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# The HR Diagram of Massive Stars

ABSTRACT

In this paper, we review the properties of the HR diagrams of galactic and LMC supergiants, focussing the attention on a few points that cannot find an easy explanation in terms of current evolutionary models. We then discuss the implications of uncertainties in the physical phenomena which are at the base of stellar model calculations. These are mass loss by stellar wind, treatment of the convective regions (overshoot versus semiconvection in the inner cores, and overshoot in the outer convection), and opacity in the ionization regions. Finally, we briefly report on recent model calculations with updated physics (in particular in the treatment of the external mixing and CNO opacity) and propose an evolutionary scheme potentially able to explain the overall properties of the HR diagram of galactic as well as LMC supergiant stars.

## INTRODUCTION

The distribution of luminous stars in the HR diagram (HRD) provides basic data for understanding the structure and evolution of massive stars. Theoretical modeling of these stars has been profoundly influenced by the existence of mass loss at rates that are significant for their evolution. The connection between O, Of, B through M, WR stars, and luminous blue variables (LBV) could be established after mass loss was incorporated in the evolutionary calculations (see Chiosi and Maeder 1986 for a comprehensive review of the subject). However, despite the great success of models with mass loss, it turned out that convection, more precisely the extension of the convective cores and the alternative between semiconvection and overshoot, likely play the dominant role. Further, the detailed comparison of theoretical models with observational data indicates that many properties of massive stars are far from being fully understood. In this review, we will concentrate on a few topics that appear to require further investigation.

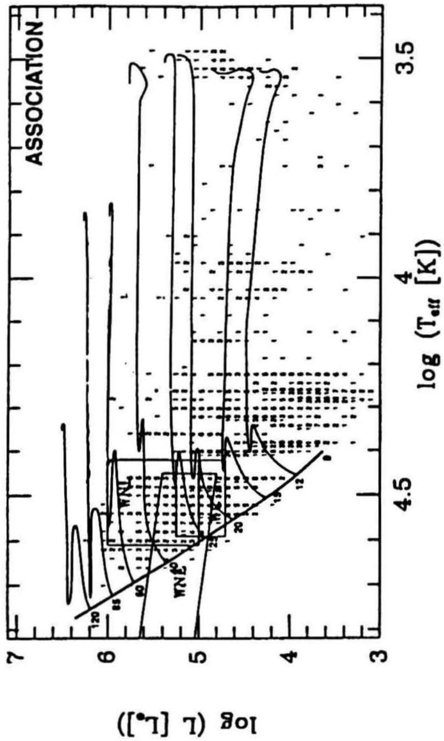

*Fig.1 The HRD for luminous stars within 3 Kpc of the Sun. The evolutionary tracks are from Maeder and Meynet (1987). Reproduced from Blaha and Humphreys (1989).*

**The Observations.** The most recent HRDs for the populations of massive stars in the solar vicinity and Large Magellanic Cloud (LMC) have been published by Blaha and Humphreys (1989) and Fiztpatrick and Garmany (1990), respectively. Figure 1 shows the HRD of all known luminous (massive) stars in clusters and associations within 3 Kpc of the sun. together with the schematic position of WR stars from Schmutz et al (1989), whereas Fig.2 shows the HRD of supergiants stars of the LMC. Although these samples are based on different selection criteria (the spectral types for the galactic supergiants and the two colour photometry for the LMC supergiants), and suffer of a certain degree of incompleteness difficult to assess, in particular among the earliest and latest spectral types, the above HRDs show common features that can be used to constrain theoretical models.

**The Luminosity Boundary**. In the HRD of galactic as well as LMC stars, the most luminous blue stars are about a factor of six brighter than the most luminous red stars (a well known result first pointed out by Humphreys and Davidson (1979). This defines a luminosity boundary in the HRD, whose implications are obvious. Since stars evolve from the main sequence towards cooler effective temperature ($T_{eff}$) at roughly constant luminosity (Chiosi and Maeder 1986), the observed absence of stars to the right of the boundary may mean that either stellar evolution proceeds so fast that the probability of observing stars with $M \geq 50 M_{\odot}$ is very low, or that the most luminous blue stars never become red supergiants but evolve directly into WR stars. Humphreys and Davidson (1979) and Chiosi et al (1978) first drew the attention to the physical significance of this empirical boundary and the lack of cool, evolved massive stars at the highest luminosities. Humphreys and Davidson (1979) suggested that the boundary is due to an instability encountered by the most massive stars as they evolve away from the main sequence and somehow related to high mass loss. As a matter of facts, the highest mass loss rates are observed along the boundary (de Jager et al 1988). The boundary itself is marked by the presence of some very luminous unstable stars, known as the LBV. The physical cause of the boundary is usually assumed to be set by the balance between the acceleration due to gravity and the Eddington gradient of radiation pressure. However, to explain the temperature dependence of the boundary for the hot stars, other effects must be included. The work of several investigators (Humphreys and Davidson 1984; Appenzeller 1986; Lamers 1986; Lamers and Fitzpatrick 1988; Davidson 1987; de Jager 1984; Boer et al 1988; Piters et al 1988; de Koter et al 1988; Carpay et al 1989) has shown that the boundary (stability limit) is the consequence of radiation pressure (modified Eddington limit accounting for variations in the opacity) for the hot stars, and turbulent pressure gradient in the atmospheres for the cool stars.

