# EVOLUTION OF MASSIVE STARS WITH MASS LOSS: SURFACE ABUNDANCES

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The location of theoretical stellar models in the upper part of the HR Diagram (HRD) depends on a variety of poorly understood physical processes which may occur during the evolution of massive stars. Among the most important we find: mass loss, convective overshoot and opacity enhancement for temperatures around $10^6$ °K. The effects of these phenomena have been recently investigated by several authors (Bertelli et al. 1983 and references therein), but, due to the large uncertainties still present in the theoretical formulation of these processes, only parametrized formulae are avaliable for model computations. Since the theoretical distribution of massive stars in the HRD turns out to be fairly sensitive to these parameters, the evolutionary scenario for massive stars is still far from being satisfactorily settled. On the other hand, due to mass loss, nuclear processed material is expected to be exposed at the surface of massive stars and then, the comparison between theoretical predictions and observations of the surface chemical composition of these objects can help in understanding their evolution and to set more stringent limits to the mentioned parameters.

To this end, evolutionary sequences corresponding to 20, 40 and 60 $M_\odot$ have been computed up to core He exhaustion, following in detail the abundance variations of CNO, Ne and Mg isotopes. Overshooting from convective cores was taken into account during both H and He burning stages, following the procedure described in Bressan et al. (1981). According to Chiosi and Olson (1981), a mass loss rate given by $\dot{M} = 3.47\times10^{-16}\ L^{1.75} \times\{RM/(1-\Gamma)\}^{1.03}\ M_\odot/yr$ was applied during the MS phase, while in the red supergiant stage a constant value of $\dot{M} = 10^{-5} M_\odot/yr$ was adopted.

Both 20 and 40 $M_\odot$ models do not present variations in their surface abundances during the MS phase. When the models enter the red supergiant region, the inward penetration of the convective envelope causes the



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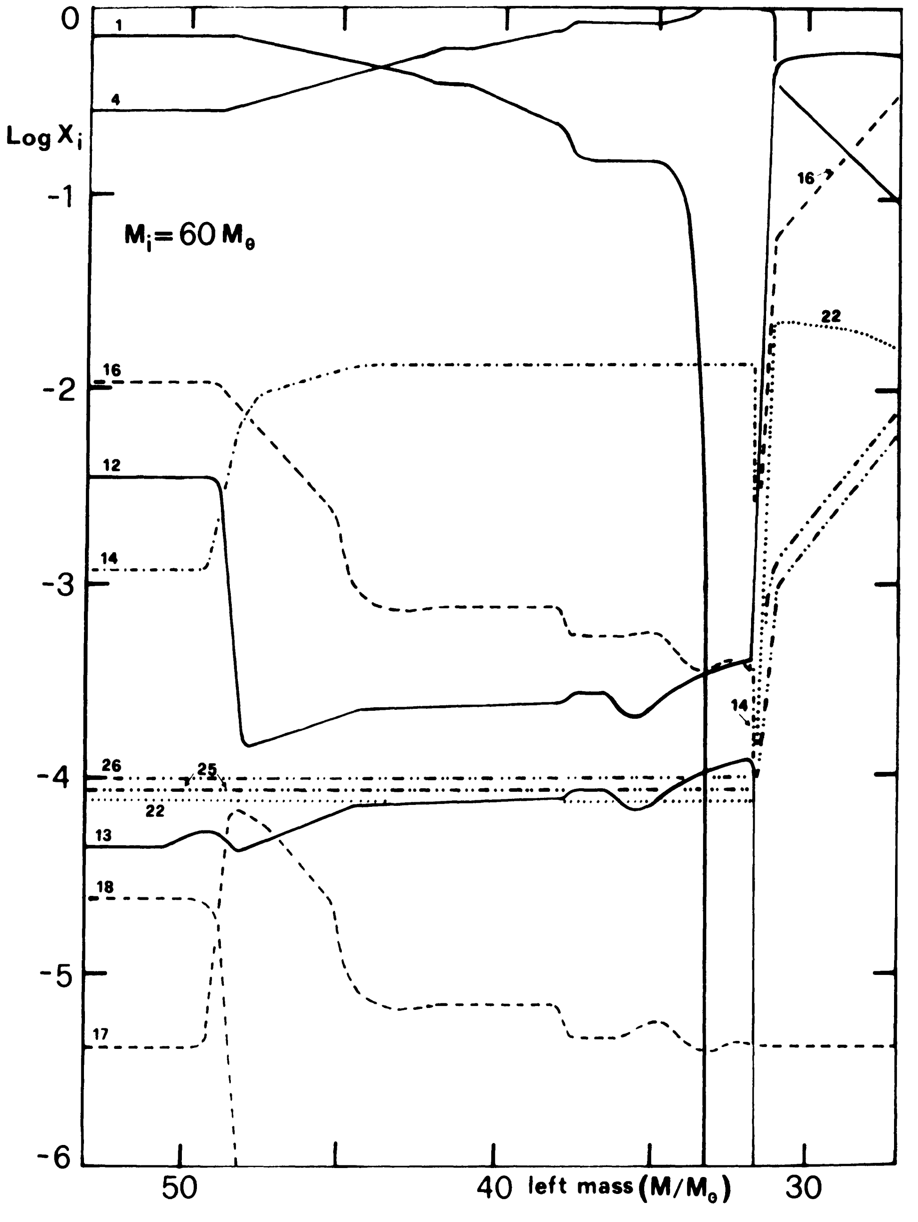


