mechanical and chemical interactions with the interstellar medium.

2. SOME BASIC OBSERVATIONAL CONSTRAINTS

Let us firstly review some of the basic observational facts, which put some severe constraints on the evolutionary models and need to be accounted for.

a) The HR diagram and basic parameters

First of all, we have to mention the properties of the upper luminosity boundary of supergiants in the HR diagrams by Humphreys and Davidson (1979). 1) Culminating at $M_{bol} = -12$ for O3 stars, the envelope of O-stars shows a decreasing luminosity for later spectral types. 2) From late B- to M-type supergiants, the envelope is rather flat. The consequence is that the brightest O-stars are about 2 magn. (in M_{bol}) more luminous than the brightest red supergiants. A rather similar behaviour is exhibited by supergiants in the Galaxy, the LMC and SMC.

The distribution of massive stars shows two other points of interest. 3) When comparing their models of constant mass evolution with the observations, Lamb et al (1976), Stothers and Chin (1976) found that the observed ratio of red to blue supergiants in the solar neighbourhood is too high by a factor of 4 with respect to model predictions.

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Thus, Lamb et al (see also Brunish and Truran, 1982 ab) concluded that most red supergiants (RSG) arise from the evolution of lower mass stars, a conclusion which was not supported by Maeder (1981 b, see also § 3a below). 4) There is too large a number of late B- and A-type supergiants (cf. Stothers and Chin, 1977; Chiosi et al 1978). On the basis of a large sample of well studied young clusters in the Galaxy and the Magellanic Clouds, Meylan and Maeder (1982) found a substantial MS widening up to spectral type A, i.e. much larger than the one present in older clusters (cf. Maeder, Mermilliod, 1981). This large MS widening for massive stars remains a very hard constraint to satisfy, and its solution may have further implications on stellar evolution.

b) Statistics of massive stars at different galactic locations

The models must evidently fit the basic stellar parameters as given by the various available calibrations. In addition, they must account for the number ratios of stars of different types. The problem is, however, complicated by the fact that many of these number ratios are strongly changing with galactic location. This is certainly a major and stimulating challenge which we have to face.

As shown by van den Bergh (1968), Humphreys (1978), Humphreys and Davidson (1979), the number ratio of red to blue supergiants varies with galactocentric location, in the sense that there are relatively more RSG towards the anticenter. The Wolf-Rayet (WR) stars also have a strongly non uniform distribution, being much more numerous in galactic interior regions (cf. Smith, 1973; see also Hidayat et al, 1981). As shown by Maeder et al (1980), the number ratio of RSG to WR stars has the strongest galactic variations, being much larger in external galactic zones. This steep galactic gradient was interpreted in terms of the effect of metallicity on mass loss rates.

Table 1 from Lequeux (1983) shows the variations of different number ratios with galactic locations. We notice that, for the range of metallicities considered, the ratio of red to blue supergiants spans a range of 5, the ratio of RSG to WR stars a range of 45, while the last column presents a variation smaller than a factor of 2. These results confirm the earlier findings by Maeder et al (1980) who emphasized that the RSG/WR number ratio may be a very useful indicator of metallicity and chemical gradient in external spiral and irregular galaxies. As noted by Humphreys, Davidson (1979) and Bertelli, Chiosi (1981), the steepness of the gradients also depends on the adopted luminosity limit. It is however verified (cf. Meylan, Maeder, 1983) that for the limits $M_{bol} = -6$ and -7.5 (which rather correspond to the lower luminosity of WR stars) the results are essentially similar.

Table I

Galactic gradients of luminous red and yellow-to-blue stars and red to Wolf-Rayet stars, and data for other galaxies. The metallicity Z is indicated. The galactocentric distance of the Sun is taken as 10 kpc., from Meylan and Maeder (1983) for the Galaxy and Lequeux (1983) for the other data.
The figures refer to $M_{bol} < -6$.

Galaxy	$Z^{(1)}$	$\frac{N(KM)}{N(OBAFG)}$	$\frac{N(KM)}{N(WR)}$	$\frac{N(KM)+N(WR)}{N(OBAFG)}$
The Galaxy, 7.5-9kpc	0.03	0.04	0.53	0.11
The Galaxy, 9-11kpc	0.02	0.07	1.4	0.12
M33	$0.02^{(2)}$	0.07	< 3	> 0.09
The Galaxy, 11-12.5kpc	0.014	0.17	$13.5^{(3)}$	0.19
LMC	0.01	0.12	8	0.14
SMC	0.003	0.20	24	0.21

(1) A homogeneous scale referring to all objects has still to be discussed; the present scale indicates only a trend
(2) Ignoring the small metallicity gradient in this galaxy
(3) Very uncertain: only 2 WRs in this region

In the case of WR stars, the frequency of WR binaries and the ratio of WN to WC stars also change with galactocentric distance (cf. Hidayat et al, 1983), as does the distribution of the WR subtypes.

c) Mass loss by stellar winds

This is a general property of all luminous stars. No unique parametrization of mass loss rates exists for stars over the whole HR diagram. Generally, the mass loss rates $\dot{M}$ increase with the luminosity (except for WR stars?), with a rather large scatter around the mean relation. Different estimates and parametrizations have been performed for OB stars, BAF supergiants, red supergiants and WR stars (cf. Garmany et al, 1981; Barlow and Cohen, 1977; Reimers, 1975, Bernat, 1979; Barlow et al, 1981; Conti, 1982; Bieging et al, 1982).

Such observed rates or some fitted parametrizations have been used by most authors of computations with mass loss, as well for massive stars (cf. § 3) as for asymptotic branch giants.

d) The case of WR stars: a flavour of controversy

The general properties of WR stars have been reviewed in the recent IAU Symposium 99 on WR stars (Ed. De Loore and Willis, 1982; see also van der Hucht, 1981; Conti, this meeting). The WR stars, which are supposed to be bare stellar cores, represent a strong constraint over the whole evolutionary scheme of massive stars.