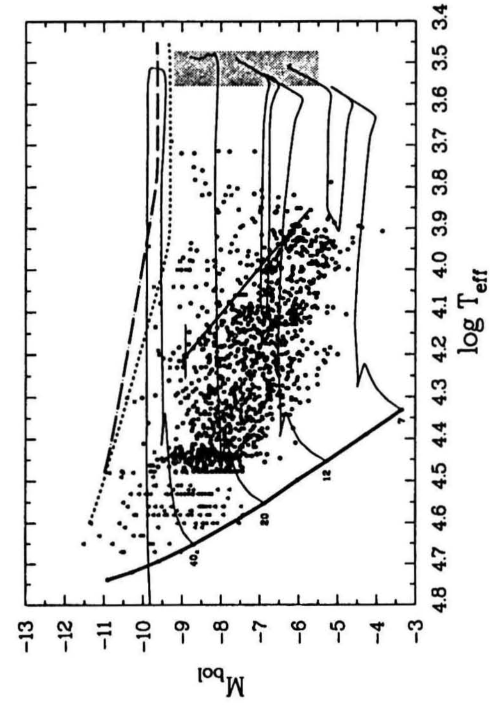

*Fig.2 The HRD for luminous stars in the LMC. The evolutionary tracks are from Maeder and Meynet (1988). The ledge is shown by the solid diagonal line. The dotted and dashed lines are the luminosity boundary from Garmany et al (1987) and Humphreys (1987). The shaded area shows the region of red supergiants. Reproduced from Fitzpatrick and Garmany (1990).*

**The Blue Hertzsprung Gap**. In this region, just to the red of the main sequence, which should be unpopulated according to the theoretical models which otherwise fit the data reasonably well, a large number of stars is found. The nature of these stars is a matter of debate (see below). They could result either from inadequacies of the conversion from spectral type, colour, apparent magnitudes into $T_{eff}s$ and luminosities or from a true evolutionary cause. It goes without saying that the galactic sample is severely biased by the uncertainty in the distance, which however is less of a problem with the LMC stars. Further, uncertainties in the individual reddening and colour excess are certainly present. This is particularly important for the LMC stars, whose $T_{eff}s$ and luminosities are almost entirely based on the two colour photometry, whereas it is less critical for the galactic stars for which spectral types are available. In this context, we would like to comment briefly on the procedure followed by Fitzpatrick and Garmany (1990) to assigne the intrinsic $(B-V)_o$ colour and absolute visual magnitude $M_v$ to the stars of LMC sample. First of all the dependence on the chemical composition is ignored, second the same reddening law is assumed to hold for all stars, and third the uncertainty in the colour excess $E_{B-V}$ is assumed to amount to 0.15. This is comparable to the mean reddening across LMC. It follows from this that large uncertainties affect the $T_{eff}$ and hence the positions of the stars in the HRD, in particular in the so-called Hertzsprung gap, whose width in the B-V colour is comparable to the uncertainty in the colour itself. All this blurs the distribution of stars in the HRD and makes the comparison with theoretical models less clear. The distribution of stellar densities across the HRD of LMC supergiants has been derived by Tuchman and Wheeler (1990) using the data of Fitzpatrick and Garmany (1990). This normalized number density of stars is shown in Fig.3 limited to stars in the magnitude range $-8 \leq M_b \leq -7$. With the aid of equilibrium models (Tuchman and Wheeler 1989), Tuchman and Wheeler (1990) examine the loci of stationary core He-burning in the HRD and conclude that the distribution of stars cooler than $LogT_{eff} = 4.3$, i.e. beyond the blue gap, is consistent with the theoretical expectation from models without core overshoot, like those by Brunish and Truran (1982a,b), which are known to ignite helium in the core at high $T_{eff}$ and evolve at gradually incresing speed towards the red where only the lifetime (short indeed) of the post He-burning phases is available to account for the red supergiants. For the stars in the gap they advance the hypothesis that a large fraction of them are secondaries that have accreted He-rich matter from the envelope of a red supergiant primary, and suggest that about 90% of the stars in the gap should be He-rich. They argue that the abundance determinations by Kudritzki et al (1989) of a few stars in this region found to be He-rich ($Y \geq 0.5$) support this idea. One may argue that inhomogeneities in the chemical composition of galactic as well as LMC supergiants, by affecting the location of red edge of the main sequence band and of the blue edge of the core He-burning band, could result into an apparent filling up of the Hertzsprung gap. It can be easily seen with aid of published evolutionary models of different composition (Maeder 1990) that the gap, although much less extended in $T_{eff}$, cannot be entirely eliminated.

