SESSION 5.

MASSIVE STAR EVOLUTION.

Chairman : R. HUMPHREYS.

1. A.MAEDER: Massive Star Evolution: Mass Loss and Mixing.
2. J.SILK: Physical Processes in Massive Star Formation.
3. C.CHIOSI: Effects of Convective Overshooting, Mass Loss (and Chemical Composition) across the HR Diagram.
4. J.P. DE GREVE and C. DE LOORE: Binary Evolution in the Upper H-R Diagram.

MASSIVE STAR EVOLUTION: MASS LOSS AND MIXING

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1. INTRODUCTION

At first it may be surprising that mass loss, overshooting and mixing, which are indeed very different physical processes, have similar consequences on stellar evolution. These various processes may increase the Main-Sequence (MS) lifetime, extend the width of the MS, bring CNO-processed materials to stellar surfaces and, in extreme cases, lead to quasi-homogeneous evolution. The physical reason of this similarity is that these processes increase the relative mass fraction of the stellar cores. Thus we understand that, on the basis of their evolutionary consequences, it may not be easy to disentangle the contributions of mass loss, overshooting and mixing processes. The present status of our knowledge on these effects, which appear to have major consequences on the evolution of massive stars, is now examined in detail.

2. EFFECTS OF MASS LOSS ON THE POPULATIONS OF MASSIVE STARS

An impressive number of authors have studied the effects of mass loss on stellar evolution, particularly on main sequence evolution (e.g. Tanaka, 1966a,b; Hartwick, 1967; Simon and Stothers, 1970; Chiosi and Nasi, 1974; de Loore et al., 1977; Dearborn and Eggleton, 1977; Dearborn et al., 1978; Sreenivasan and Wilson, 1978; Chiosi et al., 1978; de Loore et al., 1978; Stothers and Chin, 1978; Dearborn and Blake, 1979; Czerny, 1979; Chiosi et al., 1979; Stothers and Chin, 1979, 1980; Maeder, 1980; Noels et al., 1980; Bressan et al., 1981; Maeder, 1981a,b; Stothers and Chin, 1981; Noels and Gabriel, 1981; Brunish and Truran, 1982a,b; Doom, 1982a,b; Sreenivasan and Wilson, 1982; Maeder, 1983; Doom, 1984; Sreenivasan and Wilson, 1985).

Table 1 summarizes what the present author considers to be the main effects of mass loss on stellar evolution; not included are the changes of surface abundances which are examined in § 3. Firstly, the MS case is considered. It is a noticeable fact that, while a moderate mass loss

C. W. H. De Loore et al. (eds.), Luminous Stars and Associations in Galaxies, 287–300.

TABLE 1: Main effects of mass loss on massive star evolution.

MAIN SEQUENCE

★ $M_{\rm core} \searrow$, $q_c = \frac{M_{\rm core}}{M} \nearrow$, semi-convection $\searrow$

★ $L \searrow$, $L/M \nearrow$

★ MS lifetime $t_H \nearrow$ (by 5-15%)

★ moderate $\dot{M}$: MS widening
very high $\dot{M}$: MS narrowing (quasi-homogeneous evolution)

HE - BURNING PHASE

★ Large effects in HRD/Very small in log Tc vs. log ρc.
(central conditions)

★ 3 evolutionary sequences according to $\dot{M}$ and $M_{\rm initial}$
(cf. Table 2)

★ $t_{He} \simeq t_{BSG} + t_{RSG} + t_{WR}$, sharing varies with $\dot{M}$ (cf.Maeder, 1981b)

★ ***BLUE SUPERGIANTS (BSG):***

no $\dot{M}$: $t_{He} \simeq t_{BSG}$

with $\dot{M}$: $\left\{ \begin{array}{l} \text{He - phase moves to red} \\ \text{Blue loops reduced} \end{array} \right\}$ $t_{BSG} \searrow$