In particular, mechanisms such as mass loss, binary transfer, mixing etc. appear necessary for the formation of WR stars.

The scenario of massive O-stars evolving to WR stars as peeled off stars in the advanced stages has repeatedly been criticized by Underhill (e.g. 1983 ab) on the basic reason that the observed mass loss rate for WR stars "requires that much more momentum be deposited in the wind of a WR star than is available from the radiative field of a star". It is certainly true that the kinetic power of the winds of WR stars represents a sizeable fraction (2 - 10%) of the stellar luminosity (cf. Bieging et al, 1982) and it seems difficult to explain such a strong wind by the radiation field only. A possible way to solve this problem might well come from the finding (cf. § 5b) that most WR stars are vibrationally unstable. It is, however, important to reassert that the peeling-off which leads to the formation of WR stars is not due to the wind of WR stars, but rather to the winds acting during the previous evolutionary stages. These winds are not subject to controversy and lead the initially most massive stars to the status of bare cores.

The contention that the absence or weakness of H-lines in WR stars is due to ionization effects was not supported by the recent analysis by Willis (1982) and Conti et al (1983). In particular, there is no one-to-one relation between H/He ratios and WN subtypes which, as pointed out by Willis (1982) among other arguments, rules out ionization effects as the cause of the lack of observed H-lines. Moreover, the models of magnetically supported loops (cf. Underhill, 1983 ab), which are not mathematically formulated, do not seem to have accounted for some of the basic properties of WR stars, such as their overluminosity with respect to their actual mass. Also, the question arizes how these extended magnetic loops could survive in close binary WR stars.

Conversely, the model of bare core for WR stars well accounts for their observational properties, such as the range of masses and luminosity, where these stars occur (cf. Conti, 1982; Massey, 1982); their T_{eff} has been interpreted by de Loore et al (1982) in terms of extended atmosphere. This model also accounts for the overluminosity of WR stars with respect to their actual mass (cf. Maeder, 1983 ab) and for the observed chemical enhancements (cf. Smith, Willis, 1982; Willis, 1982). Their number statistics is also in agreement with the above picture (Maeder, 1982). Besides, the high mass loss rates for WR stars (in the order of $2 \cdot 10^{-5}\ M_\odot y^{-1}$ and not $10^{-7}\ M_\odot y^{-1}$ as suggested by Underhill, 1983 b) are in better agreement with the mass present (cf. de Jager, 1980) in the gaseous shells surrounding some WR stars.

Thus, it may be advisable to keep to the scenarios of massive stars evolving to WR stars, as the result of mass loss and possibly of some mixing processes.

For the purpose of completeness, let us also mention the constraints put by chemical abundances at the stellar surface (cf. § 4) as well as the potential information which could be given by a study of the instabilities in supergiants.

3. RESULTS FROM EVOLUTIONARY MODELS WITH MASS LOSS

a) Results in the HR diagram

The effects of mass loss in the HR diagram have been discussed intensely by several authors (cf. Chiosi et al, 1979; de Loore et al, 1978; Stothers, 1979; Maeder, 1980, 1981 ab, 1983 a; de Loore, de Greve, 1981; Chiosi, 1981; Falk and Mitalas, 1981, 1983; Sreenivasan and Wilson, 1982; Brunish and Truran, 1982 ab). The details of the effects of mass loss on the MS evolution have been discussed by most of the above authors and we only briefly mention these effects here: decrease of luminosity but the star is overluminous for its actual mass; decrease of the core mass, but the core mass fraction is larger; increase of the MS lifetime; MS widening for low and intermediate mass loss rates, MS narrowing for very large rates; decline of semi-convection; possible change of surface abundances.

Turning to post-MS evolution let us recall that in the case of constant mass evolution, the massive stars leave the main-sequence and end their life, whatever may be the exact nature of the core collapse, as red supergiants (cf. Lamb et al, 1976). When the standard treatment of convection with Schwarzschild's criterion is made, massive stars in the range of 15 to 50 $M_\odot$ burn helium as B-supergiants. This location in the blue is due to a large fully convective zone which homogenizes the intermediate stellar layers (effect nb. 3 below) and thus keeps the star to the blue (cf. Stothers and Chin, 1976; Lamb et al, 1976). Thus stars with constant mass spend no time or only a negligible time in the RSG stage. This is why the above authors concluded that there were too many observed RSG's with respect to what had been predicted.

In order to properly understand the evolutionary tracks of massive stars with mass loss, we must realize that four main competitive effects determine the bluewards and redwards motions in the HRD (cf. Stothers and Chin, 1979): 1) The classical envelope expansion which responds to core contraction (cf. Renzini, this meeting). 2) The increasing size of the helium core favours bluewards evolution. 3) The homogenization of the envelope by a large FCZ tends to maintain a blue location in the HRD. 4) Large luminosity/mass ratios favour the expansion of the envelope. This last effect makes the He-burning zone move to lower T_{eff} for very massive stars ($M \gtrsim 40\ M_\odot$; see Fig. 1).

The major result about the post-MS evolution of massive stars that has emerged from recent studies (cf. Maeder, 1981 ab; Chiosi, 1981) is that according to initial mass and mass loss rates, the stars may go through very different evolutionary sequences, as a result of the combination of the four above-mentioned effects. Three different evolutionary sequences can be distinguished (cf. Fig. 1):

For $M \gtrsim 60\ M_\odot$

O star - Of - BSG and Hubble-Sandage variables - WN - WC - (WO) - SN

For $25\ M_\odot \lesssim M \lesssim 60\ M_\odot$

O star - BSG - yellow and RSG - (BSG) - WN - (WC) - SN

For $M \lesssim 25\ M_\odot$

O star - (BSG) - RSG - yellow supergiant and Cepheid - RSG - SN

Overshooting or mixing will probably not affect this general scheme, but such processes might contribute to an increase of the indicated mass limits (like an increase of $\dot{M}$ would do, due to the effect nb. 2 above).

