EVOLUTION OF HIGH MASS STARS

André Maeder
Geneva Observatory
CH-1290 Sauverny / Switzerland

1. INTRODUCTION

Several properties of massive star evolution are of great interest for the understanding of young populations in galaxies: -the genetic connections predicted by the models for the various types of massive stars allow us to understand their filiation; -in order to study the differences of the relative star frequencies in galaxies, we have to know which properties affect the lifetimes in the various evolutionary stages; -the composition of stellar winds is interesting to discuss the wind injections into the interstellar material, particularly the injections by Wolf-Rayet stars, and to discuss the influence of mass loss on nucleosynthesis and chemical yields. Here we shall briefly summarize some recent results on these various problems. For more details the reader may refer to general reviews (cf. Humphreys, 1984; Maeder, 1984a,b; Chiosi and Maeder, 1986).

2. GENETIC CONNECTIONS AMONG MASSIVE STARS

At constant mass, massive stars evolve from the main-sequence to red supergiants, a stage in which they explode as supernovae. With mass loss according to recent parametrizations (cf. Garmany et al., 1981; Lamers, 1981; de Jager et al., 1985), the situation is more subtle. Three mass ranges have to be considered:
- 1. Stars with an initial mass above 60 $M_{\odot}$ evolve from the O and Of stages to very bright blue supergiants, which can be identified as Hubble-Sandage variables. The huge mass loss rate in this stage ($\sim 10^{-3}$ $M_{\odot} y^{-1}$, cf. Lamers, 1986) is sufficient to remove the outer stellar layers and to lead to the formation of a Wolf-Rayet star. There, according to the degree of peeling off, the stars may evolve through the various sub-classes (cf. Conti, 1982): WNL (L for late; hydrogen present), WNE (E for early; no hydrogen), WC (products of He burning), WO (same as WC, but larger O content).

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- 2. For initial masses between about 25 and 60 $M_\odot$, mass loss is not high enough to prevent the star to become a red supergiant. However, the high mass loss rates $\dot{M}$ in the red supergiant stage are sufficient to remove the envelope and to lead to the formation of WR stars. As in the previous mass range, the supernova explosion is expected to originate from a WR star.
- 3. Below about 25 $M_\odot$, mass loss is never high enough to remove the outer layers, and the deviations from the scheme of constant mass evolution are rather limited.

The models with mass loss account for several observed features in the HR diagram of massive stars: -the shape of the upper envelope to the star distribution in the HR diagram (cf. Humphreys, 1984); -the frequency of red supergiants and of WR stars (cf. Maeder, 1984b). Let us also emphasize that the overshooting from convective cores seems necessary to account for the observed main sequence widening in cluster HR diagrams (cf. Mermilliod and Maeder, 1986). Such an effect would somehow increase the values of the various mass limits for the three cases considered above.

2. GALACTIC GRADIENTS OF MASSIVE STARS

The galactic gradients of O-stars, blue, red supergiants and WR stars have been discussed by various authors (cf. Humphreys, 1978; Meylan and Maeder, 1983; Conti et al., 1983; Humphreys, 1984). Among the main features we notice that the number ratio WR/O increases towards the galactic center (only O stars more massive than 40 $M_\odot$ are taken, they are considered to be the precursors of WR stars). The number ratio BSG/O is about constant, while the number ratio RSG/O increases towards the galactic anticenter (BSG and RSG respectively mean blue and red supergiants). Such ratios, which concern a certain kind of stars with respect to their progenitors, do not involve the effect of possible differences in the initial mass function (IMF) or of star formation rate (SFR), but more likely the stellar properties themselves.

Opacity effects are likely to be of limited importance in massive stars, since the main opacity source is electron scattering. However, the stellar models show that the lifetimes in the various stages (BSG, RSG, WR) critically depend on the mass loss rates $\dot{M}$. Table 1 summarizes the main effects of $\dot{M}$ on the evolution during the He-burning phase. For example, we see that a strong increase of $\dot{M}$ favours the number of WRs while it may decrease the number of RSGs.