★ ***RED SUPERGIANTS (RSG):***

moderate $\dot{M}$ => $\frac{t_{RSG}}{t_{OBA}} \nearrow$
(for low $\dot{M}$: lack of RSG)

high $\dot{M}$ => $\frac{t_{RSG}}{t_{OBA}} \searrow$

$\dot{M} \nearrow$ => $\frac{t_{RSG}}{t_{OBA}} \nearrow\searrow$

★ ***WOLF-RAYET STARS (WR):***

$\dot{M}$ incrases t_{WR} / t_{OBA}
lowers threshold mass for
forming WR stars (most
from $M_{\rm initial} \geq 40\ M_\odot$)

$\dot{M} \nearrow$ => $\frac{N_{WR}}{N_{OBA}} \nearrow\nearrow$
(factor 2 on $\dot{M}$ =>
factor 17 on N_{WR}/N_{OBA})

$\dot{M} \nearrow$ => $N_{WR}/N_{RSG} \nearrow\nearrow$

Mass - luminosity relation
for WR stars

$$\log \frac{L}{L_\odot} = 3.8 + 1.5 \log \frac{M}{M_\odot}$$

produces a MS widening, a high mass loss (as it occurs above 10^2 $M_\odot$) produces a MS narrowing and quasi-homogeneous evolution. For the He-burning phase, the major results are also emphasized. Indeed, according to the mass loss rates and to the initial stellar masses, three different evolutionary sequences may occur in the HR diagram (cf. Maeder, 1981a,b, 1984): always blue; blue-red-blue; blue-red. These three different evolutionary sequences are illustrated in Table 2, and Fig. 1 also shows the corresponding HR diagram. In contrast, we recall (cf. Maeder and Lequeux, 1982) that the effects of mass loss on central conditions are very limited.

The He-burning phase is shared between the blue supergiants (BSG), the red supergiant (RSG) and the WR stages. This sharing is very dependent on mass loss rates and initial mass; quantitative information can be found in Maeder (1981a,b). The time spent as BSG is reduced by mass loss; this is due to the redwards displacement of the horn-shaped band corresponding to the He-burning phase in the HR diagram. The RSG lifetime firstly increases with moderate mass loss and then decreases with higher rates. As to the relative frequency of WR stars, it strongly increases with mass loss, because the peeling-off by stellar winds reveals the underlying bare core earlier, and also because the threshold mass for the formation of WR stars is lowered.

According to Conti et al. (1983b), the observed ratio (WR number) /

TABLE 2: Three different evolutionary sequences for massive stars.

For $M \gtrsim 60\ M_\odot$ *Always blue*

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

For $25\ M_\odot \lesssim M \lesssim 60\ M_\odot$ *Blue-red-blue*

O star - BSG - yellow and RSG - BSG - WN - (WC) - SN - *high $\dot{M}$*
SN - *moderate $\dot{M}$*

For $M \lesssim 25\ M_\odot$ *Blue-red*

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

(OB stars with $M \geqslant 40\ M_\odot$) is 0.23, while evolutionary models usually predict a ratio t_{He}/t_H of the helium- to H-burning phases of 0.10. This difficulty seems to be considerably reduced by models (Maeder, in prep.) using the new, higher $^{12}C(\alpha,\gamma)^{16}O$ rate (cf. Kettner et al., 1982). The physical reason of the longer He-lifetime is that in addition to the conversion of ^4He to ^{12}C, we also have an almost complete fusion of ^{12}C to ^{16}O, making thus more energy available than previously considered. In addition, as the He-burning reactions are more energetic, the mass fraction of the convective core is larger and more fuel is available, which also increases the He-burning lifetime. (One must notice that these effects are smaller for stars of lower masses, because less ^{12}C is turned into ^{16}O). Another effect, which also sizeably increases the WR lifetimes, is the decline of the stellar luminosity resulting from the strong decrease of the stellar mass in the WR stage. Even with the old $^{12}C(\alpha,\gamma)^{16}O$ cross-section we obtained (Maeder, 1983), due to that effect, a ratio $t_{WR}/t_H = 0.3$ for a star with an initial mass of 120 $M_\odot$.