Let us now comment these three kinds of evolution.

1. For mass loss at the currently observed rates, stars with an initial mass above 50 - 60 $M_\odot$ never reach the red supergiant (RSG) stage. For these stars, the peeling off by the winds during the main-sequence and the blue supergiant (BSG) phases is high enough to remove all the outer stellar layers. Zones which initially were in the core are revealed at the stellar surface. These stars, especially the extremely massive ones, remain quasi-homogeneous (cf. Maeder, 1980) and always stay at the blue side of the HR diagram, due to effect nb. 2 above. They firstly are BSG and Hubble-Sandage variables before becoming WR stars, probably of late WN types.

2. For initial stellar masses between about 50 and 25 $M_\odot$, mass loss at the observed rates on the main-sequence and in the BSG phase is not sufficient to remove all the outer envelope and the star rapidly reaches the RSG stage. Mass loss, even small, reduces the extension of the FCZ (effect nb. 3) and thus favours the redwards motion. This allows the stars to reach the RSG stage early enough during the He-burning phase and to experience lifetimes in the RSG longer by a factor 4 to 5 with respect to the case of constant mass, thus bringing about agreement with the observations (see Fig. 6 in Maeder, 1981 b). Then the high stellar winds in the RSG stage progressively remove the outer envelope.

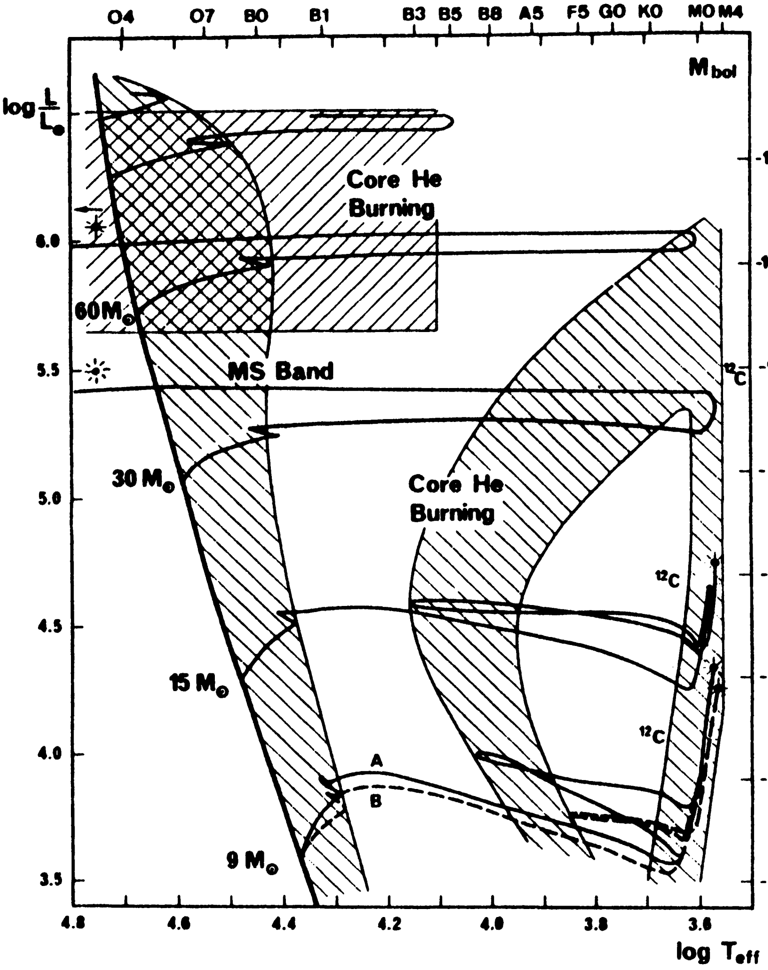

Fig. 1

The HR diagram for evolution with mass loss up to the end of central carbon burning (models B, 30 $M_\odot$; case C, Maeder, 1981 b; 1983 a, for 120 $M_\odot$). One well notices the 3 different cases of evolution for massive stars. Case 1 is illustrated by the 2 higher models of 120 and 170 $M_\odot$, case 2 by the models of 60 and 30 $M_\odot$, case 3 by 15 and 9 $M_\odot$.

When the mass fraction of the helium burning core, as a result of the decreasing total stellar mass, becomes larger than some critical value q_c (effect nb. 2), the star moves back to the blue in the HR diagram and then may become a WR star (cf. Chiosi et al, 1978; Maeder, 1981 b, q_c = 0.67 for 60 $M_\odot$, 0.77 for 30 $M_\odot$).

Thus, there may exist WR stars which are in a post-RSG phase. Clearly, high mass loss rates during this RSG phase and during previous phases favour the formation of WR stars, since then the critical q_c is reached earlier.

Thus, we have the complex situation that mass loss (at the observed rates) during the MS favours the formation of RSG in the range of masses 25 and 50 $M_\odot$, while a heavy mass loss in the red phase reduces the lifetime as RSG, since the star is then turned into a WR object. However, in all relevant cases the lifetime in the RSG stage remains much longer than in the case of constant mass evolution (cf. Maeder, 1981 ab).