**The Ledge of Blue Stars.** The density of stars in the HRD of the LMC supergiants (Fitzpatrick and Garmany 1990) shows a distinct decrease redward of $3.9 \leq LogT_{eff} \leq 4.2$ and the density dropoff forms a diagonal line, otherwise called the "ledge", going to lower luminosities at decreasing $T_{eff}$. Similar ledge is marginally discernible in the HRD of galactic supergiants (Blaha and Humphreys 1989) but somewhat washed out by the uncertainty in the distance and hence absolute magnitude of galactic stars. The most plausible explanation of the ledge is that stars of initial mass up to about $40 - 50 M_{\odot}$ either perform an extended blue loop in the HRD shortly before core He-exhaustion, like in models with semiconvection evolved at constant mass (Chiosi and Summa 1970) and in models with semiconvection and mass loss by stellar wind (Langer et al 1990), or slowly move redwards in the HRD diagram (Brunish and Truran 1982a,b). These latter models are at the base of the explanation of the blue ledge advanced by Tuchman and Wheeler (1990), who favour models without core overshoot, whereas Fitzpatrick and Garmany (1990) argue that the basic observational restrictions seem to suggest that the true mode of evolution probably resembles, at least qualitatively, either case A or case B

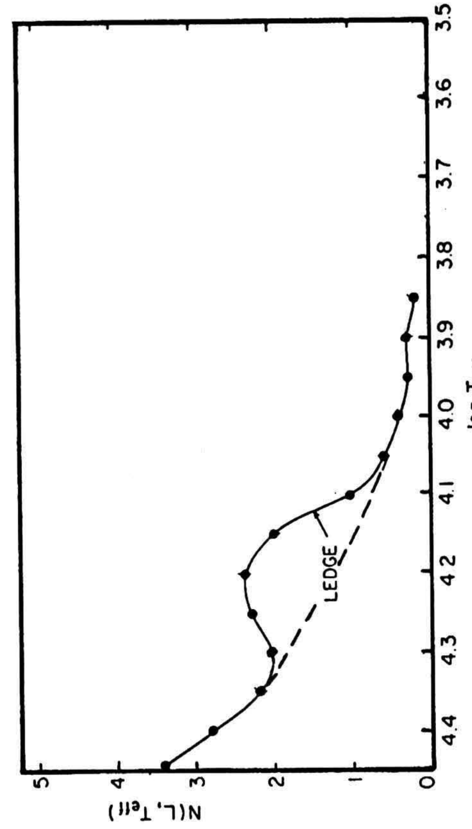

*Fig.3 The observed normalized number density of stars across the HRD according to Fitzpatrick and Garmany (1990). Adapted from Tuchman and Wheeler (1990).*

scenarios proposed long ago by Chiosi and Summa (1970). Current models with core overshoot and mass loss (Maeder and Meynet, 1987, 1988, 1989; Maeder 1990) cannot be used. In fact, with the chemical composition holding for the LMC stars and the mass range in question, these models are found to ignite and spend the whole core He-burning phase as red supergiants. Therefore, not only the ledge but also the existence of stars in the middle of the HRD cannot be explained.

**The Population of Red Supergiants.** The population of red supergiants is distinctly separated from all remaining stars in the two HRDs of Fig.1 and 2. The maximum luminosity attained by the stars in this group is about $M_b = -9.5$. There are a few differences between the population of galactic and LMC M type supergiants that can be ascribed to the different chemical compositions. The ratio of red to blue supergiants in the luminosity range $-9.5 \leq M_b \leq -6.5$ is about 1:10 (Humphreys and McElroy 1984). Since the generally accepted idea is that the vast majority of red supergiants are genetically linked to the massive blue stars, rather than AGB stars coming from lower ranges of mass (Brunish et al 1986), the obvious implication is that in the above luminosity range the evolutionary models must account not only for the existence of a rich population of blue stars but also for the red supergiants. How this can be achieved by stellar models is not very clear. The most popular view is that red supergiants are in some early stages of core He-burning although the alternative of late stage of the same phase cannot be excluded.

**The Red Hertzsprung Gap.** It is well known that very few stars occupy the region between the M supergiants and the late G supergiants. The interpretation of this gap does not give rise to particular difficulties as almost all evolutionary models, no matter whether they evolve during the core He-burning phase according to the blue-red or the blue-red-blue scheme, are known to cross this region on a very short time scale.

