PROPERTIES OF THE SCENARIO FOR THE FORMATION OF WR STARS AS POST-RED SUPERGIANTS

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Grids of evolutionary models for single stars in the range 9-120 $M_\odot$ have been computed up to the end of the central C-burning phase with up-to-date stellar physics. In addition to other results these models allow us to study the main properties of the formation of WR stars as post-red supergiants (Maeder, 1981c). Three grids of models have been computed: one for constant mass evolution (grid A) and the other two (B and C) with mass loss. As there exists no unique parametrization representing, over the various spectral types, the mass loss rates $\dot{M}$ as a function of basic stellar parameters, we have used mass loss rates fitted on the observations, applying different laws for a) OB stars, b) B-G supergiants, c) red supergiants (RSG) and d) WR stars. At a given luminosity, the rates in grid C are twice as large as in grid B and both grids encompass the central bulk of the observed mass loss rates.

The internal evolution (Maeder, 1981a) and the nucleosynthesis (Maeder, 1981b) of these models have already been studied. Let us point out the major fact for the formation of WR stars as post-RSG in the evolution shown in Figs 1, 2 and 3. RSG having suffered sufficient mass loss leave the red stage and move bluewards becoming bare cores, which are likely to be identifiable with WR stars. During the final loss of the envelope, the bluewards motion through the HR diagram is very fast (some 10^4 yr at 30 $M_\odot$) and it starts when the He + C/O core represents more than a given fraction q_c of the total stellar mass. Over a wide range of $\dot{M}$ values, q_c mainly depends on the initial stellar mass and we have q_c = .97, .77, .67 for M = 15, 30 and 60 $M_\odot$ respectively. The decrease of q_c for larger masses is one of the causes contributing to the preferential formation of WR stars from initially massive stars (in addition to the high $\dot{M}$ and to the large convective core in MS stars).

The He-burning phase may be spent in various locations of the HR diagram; for intermediate mass loss rates (cf. Fig. 1) it occurs: a) in a "horn" which covers type B-G and is rather similar to the horn occurring for constant mass evolution, b) in RSG stage, c) in WR stage for initial

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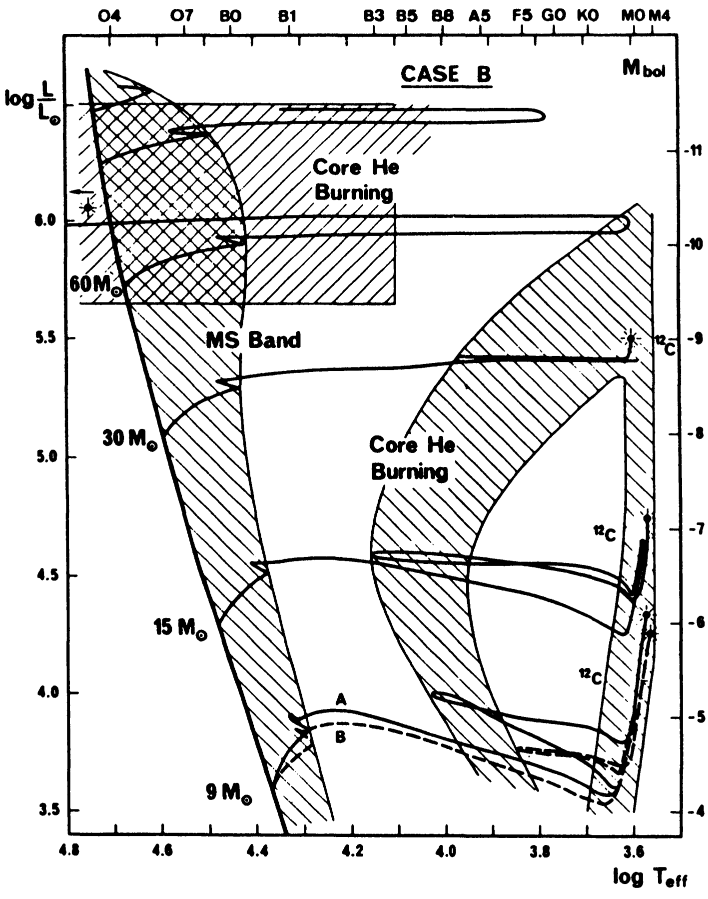

Figure 1. HR diagram for evolution with intermediate mass loss rates (case B). The initial composition is X = .70, Z = .03. The hatched areas represent the main phases of H- and He-burning. The "shiny dots" show the location of pre-supernovae models. The lifetimes are given in a paper by Maeder (1981c).