The formation of WR star as post-RSG has been studied by Chiosi et al (1979), and Maeder (1981 ab) who examined the conditions on initial masses and mass loss rates $\dot{M}$ for this kind of evolution to occur. Two main facts are worth emphasizing. a) The fraction of stellar lifetimes spent as WR stars strongly increases with initial mass and $\dot{M}$-rates in the previous stages. Since the total duration t_{He} of the helium burning phase does not change significantly, a substantial increase of the WR phase implies a corresponding reduction of the RSG phase, as $t_{He} \simeq t_{RSG} + t_{WR}$. b) The luminosity limit above which WR stars appear is very sensitive to the mass loss in previous stages. The combination of these two facts leads to a very strong increase of the expected number of WR stars with mass loss rates. As an example, it was found that an increase of $\dot{M}$ by a factor of 2 during MS and RSG phases (which is well inside the observed scatter) gives a number of WR stars larger by a factor 17. Thus, it is clear that the expected number ratio N_{WR}/N_{RSG} is extremely sensitive to change of mass loss rates and accordingly there is thus no need of strong variations of $\dot{M}$ with metallicity in order to produce large changes in the frequencies of RSG and WR stars.

3. For initial masses below about 25 $M_\odot$, the mass loss both in the blue and in the red is never large enough to remove the outer layers. After the main-sequence, the star normally becomes a RSG, then it undergoes blue loops during which a Cepheid phase may occur; later the star again becomes a RSG. We can notice that the blue extension of the loops is significantly reduced by mass loss (cf. Maeder, 1981 b); in case of high mass loss, the loops may even be suppressed.

Different authors have presented different pictures for the advanced evolution. In particular, there are sizeable differences between the above results and those by Brunish and Truran (1982 ab). For example, these authors predict that stars with initial masses smaller or equal to 30 $M_\odot$ spend less than 1% of their total lifetime in the RSG stage. Indeed, the absence of RSG from 15 - 25 $M_\odot$ progenitors predicted by Brunish and Truran is not confirmed by the observations of red supergiants in young clusters and associations (cf. Humphreys, 1978;

Humphreys and Davidson, 1979). These observations show that the major fraction of red supergiants originates from stars initially less massive than 30 $M_\odot$. The predicted absence of RSG probably results from too small mass loss rates, so that their tracks are close to those of constant mass evolution.

The models with mass loss have been compared to the observations in several studies (cf. Chiosi et al, 1978, 1979; Maeder, 1981 ab; Chiosi, 1951; Meylan, Maeder, 1982). Most observed properties, such as the shape of the cluster sequences, the formation and expected number of RSG and WR stars seem to be accounted for by the models, as well as the surface abundances in Hubble-Sandage variables and in WR stars (cf. § 4). The most accurate comparisons in the HR diagram are those made with M_V vs. $(U-B)_O$ sequences of well analysed clusters (e.g. Mermilliod, Maeder, this meeting). However, there seems to remain a stone in the garden of the model makers, it is the so-called MS widening which will be further discussed in § 5.

b) Some noticeable points about internal structure and further evolution

It is quite noteworthy that, for a wide range of mass loss rates, the He-phase ends with almost similar He + C/O core (cf. Maeder, Lequeux, 1982; Brunish, Truran, 1982 ab). For example, a model with an initial mass of 60 $M_\odot$ and which is left due to mass loss with only 25 $M_\odot$ at the end of the C-burning phase has exactly the same central conditions and the same He + C/O core as its constant mass counterpart. The comparison of the distribution of chemical elements, of the runs of temperature and density shows identical results in both cases (the physical reasons are discussed in the above ref.).

Thus, as well as a red giant may be considered as a white dwarf surrounded by an extended envelope, as much can a red supergiant be considered a WR star surrounded by a very large envelope. In the case of the white dwarf the He + C/O core is degenerate and smaller than the Chandrasekhar mass, while the WR star is not degenerate and has a larger mass.

This absence of sensitivity of central conditions to mass loss is the general rule as long as mass loss does not lead to a significant reduction in the mass of the He + C/O convective core; such a reduction occurs only when the evolution goes far enough through the WC stage, which seems to be the case mainly for stars with very large initial masses (say $M \gtrsim 50\ M_\odot$).

Thus, as a whole we can say that mass loss at the currently observed rates produces large effects in the HR diagram, while the course of the evolution of the central conditions is generally little affected.

This implies that most WR stars end their life as supernovae (cf. Maeder, Lequeux, 1982). Thus, from Fig. 1 we can note that for stars initially more massive than 25 $M_\odot$ the progenitors of supernovae generally are WR stars, while below this mass limit the progenitors are RSG stars with extended envelope likely giving rise to type II supernovae.

4. EVOLUTIONARY CHANGES OF CHEMICAL ABUNDANCES AT THE STELLAR SURFACES.

Changes of surface abundances also offer a very strong test of stellar evolution. Comparisons bearing on isotopic ratios and elemental abundances have been mainly performed for red giants and supergiants (cf. Lambert, this meeting). For hot stars, the analyses are very difficult and thus less numerous, despite their great interest. In particular, Wolf-Rayet stars offer us the most valuable possibility to directly observe stellar nucleosynthesis in the products of some nuclear reactions revealed at stellar surfaces as a result of mass loss and maybe of some mixing processes. The nucleosynthetic products visible in WR stars, unlike in red giants, are not highly diluted within a large envelope. [In WN stars one observes the results of CNO processing and in WC stars those of partial helium burning.] The WC stars are the only kind of stars in which the products of the 3α reaction and other He-burning reactions prominently manifest themselves at the stellar surfaces. This provides a very useful comparison basis with nucleosynthetic predictions.