**The Lack of Main Sequence Stars.** The inspection of Fig.1 (see also Vanbeveren 1987) reveals a lack of massive stars ($M \geq 40 M_\odot$ close to the theoretical zero age main sequence. Such an effect has also been noticed by Garmany et al (1982) using a different sample of stars. The comparison with theoretical isochrones indicates that the youngest known H-burning O-type stars have an age of about $1 - 2 \times 10^6$ yrs so that about 20% of the core H-burning lifetime is not observed. This agrees with the empirical estimate by Wood and Churchwell (1989) that about 10-20% of all O stars in the solar vicinity are embedded in molecular clouds, and therefore only indirectly detectable by their interaction with the surrounding medium. Only about $10^6$ yrs after the start of central H-burning, the circumstellar gas and dust become transparent and the star becomes visible. Since the fraction of 10-20% is comparable to or even greater than the total fraction of stars in post main sequence stages, this point together with that of the photometric completeness of the data sets are crucial in the comparison of theoretical models to the observed star frequencies [see also the discusssion by Tuchman and Wheeler (1990)].

**The Star Counts.** The star counts in different areas of the HRD of supergiant stars by Meylan and Maeder (1982) and Bertelli et al (1984) indicate that the deficiency of stars near the zero age main sequence (see also Vanbeveren 1987) for stars brighter than $M_b = -8$ likely exists in other luminosity intervals. In fact, while 10-20% of the theoretical lifetime of a star is spent outside the main sequence band, the star counts indicate that some 40% of the stars fall outside this region. In order to reconcile theory with observations, one may suppose that either the data sets are severely biased by incompleteness and/or selection effects or that the main sequence band has to extend to at least the spectral type B9. The completeness of the star samples has bee addressed by Humphreys and McElroy (1984), who conclude that the sample of galactic supergiants restricted to a distance of 3 Kpc from the Sun is photometrically complete for stars brighter than about $M_b = -8$. Various posssible causes of main sequence widening and/or changes in the core H-to He-burning lifetime ratio were suggested and investigated. These are mass loss by stellar wind, atmospheric effects on the stellar radius caused by mass loss, convective overshoot from the inner core (see below), underestimate of the classical radiative opacity in the outer layers, particularly in the region of the CNO ionization, and finally partially hidden core H-burning together with photometric incompleteness. The various hypotheses were thoroughly discussed by Bertelli et al (1984) with the conclusion that only a suitable combination of mass loss, convective overshoot, and opacity modifications could account for the observations. The effect on the morphology of the HRD were investigated by Nasi and Forieri (1990) with the aid of the synthetic HRD technique.

**The Extension of the Main Sequence.** The observed width of the main sequence provides another parameter for the structure and evolution of massive stars. Bertelli et al (1984) determined the width of the main sequence by counting stars across the HRD of the galactic supergiants, alternatively Mermilliod and Maeder (1986) fitted theoretical isochrones to the observed HRD of individual clusters. Both conclude that the main sequence extends to early or even late B type stars in the upper HRD, so that many OB supergiants are still burning hydrogen in the core. Chiosi et al (1978), Bressan et al (1981), Bertelli et al (1984), and Maeder and Meynet (1987) argued that the observed shape of the main sequence can be used to constrain the amount of mass loss and efficiency of core overshoot in evolutionary models.

**Chemical Anomalies in Evolved Stars.** On the basis of current understanding of massive stars, it follows that the same area of the HRD (the upper left corner in particular) can be populated by stars in different evolutionary stages. A large fraction of the brightest OB type stars can be more evolved than deduced for their position near the main sequence. This is substanciated by the observations of CNO processed and He-rich material at the surface of some of these stars. In fact, the group of OBN/OBC stars (Walborn 1988) and the He-rich objects close to the main sequence (Kudritzki et al 1983, 1989; Bohannan et al 1986) are considered typical examples in addition to the WR stars, whose classical interpretation is based on the exibition at the surface of CNO and $3\alpha$ processed material (see Chiosi and Maeder 1986).