We also emphasize in Table 1 that the expected number ratio of WR stars and RSG very strongly increases with mass loss. As the bulks of these two kinds of massive stars do not originate from the same mass interval, the ratio t_{RSG}/t_{WR} changes extremely steeply (cf. Fig. 6 in Maeder, 1981b) in function of the M_{bol} at MS turnoff or in function of cluster ages. Thus, at a given age, a cluster contains in general either WR stars or RSG, and therefore both rarely cohabit in the same cluster. In order to observe a possible change in the Galaxy of the ratio N_{RSG}/N_{WR} (very sensitive to $\dot{M}$-rate) for these two kinds of massive and easily identifiable stars, it is very necessary to consider in the sample all stars brighter than a given luminosity ($M_{bol} = -6$, -7 or -8). However, by restricting the sample only to clusters and associations containing WR stars (cf. Humphreys et al., 1985) one a priori excludes RSG-rich groups.

The last topic mentioned in Table 1 is the predicted mass-luminosity relation for WR stars. This relation results from the fact that WR stars, whatever their initial masses, are nearly homologous stars consisting of a large He, C, O core. It is to be emphasized that a stability analysis indicates that WR stars generally are vibrationally unstable due to the Eddington ε-mechanism.

3. MASS LOSS AND SURFACE CHEMICAL ENRICHMENTS

The surface abundances in massive stars may change during evolution as a result of mass loss by stellar winds and due to dredge-up by deep convective envelopes, as they occur in red supergiants. We also note that the intermediate fully convective zones (which usually exist in massive stars with no excessive mass loss) produce an averaging of composition over some fraction of the star, also influencing surface abundances when the concerned layers are revealed by mass loss.