The variations of the abundances of various elements during the evolution of massive stars have been calculated recently by Noels and Gabriel (1981), Maeder (1983 ab) and Greggio (this meeting). These authors have obtained the changes of chemical abundances at stellar surface due to the fact that matter originally in the convective core is revealed by the removal of the outer layers by mass loss. At the appearance of CNO products, important changes occur. The elements ^{3}He, ^{15}N and ^{18}O disappear. As the CN-cycle rapidly reaches equilibrium, the C/N ratio almost abruptly changes from about 4.1 to 0.03 (in mass). The O/N ratio slowly changes from 9.1 to less than 0.1 because the ON-cycle takes a longer time to reach equilibrium. The abundance of ^{13}C usually keeps a factor of 3.3 below that of ^{12}C. It is to be noted that the isotopes ^{16}O, ^{17}O and ^{18}O have very different behaviours (cf. Fig. 2).

A very large discontinuity marks the appearance of the various products of He-burning at the surface (cf. Maeder, 1983 a); this is likely to correspond to the beginning of the WC stage. The physical reason for this discontinuity is that the convective core in the He-burning phase does not continually decrease (which would leave a smooth transition at the border), but the core increases in mass during most of its evolution and a chemical discontinuity is thus built at the border of the core at its largest extension.

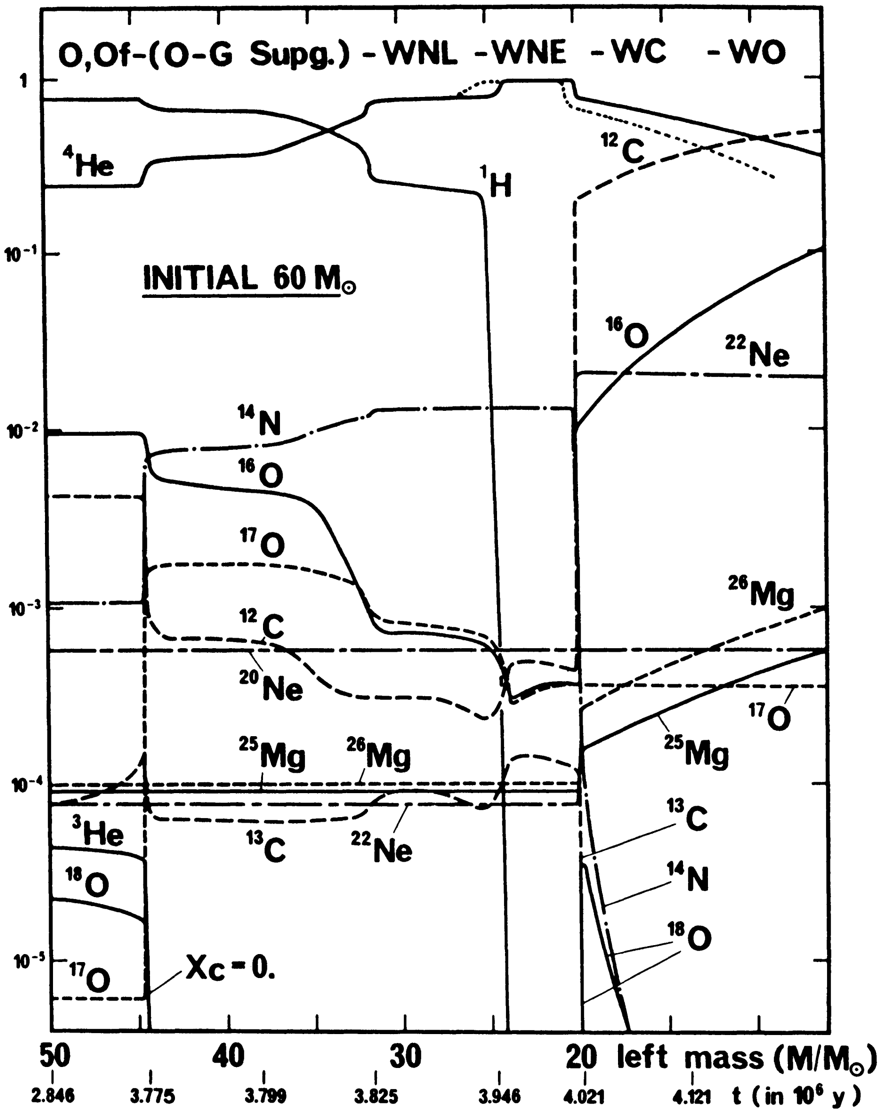

Fig. 2

Changes of the surface abundances (in mass fraction) in terms of the remaining mass for the model with initial mass of 60 $M_\odot$. The ages are also indicated on the lower axis. At the top of the figure the corresponding evolutionary status is given. The dotted line for ^{4}He in the WN and WC stage corresponds to a lower mass loss rate in the WR stage. $X_c = 0$ indicates that the central hydrogen content is zero; it is just a coincidence that the central H-depletion occurs for this model just when CNO-products appear at the surface.

We note then a very steep disappearance of ^{13}C and ^{14}N, a very temporary peak of ^{18}O and above all a vertiginous rise by more than 2 orders of magnitude of ^{12}C, ^{16}O and ^{22}Ne. The abundances of ^{25}Mg and ^{26}Mg also rise strongly, particularly in the most massive WC stars, where s-elements are therefore to be expected.

The most prominent cases of peculiar abundances occur for the so-called Hubble-Sandage variables and for the WR stars. Let us review the comparisons made in these two cases.

The evolutionary status of the Hubble-Sandage variables and in particular of η Carinae is an old problem (cf. Stothers, Chin, 1983). The location of these stars in the HR diagram well corresponds to that of post MS supergiants; however, the argument cannot be regarded as sufficient in itself. In the case of η Carinae a very decisive information is coming from the recent observations by Davidson et al (1982) who determine the following values for some of the outer condensations surrounding the central object: $C/N < 0.05$ and $O/N < 0.15$ or 0.5 (see also Walborn et al., this meeting, who also find $X = .57$, $Y = .42$). These ratios differ very much from the solar ones: $C/N \simeq 4$, $O/N \simeq 9$, and are in full agreement with the ratios obtained in the blue supergiant phase of an initial 120 $M_\odot$ star evolving with heavy mass loss (at the observed rates): $C/N = 0.025$, $O/N = 0.17 - 0.9$ (cf. Maeder, 1983 a). This provides a strong constraint on the evolutionary status of this star; it is a first necessary step in order to be able to understand the origin of their strong instabilities. Further observations of O/N and C/N ratios in other blue supergiants, particularly in clusters and associations, seem a very promising programme to be undertaken.