## 1.DISCUSSION OF CURRENT EVOLUTIONARY MODELS

**Semiconvection.** In massive stars, radiation pressure and electron scattering opacity concur to make convection more likely to occur. As a consequence of this, a large convective core is built surrounded by a large He-rich region, which is potentially unstable to convection if the original gradient in He abundance is left, but stable if suitable mixing is allowed to take place. Theoretical models picture this region of the star to undergo sufficient mixing until the condition of neutrality is restored, but to carry negligible energy flux. The gradient in He abundance depends on which condition is used to achieve neutrality, either Schwarzschild or Ledoux. The former condition tends to give more extended He gradients (and in some cases leads to the onset of a fully convective layer above the H-burning shell), whereas the latter tends to give a steeper chemical gradient without the appearence of the fully convective zone. It is worth recalling that the Ledoux criterion is a stronger condition favouring stability with respect to the Schwarzschild criterion. Evolutionary models with semiconvection were currently used to interpret massive star before the prevailing effect of mass loss by stellar wind was fully appreciated. As originally pointed out by Chiosi and Nasi (1974) and fully investigated by Chiosi et al (1978), when mass loss is taken into account semiconvection almost entirely disappears. Further, semiconvection does no longer occur if overshoot is adopted to determine the size of the convective core. Over the recent years, as models with core overshoot and mass loss gave a better interpretation of the global properties of massive stars, models with semiconvection were abandoned. The occurrence of SN1987A from a blue progenitor has provoked many questions and in particular a revival of models with semiconvection (Woosley 1988; Weiss 1989; Langer et al 1989). The basic requirement is that SN1987A has as progenitor a blue supergiant star ($LogT_{eff} = 4.0$) of initial mass of about $20M_{\odot}$ and with significant enrichment of He and C/N elements at the surface shortly before the explosion (see also Arnett et al 1989 for more details on the observational constraints for the SN1987A progenitor). This means that either the progenitor star never underwent the red supergiant phase, as some models do under suitable circumstances, or that it followed a blue-red-blue evolution and that the last excursion to the blue took place shortly after the central He-exhaustion. On one hand, evolutionary models living forever as blue supergiants cannot be safely used to interpret the overall morphology of the HRD of LMC supergiants, on the other hand current models with core overshoot, mass loss, and chemical abundances in the range appropriate for LMC seem to terminate the core He-burning phase as red supergiants (cf. Maeder 1990) without looping back to high $T_{eff}s$. The new generation of stellar models with semiconvection perform an extended loop to the blue supergiant region for suitable chemical compositions (low metal content) and fine tuning of the semiconvective treatment. The use of the Ledoux criterion (Woosley 1988; Weiss 1989) in constant mass models leads to a blue progenitor. However, when mass loss is included, the final location occurs too early, i.e. central He-burning, in contrast with the observational suggestion that the SN1987A precursor was a red supergiants a few thousand years before the explosion. Models with a semiconvective treatment intermediate between the Ledoux and the Schwarzshild criterion (Langer et al 1989) account for the blue progenitor, whereas mixing induced by rotation and mass loss by stellar wind in the previous phases secure He and C/O enrichment at the surface. If on one hand the new semiconvective models may lead to a solution of the SN1987A puzzle, the lifetimes of the major nuclear phases (core H- and

He-burnings) are not significantly different from those of the old ones, and they would run immediately into the same difficulties encountered by these latter in the interpetation of the global properties of the HRD of supergiant stars (main sequence width, star counts, etc.). Unless SN1987A is an exceptional event, the solution must be found having in mind that the same evolutionary models must account for the properties of this supernova as well as of the population of supergiant stars (WR included).

**Mass Loss by Stellar Wind.** In recent years, quantitative mass loss theory applicable to massive early type stars has been developed (Castor et al 1975; Abbott 1982; Pauldrach et al 1986; Owocki et al 1988), which allows the calculation of the mass loss rates for a given star. Self consistent models in which the mass loss rate is the result of the physical properties of the stars rather than an a priori assumption are not yet available even if efforts have been made in this direction (Langer and El Eid 1990). The new theoretical mass loss rates tend to predict a much lower decrease (a factor of 2 to 3) in the total mass of the star during its main sequence evolution with respect to previous estimates based on older theoretical studies or empirical estimates of the mass loss rates. No satisfactory stellar wind models are available for yellow and red supergiants (see Lafon and Berruyer 1991 for a recent review of the subject). All evolutionary model calculations are based on empirical mass loss rates formulated as functions of basic stellar parameters. The most recent parameterization of the mass loss rates of galactic stars all over the HRD is by de Jager et al (1988), which holds for stars from the main sequence to the latest spectral types. Suitable dependencies on the metallicity are often included to account for the fact that the mass loss rates are expected to decrease with the metallicity (see Maeder 1990). The de Jager et al (1988) rates are however replaced by suitable formulations for the stars lying in the HRD above the so-called de Jager limit (the rate is increased to about $10^{-3} M_\odot/yr$ and the WR stars for which the formulation by Langer (1989a,b) seems to be particularly appropriate. It is worth recalling that according to current empirical mass loss rates, massive stars lose much more mass than with the theoretical mass loss rates, in particular during the core H-burning phase. The reason of the discrepancy is not known. The physical response of stellar models to the action of mass loss is generally well understood (see Chiosi and Maeder 1986).