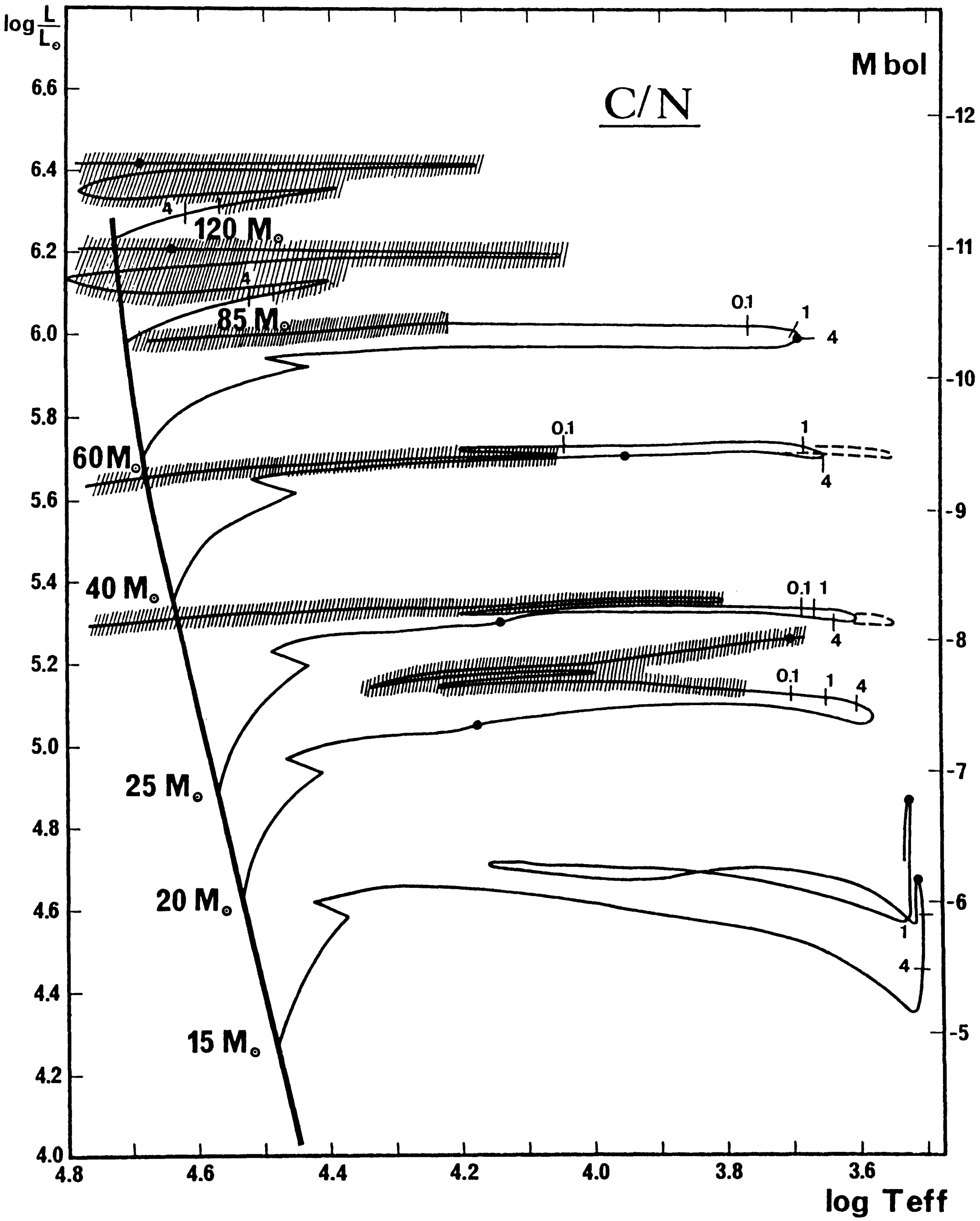

Figure 1. Values of the surface ratios $X(^{12}C) / X(^{14}N)$ along the evolutionary tracks of massive stars. The hatched parts indicate where the equilibrium value of 0.025 occurs.

