MASS LOSS AND EVOLUTION OF MASSIVE STARS

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INTRODUCTION

In the past few years both growing observational evidence and theoretical understanding have shown that mass loss by stellar wind is a common occurrence in the evolutionary history of many types of star. Recent reviews on the subject may be found in Conti (1978), Cassinelli (1979), Conti and Mc Cray (1980), Hutchings (1980a), de Loore (1979, 1980) and Sreenivasan (1979).

Therefore, in this paper we will concentrate only on those observational and theoretical aspects of the problem that demand further investigation.

Finally, as for the object of this review, we will be concerned with stars in the approximate range of initial mass 10 $M_\odot$ to 100 $M_\odot$, during their evolution from central H-burning to later phases.

1. FAILURE OF CONSTANT MASS EVOLUTION

As is well known, the HR diagram for OB and intermediate to late supergiant stars in the solar vicinity reveals several features that cannot be satisfactorily explained in terms of canonical models of massive stars evolved at constant mass. Fig. 1 shows the observational HR diagram of Humphreys and Davidson (1979) on which the regions of highest observability for constant mass models in core H- and He-burning phases have been drawn for purposes of comparison. Those models are computed with initial chemical composition typical of the youngest population (X=0.7, Z=0.02), and two alternatives for the stability condition against intermediate layer convection (see Chiosi (1978), and references quoted therein for more details on the subject). Although the exact location of main sequence and core He-burning bands may depend on many parameters of the input physics (opacity, nuclear energy generation rates, mixing length, and so forth), it is clear that those models cannot fit the observed distribution of stars in the HR diagram. In fact, the main sequence band is

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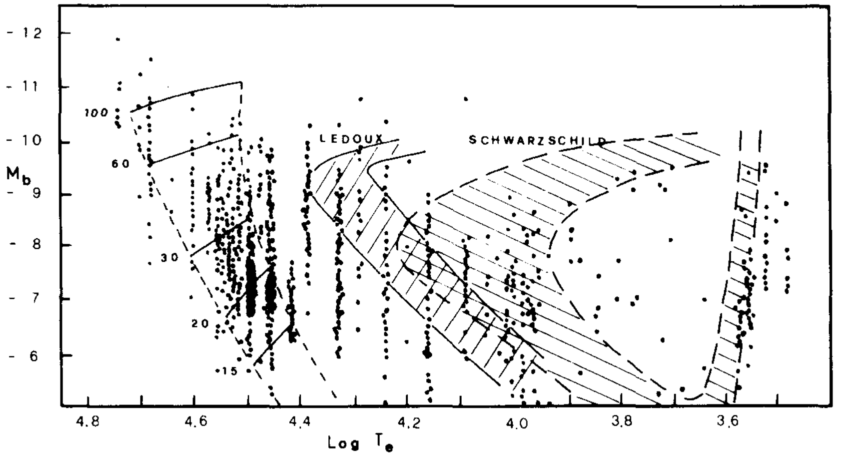

Fig. 1 - Observational and theoretical HR diagrams of super giant stars.

expected to widen at the highest luminosities, contrary to the observational evidence of a steady decline of the limit luminosity with cooling effective temperatures for the earliest type OB stars (Humphreys and Davidson, 1979).
As for the core He-burning phase, models based on the Schwarzschild-Härm criterium ($\nabla_R=\nabla_a$) for semiconvection are too cool compared with the bulk of blue supergiants, and also predict too many red supergiants for masses greater than about 30 $M_\odot$. Models based on the Ledoux criterium ($\nabla_R=\nabla_a+\nabla_\mu$) show the general trend of distribution of blue supergiants, but cover too narrow a range of effective temperatures, and once more predict too many red supergiants at the highest luminosities. Both the crowding of blue stars in the spectral range B0-B1, the wide spread of later type stars, and the lack of very luminous red supergiants cannot be reproduced by those models. Although several causes have been invoked to explain the above discrepancies between theory and observations, like a spread in the initial chemical composition parameters or yet poorly known processes in the stellar interiors, mass loss by stellar wind is the most appealing one, as the existence of stellar winds is strongly indicated by current observations.

2. RATES OF MASS LOSS

Mass-loss rates that may be significant for the evolution of massive stars are inferred from current observations throughout the HR diagram (Conti, 1978; Hutchings, 1980; Reimers, 1975; Cassinelli, 1979). As the correct determination of the rate of mass loss from stars of different spectral type is important for the understanding of the physical nature of the winds, and the evolution of these stars as well, a conci

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se summary of current mass-loss rate estimates, and their parametrization in terms of basic stellar quantities might be of general interest.