$M \gtrsim 60\ M_\odot$. The most massive stars do not even make a redwards excursion and directly evolve to WR stars, following what we have called the quasi-homogeneous evolution (Maeder, 1980). Fig. 2 shows the evolution for larger mass loss rates (case C). The horn has disappeared and the He phase is mainly spent as RSG and WR stars (for $M \gtrsim 15\ M_\odot$). Note that in the case of 15 $M_\odot$, the critical q_c is only reached at the very last moment and the WR stage has a negligible duration in that case, i.e. 0.7 % of the MS lifetime (see also Fig. 4).

The internal evolution of a star of initial 60 $M_\odot$ is shown in Fig. 3. After the RSG stage, the WR stage has been computed with 3 different

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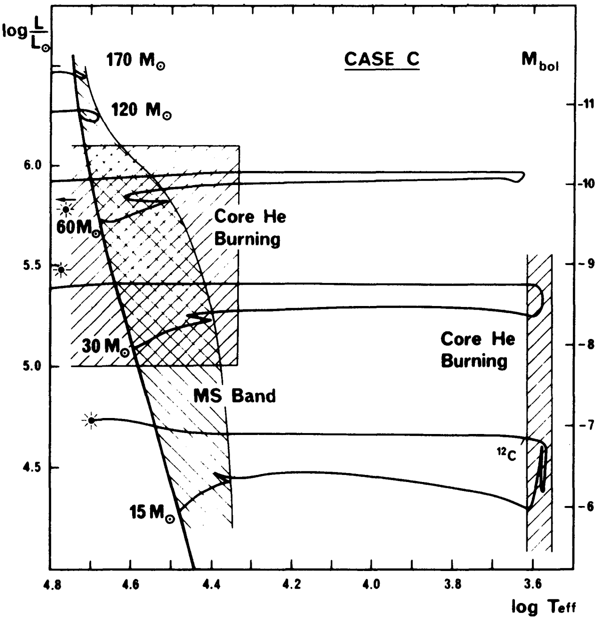

Figure 2. Evolution in the HR diagram with mass loss rates a factor of 2 higher than in case B at a given luminosity (case C)

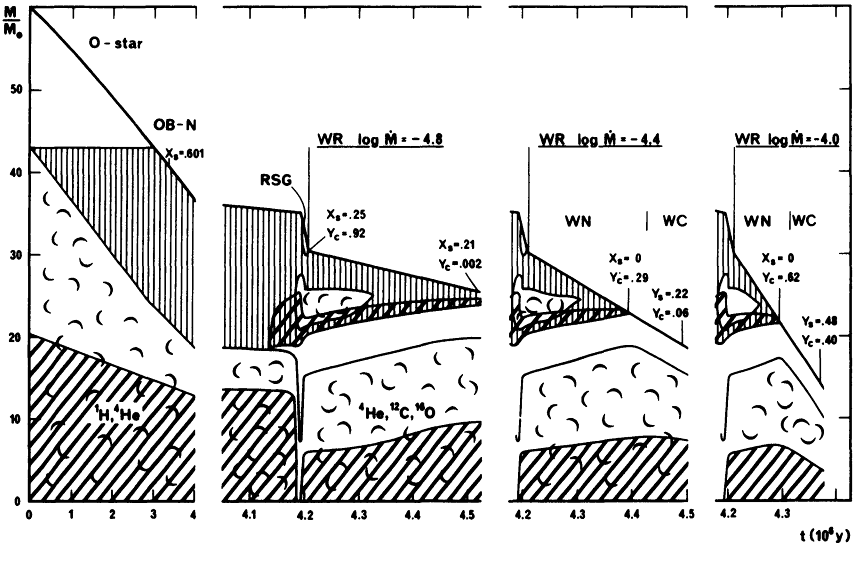

Figure 3. Evolution of the structure of a 60 M⊙ star (case C). Cloudy regions: full convection; heavy diagonal hatchings: nuclear energy rate higher than 10^3 erg $g^{-1}s^{-1}$; vertical hatchings: variable H and He contents. In the He-burning phase, 3 cases with different Ṁ have been considered.