In the conspicuous case of Wolf-Rayet stars, observations of chemical abundances have been made and analysed recently by Smith and Willis (1982), by Willis (1982), by Nugis (1982) and by Conti et al (1983). Generally speaking, the observed abundances for WNL, WNE and WC and WO stars are consistent with a progression in the exposition of nuclearly processed material from the CNO-cycles and then from He-burning reactions. The C/He, N/He and C/N ratios obtained by Smith and Willis or Nugis for WNL, WNE and WC stars have been compared in detail with the model predictions (Maeder, 1983 a). The general agreement between the observed ratios, which differ very much (10^2 for C/N) from the solar ratios, cannot be accidental, and it is a strong confirmation of the advanced evolutionary stage of WR stars as left over cores resulting from the peeling of massive stars by stellar winds. The models also suggest that the determinations of abundances for neon and magnesium in WC stars would be highly useful.

Finally, let us note that the connection between the anomalies of ^{12}C, ^{22}Ne, ^{25}Mg and ^{26}Mg in the galactic cosmic rays and the predicted excesses of these elements in WC stars has been examined (cf. Cassé, Paul, 1982; Maeder, 1983 b) with positive conclusions.

5. TOPICAL PROBLEMS AND PROGRESS NEEDED: MS WIDENING, FORMATION AND GALACTIC DISTRIBUTION OF WR STARS

Here we examine some problems arising in comparing models and observations and which potentially are lines for further progress in years to come.

a) MS widening

Standard models with mass loss do not account for this effect. The theoretically predicted gap following MS evolution extends in the HR diagram from log Teff = 4.38 to 4.15, which indeed corresponds to a narrow range of spectral type, i.e. from 09.5 to B2.5. Massive close binaries which, due to mass transfer, would be prevented from evolving to RSG could lie in this location. However, in view of their expected number (cf. Burki, Mayor, 1983) and of the large excess of stars outside the MS band (cf. Meylan, Maeder, 1982), the MS widening seems to be a real effect. Claims about the effect of a spread in the formation times of stars in a cluster have also been made (cf. Doom et al, this meeting). However, this should not affect diagrams such as those by Humphreys and Davidson (1979), which anyhow contain clusters of various ages. Moreover, it could perhaps be useful, before assigning different ages to the upper MS stars of a given cluster, to correct the colour magnitude diagrams for the well known effects of differential interstellar reddening, large rotational velocities and unsolved binaries.

Bressan et al (1981), Doom (1982 ab) have constructed models of massive stars with convective overshoot, a process which is known to extend the MS band (cf. Maeder, 1975). However, it is clear (cf. Bertelli et al, 1983) that this process is insufficient to explain alone the observed effect. More recently, Bertelli et al have shown that a suitable combination of mass loss, overshooting and opacity bumps is able to bring a satisfactory agreement. The central question relates obviously to the question of the existence or non-existence of the opacity bumps. Finally, we must note that other mixing processes may also be very efficient in massive stars, in particularly turbulent diffusion (cf. Maeder, 1982).

For the time being, the MS widening has received no satisfactory answer and it certainly remains a major line of research for the next years.

b) Formation of WR stars

This problem has been the object of several reviews in recent years (cf. IAU Symposium 99, Ed. de Loore and Willis, 1982). The question of the minimum value of the initial stellar mass for forming WR stars is a very important one in this context.

From number statistics, Firmani (1982) suggested a value of 20 $M_\odot$, similar to that proposed by Chiosi (1981) and Maeder (1981 b, 1982). Recently, Conti et al (1983) concluded from the analysis of the galactic distributions of O and WR stars that most WR stars originate from stars initially more massive than 40 $M_\odot$. If this limit is accepted as such, it implies (cf. Conti et al) that there is a substantial excess of WR stars with respect to theoretical predictions. More recently, Schild and Maeder (1983), from the analysis of WR stars in clusters, supported a value of 20 $M_\odot$, noting however that the majority of WR stars may originate from stars more massive than 40 $M_\odot$.

Over the last 40 years WR stars have successively been associated with almost all possible evolutionary stages (cf. bibliography by Simon and Stothers, 1969). It is not the aim here to review all these possibilities. Four main and non exclusive scenarios which may fulfil the above observational constraints seem to emerge nowadays (cf. IAU Symposium 99):

- Mass transfer in binaries
- Mass loss in MS stars (Conti's scenario, 1975)
- Mass loss in supergiants, particularly in red supergiants.
- Mixing by various processes.

In view of their surface compositions and frequencies, il is very likely that most WR stars are in the He-burning stage, although some of the massive WNL stars may still be near the end of the H-burning phase.

We shall not examine here the details of the various scenarios. The case of WR binaries has been studied by the Brussel group (cf. de Loore, de Greve, 1981). Recently, Hidayat et al (1983) have found 34% of binary WR stars and have suggested that their real number could be above 50%. The original Conti's scenario (cf. Conti, 1975; Chiosi et al, 1979) must probably be modified so as to include during post MS evolution an excursion through the stage of the Hubble-Sandage variables with very high mass loss rates, before the star becomes a WR star (cf. Maeder, 1983 a). Recently, Lamers et al (1983) have suggested that P Cygni is on its way to the WR stage, which would be an illustration of this case. The properties of WR stars, which are post-RSG, have been examined above. Hidayat et al (1981) have suggested that WC 8.5 and WC 9 stars could correspond to this case.