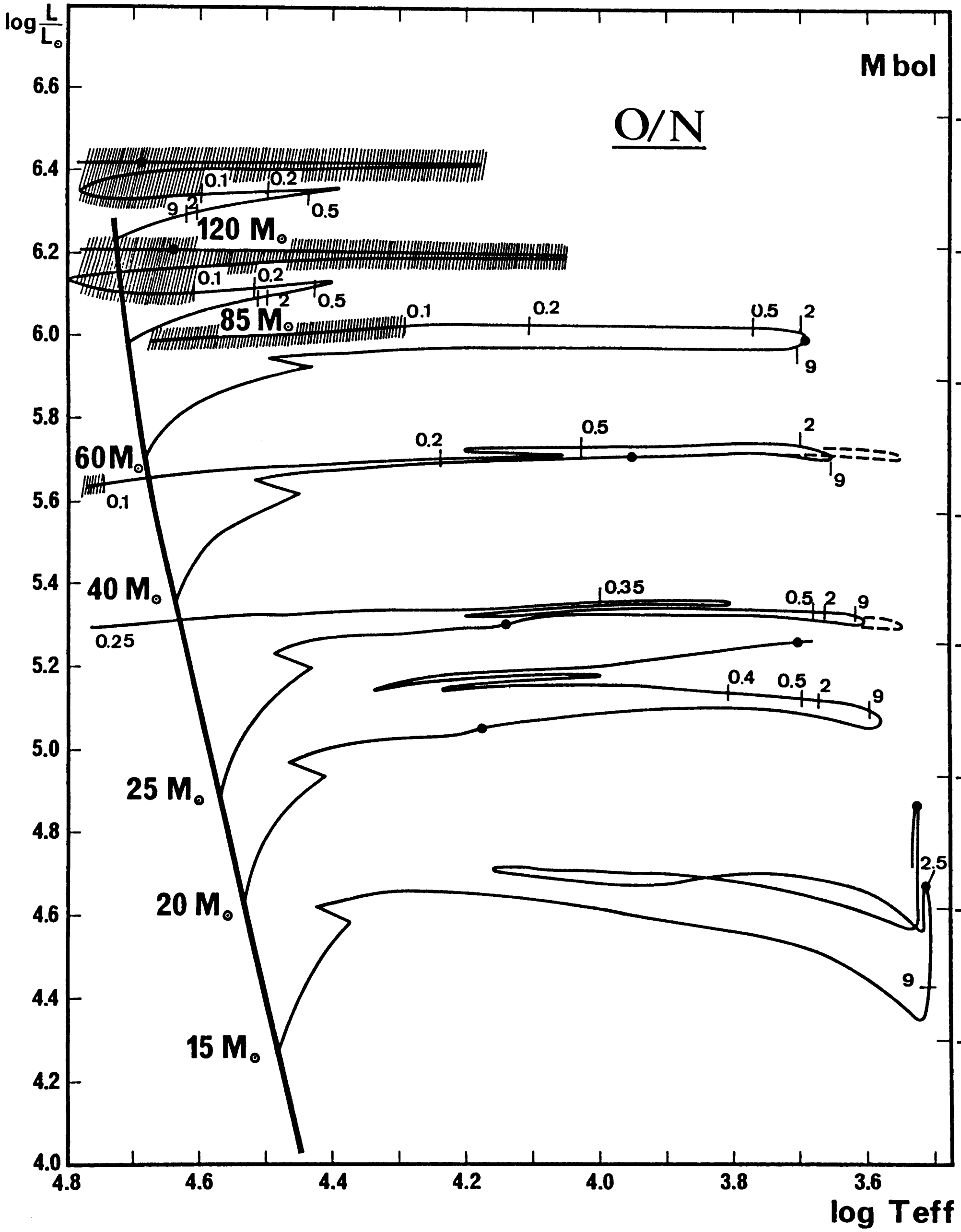

Figure 2. Values of the surface ratios X(^{16}O) / X(^{14}N) along the evolutionary tracks of massive stars. The hatched parts indicate where the equilibrium value of 0.1 or smaller occurs.

Calculations taking the above effects into account have been made by Noels et al. (1980), Noels and Gabriel (1981), Maeder (1983), Greggio (1984) and Maeder (1985). The effects of more sophisticated, but uncertain hydrodynamical processes have generally not been included, as it is firstly necessary to have a standard basis for comparison with observed CNO abundances (cf. also § 4). Spectroscopic observations of CNO elements constitute a powerful test of stellar evolution, particularly with regard to the possibility of deviations from the standard case. Detailed evolution of the surface abundances of ^{1}He, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{20}Ne, ^{22}Ne, ^{24}Mg, ^{25}Mg and ^{26}Mg in stars of initial masses 120, 85, 60, 40, 25, 20 and 15 $M_\odot$ have been calculated by the author (1983, 1985). For 60 $M_\odot$ and lower masses, the surface abundances of CNO processed elements change step-like rather than continuously as in higher masses. The "plateaux" are due to the convective zones, which average the chemical composition over some parts of the stars. When mass loss unveils these chemically homogeneous regions, the composition keeps rather constant for some time.

Of all chemical changes at stellar surfaces, those of C/N and O/N ratios are among the largest and observationally the most accessible ones. As an example, the C/N ratio may change from 4 (cosmic value in mass fraction) to $2.5 \cdot 10^{-2}$ (equilibrium CNO value) and to 10^{14} in WC stars which, as is known, exhibit products of partial He-burning.

Fig. 1 shows the changes of the ^{12}C/^{14}N ratio during the evolution in the HR diagram. On the tracks, the value of $X(^{12}C) / X(^{14}N) = 4$ is indicated at the latest point where it occurs; the values 1 and 0.1 are also given (all data in mass fraction). The hatched area indicates where the equilibrium values of about 0.025 are expected. We notice that for stars brighter than $M_{bol} = -10.5$, equilibrium C/N ratio can be found everywhere in the HRD. For initial masses between 60 and 25 $M_\odot$, the stars keep their standard abundances until the red supergiant stage is reached and departures only occur in later phases. Below 20 $M_\odot$, equilibrium C/N no longer occurs.

Fig. 2 shows the distributions of the ^{16}O/^{14}N ratios in the HRD (data also given in mass fraction). Equilibrium O/N ratios only occur for initial masses larger than 60 $M_\odot$, in particular in the LBV stars and in further evolutionary phases. For lower masses, deviations from the standard O/N ratio appear in stages later than the supergiant stage; the smaller the initial masses, the more limited these deviations are, as normally expected.