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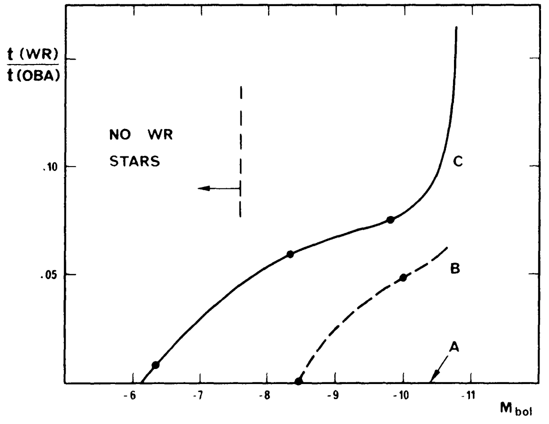

Figure 4. The ratio of lifetimes in the WR stage relative to that in OBA types as a function of luminosity and for various cases of mass loss (A: no mass loss; mass loss rates in case C are twice as large as in case B).

values of $\dot{M}$. The value log $\dot{M}$ = −4.4 is that proposed by Conti (1981). For high enough $\dot{M}$, the WR stars operate the transition from WN to WC stars when the H shell has reached the stellar surface and the ^{12}C and ^{16}O formed by 3α reaction are exposed at the surface. Fig. 3 shows that the ratio t_{WC}/t_{WN} of the times spent in both phases is an increasing function of $\dot{M}$ in the WN stage.

Fig. 4 shows the ratio t_{WR}/t_{OBA} of the lifetimes in the WR and OBA types: 1) The relative time spent as a WR star strongly increases with luminosity and $\dot{M}$ over the previous stages, 2) the threshold (minimum. L) for WR stars appearance is very sensitive to mass loss: without mass loss, no WR would form as post-RSG, for case B the threshold is M_{bol} = −8.5 and at M_{bol} = −6.1 for case C. The observed threshold lies around M_{bol} = −6 to −7, if we consider the data by Barlow et al. (1981) and the fact that WR stars as faint as M_V = −2 have been found recently (Breysacher, 1981; Turner, 1981). This corresponds to case C. These observations also show that the ratio N_{WR}/N_{OBA} is 0.053 in the solar neighbourhood (cf. Maeder, Lequeux and Azzopardi, 1980, MLA) which is also in agreement with curve C in Fig. 4. We note that the theoretical ratio t_{WR}/t_{RSG} is changing very much with $\dot{M}$, an effect which is probably responsible for the large galactic changes of N_{WR}/N_{RSG} through the Galaxy (cf. MLA). Clearly, not all WR result from single star evolution (see other paper, this book) but we already notice that the post RSG channel gives results in agreement with the observed properties of WR stars.

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DISCUSSION FOLLOWING MAEDER

Underhill: One must recall that mass loss plus radiative equilibrium, which is all that interior models tell us, are insufficient conditions for causing a Wolf-Rayet spectrum to appear, see papers on line-formation in moving atmospheres. Adding a hypothetical dependence of the rate of mass loss on Z in order to understand the positions of stars in the HR diagram is a procedure which is unsupported by our present knowledge about the formation of stellar spectra. You must go through the theory of stellar spectra in order to relate a spectral type to a model star formed according to the theories of stellar evolution.

Chiosi: Concerning the gradients of supergiants to Wolf-Rayet and the dependence on the metallicity I want to emphasize that the gradients you have derived depend on the way you have grouped stars according to the radial distance. Also they depend heavily on the luminosity limit of the sample, because if you compare blue supergiants with Wolf-Rayet stars that are cut off at very different luminosities, there is an internal contradiction. As far as we understand the Wolf-Rayet problem in terms of evolution with mass loss, there is no way of having final products representing Wolf-Rayet stars at higher luminosities than the progenitors. So let us assume that the two types of objects have the same luminosity cut-off; then the correlation you found disappears or at least is very much weakened.

Maeder: No. All your argumentation is based on the assumption that the lower M_{bol} for Wolf-Rayet stars is -7.5. We heard in this meeting by Turner and also Breysacher confirming this, that there may be Wolf-Rayet stars down to M_V = -2 to -3, and if we adopt a B.C. of -3 to -3.5 we may have a lower bolometric luminosity than -7.5. Considering the red supergiants as a whole, i.e. class I, Ia and Ib and considering also the Wolf-Rayet stars, the sample is significant.