The major question is to know whether the metallicity Z influences the mass loss rates (in any stage). An almost linear relation $\dot{M} \sim Z$ has been predicted (Abbott, 1982). However, the observations are not yet accurate enough to allow to confirm or refute it. If such a relation, firstly suggested by Maeder et al., 1980, is confirmed, we would have a direct link: metallicity Z influences $\dot{M}$, which in turn affects the lifetimes. Such a connection would account for the higher relative frequency of WR stars in interior galactic regions (high Z) and also

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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 $M_{initial}$

★ $t_{He} \simeq t_{BSG} + t_{RSG} + t_{WR}$, sharing varies with $\dot{M}$

★ *BLUE SUPERGIANTS (BSG):*

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

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

★ *RED SUPERGIANTS (RSG):*

moderate $\dot{M}$ => $\frac{t_{RSG}}{t_{OBA}} \uparrow$

(for low $\dot{M}$: lack of RSG)

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

$\dot{M} \uparrow$ => $\frac{t_{RSG}}{t_{OBA}} \wedge$

★ *WOLF-RAYET STARS (WR):*

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

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

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

Mass - luminosity rélation for WR stars $\qquad \log \frac{L}{L_\odot} = 3.8 + 1.5 \log \frac{M}{M_\odot}$

TABLE 1: Main effects of mass loss on the He-burning phase.

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for the lower RSG frequency there. Similarly, it could account for the opposite trend towards galactic anticenter (lower Z). Thus, the $\dot{M}$ vs. Z dependence is a great question to be answered by future space observations.

3. COMPOSITION OF THE STELLAR WINDS AND MASS LOSS EFFECTS ON THE CHEMICAL YIELDS

Mass loss, when removing the outer stellar layers, may reveal at stellar surface the products of CNO burning and even of partial He burning (case of WC stars). Convective dredge up, overshooting and mixing may also contribute to the changes of abundances at stellar surfaces. The problem has been discussed recently and a cartography of the expected C/N and O/N ratios in the upper part of the HR diagram has been established (cf. Maeder, 1985). The comparison of models and observations for OB stars (cf. Kudritzki, 1985), Hubble-Sandage variables and WR stars is quite satisfactory.

Among the various elements ejected by WR stars, the case of ^{22}Ne is the most striking. The overabundance of ^{22}Ne in WR stars is about 10^2 (with respect to solar values) and the estimate of the chemical yield in ^{22}Ne suggests that most of the ^{22}Ne in the Galaxy originates from WC stars. There is an excess of ^{22}Ne by a factor of 4 in the galactic cosmic ray source (GCRS) and a model has been made (cf. Maeder, 1984) showing that the excess of ^{22}Ne in GCRS is likely due to the fact that most galactic cosmic rays originate from inner galactic regions. There, WC stars are more numerous than in the solar neighbourhood; thus, the ^{22}Ne injection is larger in inner galactic regions. Galactic cosmic rays are messengers from these inner regions, and this is likely to be the reason why the GCRS abundances show an excess of ^{22}Ne with respect to the solar abundance.

The effects of mass loss on the chemical yields have been studied by Chiosi and Caimmi, 1979; Chiosi and Matteucci, 1982; Maeder, 1981, 1984a; Mallik and Mallik, 1985; Chiosi and Maeder, 1986. As main results we note that for larger initial stellar masses, more and more new helium is ejected by stellar winds, rather than by supernovae. As to the heavy elements, most of them are ejected by supernova explosions and only a small fraction originates from the winds of WC stars. This concerns ^{12}C, ^{16}O, ^{22}Ne, ^{25}Mg, ^{26}Mg and s-elements. We emphasize the general trend that high mass loss rates increase the helium yield. In this case, a lot of helium is ejected and thus preserved from further destruction. For metals, a high $\dot{M}$ has therefore the consequence to reduce the metal yields. Such a situation only significantly occurs for masses above 50 $M_{\odot}$.

It is desirable that future works investigate the effects of new opacities, cross-sections, mass loss rates, as well as overshooting or the chemical yields, with the help of new grids of models.

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