*Fig.1 Evolution of the chemical abundances in mass fraction as functions of the remaining stellar mass for the 60 $M_\odot$ model. The mass number of the various species is indicated.*

dredge up of CNO processed material: the surface $^{14}N$ abundance gets enhanced, while $^{12}C$ and $^{16}O$ are depleted. The surface $^{12}C/^{13}C$ ratio is considerably lowered and, to a minor extent, even the $^{16}O/^{17}O$ and $^{17}O/^{18}O$ ratios are affected. The predicted abundances are:

C/N≅ 0.87 O/N≅ 2.11 $^{12}C/^{13}C$≅ 18.31 $^{16}O/^{17}O$≅ 1014 $^{17}O/^{18}O$≅ 0.87

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$C/N \cong 0.27$ $O/N \cong 0.70$ $^{12}C/^{13}C \cong 23.08$ $^{16}O/^{17}O \cong 610.4$ $^{17}O/^{18}O \cong 1.42$ for the 20 and 40 $M_\odot$ models respectively. The subsequent evolution is spent in the red part of the HRD and the model is expected to give rise to a type II SN event. Due to the huge mass loss and to the large size of the convective core, the 60 $M_\odot$ model starts exhibiting CNO processed material at the surface while still on the MS. Following the representation adopted by Maeder (1983), Fig.1 shows the behaviour of the surface abundances as functions of the remaining stellar mass. Since the dilution due to convection is not present, the surface composition of the model during the late MS evolutionary stage corresponds to equilibrium CNO abundances: $C/N \cong 0.02$ and O/N steadily decreasing down to 0.05. When H is ignited in a shell, the envelope expansion causes a redward excursion, which is stopped and reversed by the mass loss. Eventually, the model enters the blue region of the HRD with a low surface H abundance and is taken to represent a WNL star. Further removing of the outer layers brings complete CNO processed material at the surface and the H abundance drops to zero. In this stage, the model may represent a WNE object. WN stars are then predicted to exhibit CNO equilibrium abundances, that is $X_N/X_{He} = 1.5 \times 10^{-2}$ and $X_C/X_{He} = (3.8 \div 5.5) \times 10^{-4}$. When He burning products appear at the surface, the abundances suffer an abrupt change: $^{12}C$, $^{22}Ne$ and $^{16}O$ are enhanced by factors of $\sim$500, 200 and 100 respectively, while $^{14}N$ and $^{13}C$ virtually disappear. In this stage the model is taken to represent a WC star and may eventually turn into a WO star, as the surface $^{16}O$ abundance keeps steadily growing.

In order to investigate upon the effect of an opacity enhancement for $T = 10^6$ °K, a 20 $M_\odot$ evolutionary sequence has been computed adopting the Bertelli et al. (1983) algorithm for the opacity. In this case, the model spends $\cong$ 15% of its total core H burning lifetime as a red supergiant, suffering a huge mass loss. As a consequence, the H rich envelope is removed and the model returns to the high temperature region of the HRD. The dredge up of CNO processed material modifies the surface abundances during the red supergiant stage and the predicted values are: $C/N \cong 0.99$ $O/N \cong 2.52$ $^{12}C/^{13}C \cong 19.65$ $^{16}O/^{17}O \cong 685.4$ $^{17}O/^{18}O \cong 1.14$. Further removal of the outer layers eventually exposes H poor material at the surface and the subsequent evolution of the surface chemical abundances is very similar to that already described for the 60 $M_\odot$ model.

These results support the evolutionary scheme according to which single WR stars originate from massive progenitors and the WC objects are bare He burning cores. In particular, strong Ne and Mg surface overabundances are predicted for WC stars. The predicted relative number of WR stars with respect to their massive progenitors can be greatly increased if an opacity bump around $10^6$ °K is present, so that the star suffers a high mass loss rate for an appreciable fraction of its core H burning lifetime.

However, the results are fairly dependent on the rate of mass loss which is assumed in the red supergiant stage. Finally, a non negligible fraction of massive O-type stars is predicted to show a surface N overabundance, due to the effect of overshooting and mass loss. The same processes are extremely important in determining the surface composition of red supergiant stars.
A full account of these calculations will appear elsewhere (Greggio 1984).

## REFERENCES

Bertelli,G., Bressan,A.G., Chiosi,C. 1983, preprint
Bressan,A.G., Bertelli,G., Chiosi,C. 1981, Astron. Astrophys. 102, 25
Chiosi,C., Olson,G.L. 1981, private comunication
Greggio,L. 1984, in preparation
Maeder,A. 1983, Astron. Astrophys. 120, 113

## DISCUSSION

Audouze: I would like you to comment on the many discontinuities of the $^{17}O$ abundance curves calculated in your 60 $M_\odot$ and 20 $M_\odot$ models. Moreover, how do you explain the fact that there is no $^{18}O$ present in the inner zones? Are these two features connected with the uncertainties on the nuclear reaction rates?

Greggio: The discontinuities shown by the abundance curves reflect the distribution of the $X_i$ with radius inside the star and the mixing episodes occurring during the evolution. For the 60 $M_\odot$ model, for example, the first rise in $X_{17}$ is due to its production up to the equilibrium value, while the following trend simply reflects the $^{16}O$ behaviour, since layers in which the two O isotopes exhibit equilibrium abundances appear at the surface. The first plateau is due to the surface convection, developing during the redward excursion of the evolutionary model, while the second plateau is due to the development of an intermediate fully convective region, above the H-burning shell. Other details depend on the evolution of the temperature structure in the hottest radiative layers and on the sensitivity of the thermonuclear reaction rates to temperature variations.
The lack of $^{18}O$ which you refer to is due to the fact that, when the He-burning convective core has attained its maximum size, all the $^{18}O$ has already gone into $^{22}Ne$. The result is however dependent on the overshooting (see Maeder, this conference).

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