Turning now to the observations, we notice that the LBV variables and the WR stars are the best examples for changes of surface abundances. In the case of the LBV star η Carinae, Davidson et al. (1982, 1984) determined the abundances in some of the outer condensations surrounding the central nebula and found ratios C/N < 0.05 and O/N < 0.15 – 0.5 (in number). These ratios differ very much from the solar ones (C/N ≃ 4, O/N ≃ 9) and are in full agreement with the values obtained in the blue supergiant phase of an initial 120 $M_\odot$ star evolving with mass loss. These observed abundances provide a strong constraint on the long standing problem (cf. Stothers and Chin, 1983) of the evolutionary status of the LBV stars.

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, 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. As Wolf-Rayet stars directly exhibit the products of CNO-cycles (WN stars) and of the He-burning (WC stars), they offer us a most valuable check on the basic nuclear reactions operating in stars. This check proves very satisfactory (cf. Maeder, 1983), but more elements should be observed.

Recently a beautiful result has been obtained by van der Hucht and Olnon (cf. this book) from IRAS low resolution spectrograph. For the WC8 component of the WR binary γ^2 Velorum, they found a ratio N_{Ne}/N_{He} = 0.011, which corresponds to X(Ne) / X(He) = 0.06. This is in complete agreement with theoretical models (Maeder, 1983), which predict X(Ne) / X(He) between 0.025 and 0.07 for the beginning and end of the WC stage respectively. This value is an order of magnitude larger than the standard cosmic ratio (about $5.4 \cdot 10^{-3}$ in mass fraction). This interesting IRAS result is the first direct evidence for the theoretically predicted surface enrichtment of WC stars in Ne. This very high Ne enrichment is due to the isotope ^{22}Ne, which usually is only about 10% in number of the whole of the atoms of Neon. WC stars are thought to be the major source of ^{22}Ne in the universe (Maeder, 1983) and the origin of the excess of ^{22}Ne in galactic cosmic rays has recently been discussed in relation with WC stars (Maeder, 1984).

As shown by Figs. 1 and 2, non-standard C/N and O/N ratios are also expected for supergiants in stages following the red supergiant phase. Claims have been made by Luck and Lambert (1981) that the CNO abundances at the surface of Cepheids bear the signature of some non-standard mixing. Iben and Renzini (1983) showed, however, that a detailed inspection of the data does not support this conclusion.

4. OVERSHOOTING AND ROTATIONAL MIXING

In the study on cluster sequences in the mass range of 1 $M_\odot$ to 9 $M_\odot$, Maeder (1974, 1976) and Maeder and Mermilliod (1981) pointed out that the observed main sequences extend farther in the HR diagram than was predicted by standard models constructed with Schwarzschild's criterion.

No change of initial helium abundance or of metal content was able to bring theory in agreement with observations. They concluded that an overshooting process increasing the core mass by 20-40% could reproduce the location of cluster turnoffs. As a rule of thumb, let us mention that a star of a given mass with overshooting behaves to the first order like a model of higher mass without overshooting.

Several new studies about convective overshoot recently appeared (Bressan et al., 1981; Stothers and Chin, 1981; Matraka et al., 1982; Doom, 1982a,b; Eggleton, 1983; Bertelli et al., 1985; Doom, 1985; Stothers and Chin, 1985; Langer and Sugimoto, 1985; Xiong Da Run, 1985). On the theoretical side, the situation remains rather confuse: there are large differences in the distance of overshooting predicted by the various theoretical models. For example, Langer and Sugimoto find a negligible or even zero overshoot, while Xiong Da Run finds a very large one (typically a ratio d_{over}/H_p of the overshooting distance to the pressure scale height at the edge of the classical core equal to 0.7). The Roxburgh criterion (1978) has been claimed to contain inconsistencies (cf. Eggleton, 1983; Bertelli et al., 1985), a point of view which is not supported by Doom (1985).