Internal mixing may also considerably favour the formation of WR stars, by contributing to the homogeneisation of the star (which reduces the ratio of central to average density and favours instability) and to the appearance of the products of nuclear burning at the stellar surface. Such models, with overshooting and turbulent diffusion, have been performed by Maeder (1982).

Recently Bertelli et al (1983), in the line of their proposed interpretation for the MS widening, have suggested that the combination of mass loss, overshooting and opacity bumps plays a dominant role in accounting for the properties of WR stars; here as for the MS widening, this interpretation is subject to the reality of the opacity bumps.

For now, it is clear that many processes may separately or simultaneously favour the formation of WR stars, but their exact relative importance is still rather uncertain.

A major question about WR stars is also that of the origin of the very high wind of WR stars (cf. § 2). A recent analysis of non-adiabatic, linear radial pulsations during the evolution of massive stars (cf. Maeder, Lovy, in prep.) has shown that many of the models which are turned blue and which consist of bare cores identifiable with WR stars, are vibrationally unstable. The growth time of the instability is short, values as small as 5 days have been found for periods of 30 minutes, which implies a strong instability. Thus, it is tempting to suggest, and I do it, that the mechanical energy injected by the internal pulsations into the extended atmosphere may significantly contribute to the large wind of WR stars. As the wind is optically thick, we may in most cases not be able to directly observe the pulsations, which would then manifest themselves mainly through the enhancement of the wind.

It is well known (cf. Ledoux, 1941) that the limit of vibrational instability for homogeneous stars of mass M is given by $\bar{\mu}^2 M \cong$ const. (cf. also Ziebarth, 1970), where μ is the mean molecular weight. Massive stars may become, due to mass loss, quasi-homogeneous (Maeder, 1980, 1983 a). Thus as $\bar{\mu}$ increases due to nuclear processing, M must decrease so as to satisfy the above expression. As the instability grows if $\bar{\mu}^2$ M becomes too large, I suggest that during their evolution WR stars keep at the edge of the vibrational instability. The instabilities found in the above mentioned calculations support these views.

c) Distribution of WR stars in galaxies

Many observations suggest a change of various properties of massive stars and WR stars with galactocentric distance and from one galaxy to another (cf. § 2b). As there are several processes contributing to the formation of WR stars, it was proposed that the relative importance of the channels, or more precisely the "traffic" through each of the various channels leading O and Of to WR stars changes very much with initial metallicity and thus galactic location (Maeder, 1981). In certain cases some channels are absent, while they may be very much run through in other cases. For example, in the SMC only the binary channel seems just capable of succeeding in WR star formation while the possibilities of the other channels appear too small. The absence of these other evolutionary channels also accounts for why the overall WR frequency is so weak in the SMC.

Inversely, in the zone located in the direction of the galactic centre, the non-binary channels are strongly operating and this may explain why the overall WR frequency is so much higher there than in the SMC, and simultaneously why the number ratio (binary WR/all WR) is small there.

The dependence of the mass loss rates on the initial metallicity was considered to strongly influence the formation of WR stars as a result of MS or RSG mass loss and therefore to be responsible for the observed gradients of WR stars in the Galaxy (cf. Maeder et al, 1980; Maeder, 1981 c; Lequeux, 1983). In the case of OB stars, the theoretical models of the stellar winds by Abbott (1982) indicate an almost linear increase of $\dot{M}$ with initial metallicity. For RSG, Kwok (1980) has also suggested an increase of $\dot{M}$ with metallicity, although the dependence might be weaker than for OB stars. Thus, a higher Z involves a higher $\dot{M}$, and the models of § 3a show that this produces in turn an increase of the expected number of WR stars and a corresponding decline in the number of RSG. It was emphasized that even a very mild dependence of $\dot{M}$ on Z is sufficient to explain a dependence such as that shown in Table 1 due to the very high sensitivity of N_{RSG}/N_{WR} vs. $\dot{M}$.

An alternative interpretation was proposed by Bertelli and Chiosi (1981), Garmany et al (1982) who suggested that the galactic gradient of WR stars just reflects the galactic gradient of O-stars. Subsequently, Meylan and Maeder (1983) showed that the galactic gradient of WR stars is steeper than that of O-stars, and that the gradient of RSG is of the opposite sign; consequently, they cannot only be the reflect of the IMF. The more recent episode of this story is due to Bertelli et al (1983) who suggested that the dependence of the opacity bumps on metallicity plays the dominant role in accounting for the properties of WR stars, which still rests on the hypothetical existence of opacity bumps, which were not quite supported by A.N. Cox in this meeting. Finally, although their origin is still subject to discussions, let us emphasize that these various gradients of massive O-stars, of WR and RSG stars must have considerable effects on galactic properties, such as colours, distribution of HII regions, supernovae and nucleosynthetic yields, an important subject which has not been considered in this review.

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DISCUSSION

Tayler: About 10 years ago a variety of authors (Appenzeller, Papaloizou, Talbot, Ziebarth) independently showed that vibrational instability would be stabilized at finite amplitude so that such stars would live longer than previously believed. Do you have any new ideas on this point?

Maeder: The point I emphasized is in fact different. I meant that even if the massive star is vibrationally stable during MS evolution, it may become vibrationally unstable when, due to mass loss by stellar winds, the star becomes an almost homogeneous bare He or He + C/O core with a real large mass. Now I think that massive bare cores are probably also limited to finite amplitudes by non linear effects as you mention, and this is why I suggested that they are evolving keeping at the edge of vibrational instability.