**Convective Overshoot.** The argument for the occurrence of convective overshoot is that the traditional criteria for convective stability look for the locus where the buoyancy acceleration vanishes. Since it is very plausible that the velocity of the convective elements is not zero at that layer, these will penetrate (overshoot) into regions that are formally stable. If the physical ground of convective overshoot is simple, its formulation and efficiency are much more uncertain. This reflects into the variety of solutions and evolutionary models that have been proposed. Major contribution to this subject are by Shaviv and Salpeter (1973), Maeder (1975), Cloutman and Whitaker (1980), Bressan et al (1981), Stothers and Chin (1981, 1990), Matraka et al (1982), Doom (1982a,b;1985), Bertelli et al (1985), Da Run (1983, 1986), Langer (1986), Baker and Kuhfuss (1987), Renzini (1987), Maeder and Meynet (1989, 1991) Aparicio et al (1990), Alongi et al (1991). In those studies the overshoot distance at the edge of the convective core has been proposed between zero and about 2 Hp (pressure scale height). As most of the evolutionary results depend on the extension of the convective regions (cores and external envelopes), this uncertainty is critical. Since a generally accepted theory for overshoot is not yet available, most of those studies seeked to constrain the efficiency of overshoot by comparing parametrized models with observations. Among others we recall the following studies. Maeder and Mermilliod (1981) analysing clusters like the Pleiades noticed that the main sequence extends to too bright a luminosity to fit standard models with Schwarzschild convection and semiconvection (Brunish and Truran 1982a,b) and suggested a certain amount of overshoot. This result was reinforced by Mazzei and Pigatto (1989) who showed that the sequential star formation invoked by Stothers (1985) to fit the Pleiades is not necessary if overshoot models are adopted. Further, Barbaro and Pigatto (1984) and Chiosi and Pigatto (1986) argued for overshoot in the stars with mass in the range $1.5 - 2.2 M_\odot$ by pointing out that while the base of the red giant branch is populated in clusters older than about $2 - 3 \times 10^9$ yr, the base of the red giant branch is not well populated in clusters of age $1-2\times10^9$ yr as if in this mass range degenerate He-ignition and He-flash were avoided as they are for stars of higher mass, but in contrast with standard models. Barbaro and Pigatto (1984) and Bertelli et al (1985) suggested that overshoot could lead to larger core masses and hence non degenerate core He-ignition also in this range of stellar ages (initial masses). Further support is given by the study of

Andersen et al (1990) and Napiwotzki et al (1991) on the position in the HRD of a few stars with well determined Teff's and gravities. Chiosi et al (1989) have examined the key LMC cluster NGC1866 where the turn-off mass is $4 - 5M\odot$ and convincingly shown that overshoot models fit better both the overall morphology of the HRD and the luminosity function of main sequence stars. This conclusion was also reinforced by the study of the Cepheid stars in the LMC cluster NGC2157 by Chiosi et al (1991), where it was shown that the use of overshoot models brings into agreement the evolutionary and pulsational mass of these stars. The need for convective overshoot in young galactic clusters has been discussed in great detail by Mermilliod and Maeder (1986) and Maeder and Meynet (1987, 1988, 1989) to whom we refer. As already recalled, the main argument is the extension of the main sequence band which cannot be easily explained even including the effect of unresolved binary stars. Another way to seek evidence for or against models of massive stars with overshoot (and mass loss) is to examine instead of single clusters, where stars are more or less coeval, large samples like those shown in Figs. 1 and 2. The claim is that in order to account for the number of B and A type stars one must broaden the main sequence with convective overshoot. Bressan et al (1981) and Meylan and Maeder (1982) discussed the number of supergiants of various spectral types versus main sequence stars and argued that too many post main sequence stars are present compared to the main sequence stars. The suggestion was made that mass loss and core overshoot could widen the main sequence band up to the spectral B2. Reconsidering this problem, Bertelli et al (1984) concluded that in addition to mass loss and core overshoot, also the opacity in the CNO ionization region should be increased in order to get a satisfactory agreeement between stars counts and theoretical lifetimes in various areas of the HRD. Since the completeness of the star samples and in particular undercounting of the main sequence stars (see the above discussion of this topic) may severely affect these conclusions, Nasi and Forieri (1990) have performed simulations of the HRD diagram of galactic supergiants, in which not only mass loss, core overshoot and modified opacities were included (either separately or at the same time) but also the problem of incompleteness in the counts of main sequence stars was carefully investigated. These simulations clearly indicate that even considering that a fraction (see Wood and Churchwell 1989) of main sequence stars are missing from the star samples either by photometric incompleteness or intrinsic invisibility, core overshoot and opacity variations are needed, whereas mass loss play a secondary role in this respect.