On the observational side, the results look more consistent. Various observational features in MS (cf. Maeder, Mermilliod, 1981) and in post-MS evolution (cf. Bertelli et al., 1985) are well accounted for by models with overshooting. Stothers and Chin (1985) find a good agreement between cluster sequences and models of massive stars with a moderate overshooting, corresponding to 20-40% of core extension. Recently, detailed comparisons between theoretical isochrones of models with mass loss and observed sequences of 25 young clusters have been made (Mermilliod, Maeder, 1986). These clusters are carefully discussed for reddening, distances, membership, binarity and stellar peculiarities; account is also given for the possible effects of unsolved binaries, of rapidly rotating stars, of differences in mass loss rates and opacities. The comparisons indicate that: 1) For the very young clusters with turnoff at type earlier or equal to B0, the theoretical main sequence band with mass loss could be too wide with respect to the observed main sequence band. 2) For older clusters, the width of the theoretical main sequence band is too small compared to the observations. The discrepancy amounts to 1.0-1.5 mag for clusters with an age between 10^7 and $2.1 \cdot 10^7$ y. It is unlikely that the differences can be due only to mass loss rates. On the basis of various models, we propose that some extra mixing, overshooting or turbulent diffusion is at the origin of the observed differences. If we attribute the whole difference to the overshooting process (which is by no means certain, see below), a ratio $d_{over}/H_p = 0.3$ could be tentatively estimated on the basis of massive stars in the range of 9 to 15 $M_\odot$.

Zahn (1983) has made a detailed discussion of the instabilities generated by stellar rotation, which is a long standing problem since the time of Eddington. Other recent works have also been made by Sreenivasan and Wilson (1982, 1985). Let us consider the main steps of Zahn's developments:

- The meridional circulation resulting from thermal imbalance generates a small differential rotation.
- This differential rotation is insufficient for generating shear instabilities between adjacent layers. However, the small differences in angular velocity Ω create some horizontal turbulence of meteorological nature. This turbulence is two-dimensional and in itself it leads to no vertical mixing.
- The 2-D turbulence cascades, as turbulence always does, towards small scales until inertial terms become larger than Coriolis terms. Then, this small scale 2-D turbulence becomes 3-D.
- The small scale tail of the 2-D turbulence produces vertical exchanges and a diffusion mixing characterized by a diffusion coefficient $D = Re^{*}\nu$, with

$$Re^{*} = \frac{K}{\nu}\,\frac{\Omega^{2} r}{g}\,(\nabla_{ad} - \nabla_{rad}) \qquad (1)$$

Re^{*} is the modified Reynolds number, ν the viscosity and K the radiative diffusivity. In order to obtain the value of Re^{*} at each level r in the star, we need to know $\Omega(r)$. Following a suggestion by Schatzman, we may suppose that the star is just at the verge of the axisymmetric baroclinic instability (Knobloch and Spruit, 1983), which is the first instability met by a differentially rotating star. In this case, Re^{*} becomes

$$Re^{*} = \frac{8r}{\left(\frac{\partial \ln \Omega}{\partial \ln r}\right)^{2} H_p} \quad \text{with} \quad \frac{\partial \ln \Omega}{\partial \ln r} = \left(\frac{8\nu\, N^{2}}{K\, \Omega^{2}}\right)^{\frac{1}{2}} \qquad (2)$$

where N is the Brunt-Väisälä frequency. Account must also be given to stabilization by μ-gradients.

It is generally believed that mild diffusion processes may be significantly acting only in low mass stars, where the MS lifetimes are long enough. However, the radiative viscosity is so large in massive stars that the diffusion timescales may become shorter than the MS lifetime (Maeder, 1982).