Kudritzki: What are the amplitudes of the theoretical WR-model vibrational instabilities? Could they be observed?

Maeder: The analysis we made is a non-adiabatic linear analysis, and therefore tells us the values of the periods and whether the models are unstable or not, but does not give the amplitude size. Some WR stars are known to be unstable but it is not clear what kind of instability we observe. However, it has to be noted that the wind of WR stars is thick and the optical depth $\tau \simeq 1$ from where the spectrum is supposed to come is still in the wind. This very strong wind might probably be the external manifestation of the internal instability.

Schatzman: Just a reminder. The instability is due to the kappa-mechanism or to the epsilon-mechanism?

Maeder: The vibrational instability I mentioned is due to the kappa-mechanism. The destabilizing role of radiation pressure is also important in this context.

Cox: I understand that you get much shorter growth rates now than were obtained by previous investigators. Is this because the surface material is no longer H + He, but now is carbon-rich in these Wolf-Rayet stars?

Maeder: Yes, a strong vibrational instability has been found, particularly for WC stars. For example, a 24 $M_{\odot}$ in the WC stage, i.e. a star with He + C + O envelope, shows a growth time of the pulsation amplitude of about 5 days, which is a very short time.

Bertelli: The observations seem to indicate that massive stars spend more than the core He-burning lifetime in the WR + RS phases. On the other hand only a small fraction of the central He-burning lifetime is available for models in the mass range 20 to 40 $M_{\odot}$ to appear as RS and, eventually, WR stars, if traditional models undergoing a moderate mass loss in the blue phase are considered. Can you comment on this point?

Maeder: It is quite clear that there is an excess of stars outside the MS band with respect to what is predicted by all published sets of stellar models. The question of an excess of WR stars is much more uncertain and it mainly remains on the lower mass limit assumed for their progenitors. If you take 40 $M_{\odot}$ for this limit, there is excess; for 20 $M_{\odot}$ there is none.

Humphreys: Although I believe that gradients in the B/R and WR/R ratios exist, I want to caution about the statistics especially for the red supergiants interior to the sun, e.g. 7-9 kpc galactocentric distance. Our knowledge of the M supergiants is very incomplete in this distance range, and in the 11-12 kpc range the numbers are highly influenced by one association, h and χ Per and the surrounding association. It could be just a perturbation.

Cassé: As far as nucleosynthesis is concerned I would like to point out that WR stars, or more particularly WC stars at the end of their evolution, could be generous sources of s-process element (at least up to mass 90, see e.g. Lamb et al, 1976). WC stars can be considered as open-cast mines of ^{25}Mg, ^{26}Mg, ^{58}Fe and s-process element at the end of their career and the extraction is automatically done by the wind.

Maeder: I fully agree with you and we have considered the possibility of excesses of ^{12}C, ^{22}Ne, ^{25}Mg and ^{26}Mg in the cosmic rays originating from WC stars and the results are very encouraging.

Vanbeveren: The fact that viscosity in the interior of massive stars is so high, doesn't that prevent somehow large scale overshooting?

Maeder: The high radiative viscosity certainly contributes to damp overshooting, however the buoyancy forces are also much stronger in massive stars and hence the balance of both intervenes. In this context we must remember that large viscosity would strongly favour turbulent diffusion.

de Groot: There may be additional observational evidence for vibrational instability: Just recently Lamers and his students have found from the UV lines in P Cygni that an absorption component drifts in velocity with a time scale of about 1 year. Can you say from your calculations whether this time scale is about right for vibrational instability?

Maeder: Before being able to say whether this is in agreement or not, the oscillation modes of the given star have to be identified. The vibrational instabilities have shorter periods than the one you quote. Thermal readjustments, shell ejections, for example, may perhaps also be considered in this context.

Gurm: Are supergiants intrinsic variables or just present a surface phenomenon of the rising convection cells which would be large size to the order of the radius?
If these are intrinsic variables, how do you explain the multiplicity of the periods of the variables amongst the supergiants?

Maeder: I would suggest supergiant stars are intrinsic variables, at least as far as intermediate time scales are considered (from a few days to one year). Very short term variations (shorter than one day) could be associated to surface phenomena.
Most periods satisfy a period-luminosity-colour relation. However, differences and scatter could be introduced by the fact that some supergiants are on blueward and some others on redward tracks with differences in the internal structure.

Audouze: According to you, what is the minimum initial mass for a star to become a Wolf-Rayet star , (taking into account current rates of mass loss)?

Maeder: The minimum initial mass leading to WR stars is around 20 or 25 $M_\odot$, on the basis of WR stars present in clusters. The average observed mass loss rates lead to a slightly higher value (~30 $M_\odot$). However, one has to account that the scatter and uncertainty of mass loss rates are large.

Conti: André Maeder has been discussing a lower mass limit for W-R stars of 25-30 $M_\odot$, while our number is closer to 35-40 $M_\odot$. In a spirit of compromise I would suggest 33 $M_\odot$. Seriously, though,our numbers are not inconsistent with one another, given the uncertainties. I do feel the value is higher than 20 $M_\odot$, however.

Tayler: We were told yesterday that there are a few masses for OB and WR stars. Do these masses agree at all with the masses suggested by theoretical evolutionary tracks?

Conti: There are a few masses for doubled OB systems not too far up the main sequence (to type O8V). These agree with theoretical tracks. However, the predicted mass losses by stellar winds are insufficiently large in these stars to be readily discernable in the binary data. There is some additional X-ray binary pulsar information that gives masses of the neutron star companions. These stars are invariably undermassive for their luminosity, suggestive of previous mass loss. The wind rates required are a little high but the deductions are complicated by previous evolutionary history of these close binary systems. In other words, we don't have any direct, that is binary, evidence of that correctness of the wind mass loss formulations in a quantitative sense.