**Radiative Opacities.** Many evolutionary calculations were carried out with the Cox-Stewart or Los Alamos opacities (Cox and Stewart 1965, 1970a,b; Huebner et al 1977). However other opacities were also used, e.g those by Carson (1976 unpublished). Cox's and Stewart's opacities are based on the hydrogenic atomic model, whereas Carson's opacities rest on the hot "Thomas-Fermi" approximation. The two opacities are quite similar but for the region of the CNO ionization where in the Carson opacity a pronounced bump is present. The Huebner et al. (1977) opacities do not possess this bump even if they are significantly higher than the old Cox-Stewart opacity in the same region. The use of the Carson opacity instead of the Cox-Stewart opacities had for effect an enormous enlargement of the main sequence which could extend all across the HRD in the range of most massive stars (Stothers 1976; Stothers and Chin 1977, 1978). Although Carson's opacities have been retracted (Carson et al 1984), Bertelli et al (1984) have introduced an opacity bump in the CNO ionization region of the Cox-Stewart opacity and studied the effects on the location in the HRD of models with core overshoot and mass loss. These models were particularly successful in explaining the overall properties (main sequence extension, lifetimes, etc) of massive stars. However, since the existence of this bump was questioned by various authors, those models were abandoned. Recently, Iglesias et al (1990) and Iglesias and Rogers (1991) have presented new opacity calculations for populantion I and II stars showing that a significant increase in the opacity (bump-like structure) is present. The comparison of the new opacities with the one adopted by Bertelli et al (1984) shows that the peak values are almost identical whereas the temperature at which the peak occurs is $LogT = 5.80$ in Bertelli et al (1984) and $LogT = 5.38$ in Iglesias et al (1990). Although the suggestion advanced by Bertelli et al (1984) turns out to be correct, the difference in the peak temperature is important as the evolutionary models are very sensitive to the opacity structure. Since in the new opacity by Iglesias et al (1990) and Iglesias and Rogers (1991) the bump is located further out in the star, we expect that stellar models will respond less to the opacity than in the model calculations by Bertelli et al (1984). Nevertheless, with the new opacities the stellar models will behave differently as compared to those in which standard radiative opacities are adopted (see below).

**General Remarks.** In light of the above discusssion it seems that each evolutionary scheme is able to account for some but not all observational constraints at the same time. If the inclusion of mass loss is generally accepted, whether overshoot should be preferred to semiconvection or whether a bump-like feature in the radiative opacity of the outermost layer of a star is real is not very clear. Since there seems to be some evidence for overshoot in the low and intermediate mass stars, very likely this will occur in massive stars as well, even if the observational evidence is less clear. The great advantage with the overshoot models is the net increase in the core H-burning lifetime, the lower ratio of core H to He-burning lifetime, the widening of the main sequence, and the much easier exposition of nuclearly processed material at the stellar surface either by mass loss or external mixing or both. The negative aspect with overshoot models is that they are somehow reluctant to perform extended loops in the HRD for masses in the range 15 to 50 $M\odot$ independently of the chemical composition, as shown by the extensive calculations of Maeder (1990) with different chemical compositions. Alongi et al (1991) have shown that models of intermediate mass stars, in which both core and envelope overshoot are allowed to occur, perform wide loops in the HRD. Envelope overshoot takes place at the base of the convective envelope, in the stages of core He-burning along the Hayashi line. If this holds for massive stars too, it is the kind of models we would like to have to account for the distribution of stars in the middle of the HRD. As far as the opacity is concerned, the calculations by Iglesias et al (1990) indicate that the bump in the CNO ionization region is real. Therefore, these new opacities replace the old ones.

## 2. NEW MODELS FOR MASSIVE STARS

In this section new evolutionary models with mass loss by stellar wind, convective overshoot both from the central core and outer convective envelope (when external convection occurs), and revised opacities are presented. The mass loss rate is according to de Jager et al (1988) in all evolutionary phases below the de Jager limit, it is increased to $10^{-3} M_\odot/yr$ above the de Jager limit, and it follows the Langer (1989) prescription for the WR stages. The radiative opacity is from Huebner et al (1977) corrected according to Iglesias et al (1990) in the CNO ionization region. Where appropriate, the opacity includes the molecular contribution (Alexander 1975; Alexander et al 1983; Bessel et al 1989). The nuclear reaction rates are by Caughlan and Fowler (1988). In particular, their value for the $C^{12}(\alpha,\gamma)O^{16}$ reaction is adopted. Core overshoot is based on the formalism of Bressan et al (1981) with the parameter $\Lambda_c$, whereas envelope overshoot is according to Alongi et al (1991) with the parameter $\Lambda_e$. The density inversion which usually appears in the outermost layers of a star at high luminosity and low $T_{eff}$ is inhibited by imposing that $dln\rho/dlnP \geq 0$, which determines a suitable temperature gradient intermediate between the adiabatic and radiative values in the region potentially affected by the density inversion. Various chemical compositions have been adopted to braket the range spanned by galactic and LMC stars. Finally, the effect of various combinations of the parameters $\Lambda_c$ and $\Lambda_e$ have been tested. A more detailed report of these results will be given elsewhere (Bertelli et al 1991).