Models with different angular velocities have been computed for a 40 $M_{\odot}$ star according to the above scheme, including also mass loss and overshooting. The results (Maeder, 1986) essentially show two different types of evolution:

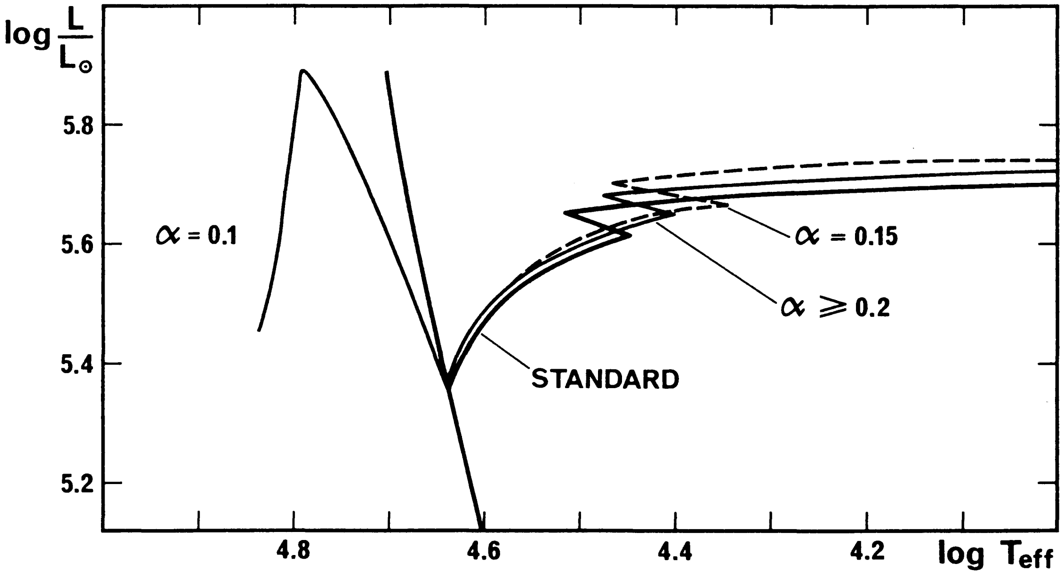

Figure 3. Evolutionary tracks of an initial 40 $M_\odot$ star for different values of $\alpha \equiv \partial \ln \Omega / \partial \ln r$.

A) Classical evolution: In case of low and moderate rotation, the stabilizing effect of the μ-gradient severely limits the extension of turbulent diffusion and all models nearly follow the same tracks close to the classical ones (with overshooting). The evolution is essentially inhomogeneous; the MS lifetime and the surface CNO abundances undergo only very limited changes.

B) Mixed models: For fast rotation (or low $\partial \ln \Omega / \partial \ln r$ according to expression 2), the stabilizing effect of the μ-gradient is unable to prevent mixing. This evolution resembles the homogeneous one giving bluewards tracks in the HR diagram (cf. Fig. 3). Processed CNO elements rapidly appear at the stellar surface. The luminosity firstly increases strongly. In view of its composition, the star becomes a WR star and then undergoes a decline in luminosity due to the rapid decrease of its mass. Mainly because more nuclear fuel is available, the MS lifetime is larger by about 55%.

The switching from one behaviour to the other occurs quite rapidly in terms of $\partial \ln \Omega / \partial \ln r$; the critical value lies between 0.10 and 0.15. Observationally, the mixed models seem to be interesting for explaining those of OBN stars, which often occur as blue stragglers in clusters (cf. Schild, 1985). Future works, both theoretical (since expr. 1 may contain uncertain numerical factors, cf. Zahn, 1983) and also observational, will allow us to determine the critical limiting rotational velocity, which we provisionally estimate to be of the order of a few hundredths of km/sec.

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Discussion : MAEDER.

SREENIVASAN :

We have recently shown that massive stars (WR stars and supergiants) are overstable for non-radial pulsations (retrograde modes) due to Kelvin-Helmholtz instability, driven by differential rotation. We have also shown that significant rotation produces "blue stragglers" due to rotational mixing. An extended core and the peeling off of the outer layers due to mass loss reveals "abundance anomalies" much earlier in the evolution of a star.

I therefore believe that a confrontation of observations with the prediction of these new models should be more profitable and is along the right direction (as you have also observed).

KONTIZAS M. :

At which ages of star clusters does one expect to find blue stragglers?

MAEDER :

Usually, blue stragglers occur in old clusters with an age of the order of a few billion years. A good example is NGC 7789. However, as I mentioned, some N-enriched O-type stars in very young clusters are located to the blue side of the considered cluster turnoff.