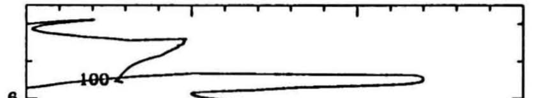

*Fig.4 The HRD of models with mass loss by stellar wind, core and envelope overshoot, and revised opacity (see the text for more details). The thick portions of the evolutionary sequences are the stages of stationary He-burning in the loop.*

Fig.4 shows the HRD for models with chemical composition $Y = 0.25$ and $Z = 0.008$ (appropriate for LMC), and overshoot parameters $\Lambda_c = 0.5$ and $\Lambda_e = 0.7$. Limiting the discussion to the luminosity range $-9 \leq M_b \leq -6$, we notice the following points of interest. The main sequence band extends to $T_{eff}$s in the range $4.3 \leq LogT_{eff} \leq 4.4$ thus encompassing a large fraction of the blue stars of Fig.2. The core He-burning phase of stars in the mass range $9-20M_{\odot}$ takes place partly in the red supergiant region and partly in a loop, which may extend to $LogT_{eff} = 4.2$. The ratio of the core He-burning lifetime in the red to that in the loop decreases from 0.5 for the 12 $M_{\odot}$ star to 0.2 for the 20 $M_{\odot}$ star. It goes without saying that the morphology of the HRD varies with $\Lambda_c$ and Z. Independently of the metallicity, models with $\Lambda_c = 1$ and $\Lambda_e = 0.7$ spend the whole core He-burning phase along the Hayashi line. It is not known whether with a more efficient envelope overshoot extended loops are possible. The study of Aparicio et al (1990) and Alongi et al (1991) suggest that $\Lambda_c = 0.5$ ought to be preferred. With this latter value for $\Lambda_c$, loops are missing for Z=0.02, whereas they occur at lower metallicities (the loop of a $15M_{\odot}$ star with Z=0.004 extends to $LogT_{eff} = 4.3$). The effect of the opacities is more subtle. Since the opacity bump is related to the metallicity, its effect will be more pronounced for high Z, and will become less important at decreasing metallicity. As pointed out by Bertelli et al (1984) the most important effect of this type of opacity is to widen the main sequence band. Models were calculated for a $20M_{\odot}$ star with solar composition which could extend the main sequence band all across the HRD (Bertelli et al 1984). It is clear that the new models can explain several properties of the HRD. First of all, they can account for the occurrence of blue and red supergiants at the same time. The convolution of regions in the loop where the stationary burning occurs (thick parts of the evolutionary tracks) naturally defines a ledge of blue stars in the HRD. Since these models resemble the old ones of Chiosi and Summa (1970) even if they greatly differ in the basic physics, the suggestion made by Garmany and Fitzpatrick (1990) to explain the blue ledge finds quantitative support. There remains the problem of the stars in the Hertzsprung gap. The hypothesis of binary stars can be tested with aid of the synthetic HRDs. Bertelli at al (1991) find that the inclusion of 25% of binary stars does not appreciably alter the morpholgy of the HRD and, in particular, does not populate the gap at the desired level. It is worth recalling that the gap in the theoretical plane, when translated into the observational plane (see Fig. 1 of Fitzpatrick and Garmany (1989)), corresponds to $\Delta(B-V) =$ in the range 0.10 to 0.2 fairly close to the mean uncertainty in the colour excess intrinsic to the method used to deredden the stars. One may be tempted to conclude that in the case of the LMC HRD the many stars falling in the gap are the result of insufficient precision in the conversion of apparent magnitudes and colours into luminosities and $T_{eff}$s. However, since the HRD of galactic supergiants shows similar distribution of stars, most likely the gap is truly populated. We would like to suggest an alternative explanation. Looking at the star density distribution of Fig.3, one may perhaps see two components: a monotonically decreasing distribution resembling the law at which stars obeying the evolutionary rate of the core H-burning phase are expected to distribute in the HRD (see Bertelli et al 1984), and an additional contribution in the range $4.05 \leq LogT_{eff} \leq 4.25$, which can be reasonably identified with stars in the loop of the core He-burning phase. It is plausible that the chemical composition is not the same for all stars in the LMC sample, roughly going from one third solar to solar. In such a case we may suggest the following scheme. Stars with high metallicity give rise to the main sequence widening across the so-called gap up to say $4.0 \leq Log_{Teff} \leq 4.1$, and contribute to part of the red supergiants. They will not loop back to high $T_{eff}$. Stars of low metallicity do not contribute to the main sequence widening (their main sequence band is in fact narrower), but perform a loop during the core He-burning phase, spending part of their lifetime as red supergiants. The external mixing along the Hayashi line may increase the surface content of He and CNO-processed material as perhaps indicated by the anomalous abundances of the few stars for which data are available. The role of envelope overshoot in this scenario is not fully understood and deserves further analysis. Admittedly, this scheme is more complex than usually assumed and requires careful analysis, however it has many advantages over other more simple interpretations. In our view, no scheme exists based on a single assumption (mass loss, semiconvection, overshoot, opacity) that is able to match all the constraints imposed by the observational data. Of the above four basic physical processes, convective overshoot and opacity perhaps play the dominant role.

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