2.1. Early Type Stars.

Since the early work of Morton (1967) on ultraviolet spectra of few early type stars, many efforts have been made to improve the observational information. Snow and Morton (1976) pointed out that mass loss by stellar wind is a common property of all early type stars brighter than about $M_b \simeq -6$. Barlow and Cohen (1977) and Abbott et al. (1980) found that the rate of mass loss from luminous OB stars depends only on a low power of the luminosity, in agreement with the theoretical predictions of the radiation pressure driven wind theory of Lucy and Solomon (1970) and Castor et al. (1975). On the contrary, Lamers et al. (1980) and Conti and Garmany (1980a,b) pointed out that stars of the same luminosity show a large range of mass loss rates, in contrast with predictions of the radiation pressure theory. This result has been recently questioned by Gathier et al. (1980) who reanalyzing Copernicus data for a selected sample of OB stars drastically reduced the scatter indicated by Conti and Garmany (1980 a,b). The most interesting result of these recent observational analyses is not in the scatter itself, which might be of experimental nature, but the rather convincing evidence of a systematic increase of the mass loss rate along the transition from OV to OI, Of and likely also to WR stars. Even in the case of the smallest scatter (about a factor of four) suggested by the available data, such an increase of the rate of mass loss during the evolution of stars, which are known to evolve at virtually constant luminosity, cannot be fitted into the radiation pressure driven wind theory. These facts led Chiosi (1980a,b) and Lamers (1980) to suggest parametrizations of the mass-loss rate in terms of mass, luminosity and radius which differ from the simple luminosity dependence of Barlow and Cohen (1977), and Abbott et al. (1980). Though similar, the above parametrizations are quantitatively different, the ultimate reason of it being in the different sources of data that were used to perform the empirical analyses. In particular, Chiosi's (1980a) formulation ($\dot{M} \propto L^{0.75}(R/M)^{2.5}$) based on the data of Conti and Garmany (1980a) fairly agreed with the dependence predicted by the fluctuation theory of mass loss of Andriesse (1979), whereas Chiosi's (1980b) analysis of Conti and Garmany (1980b) data, gave a different relation ($\dot{M} \propto L^{2}(R/M)^{3.0}$). The parametrization suggested by Lamers (1980) ($\dot{M} \propto L^{1.42}R^{0.61}M^{-0.99}$) neither recovers the ones proposed by Chiosi, nor agrees with Andriesse's (1979) prediction.

Fig. 2 summarizes the available observational data and theoretical predictions of Chiosi (1980a,b) and Andriesse (1979) for purposes of illustration.

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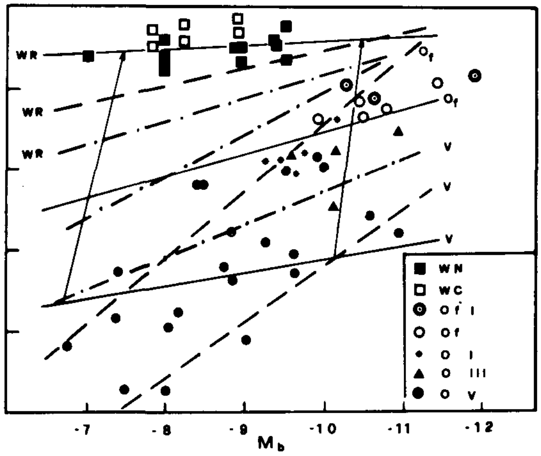

Fig. 2 - $\dot{M}$-M_b relationship. Conti and Garmany (1980b) data for O stars, Barlow et al. (1980) data for WR stars. Continuous line refers to Chiosi(1980a), dashed line to Chiosi (1980b), dotted-dashed line to Andriesse(1979).

On the theoretical side, this discovery has spurred the reconsideration of some older theories like the imperfect flow model of Cannon and Thomas (1977), and the above mentioned statistical model of Andriesse, which works out the effects of stochastic variations in the outer layers of the stars. From the point of view of the evolution of massive stars, the difference among different parametrizations in terms of mass loss is enormous. In fact, if the mass loss rate depends on the luminosity alone, the rate will remain about constant as the star evolves from the main sequence to later stages. On the contrary, if the rate is a function of luminosity, radius and mass, the rate of mass loss may increase by orders of magnitude. The evolutionary results will substantially differ in the two alternatives.

2.2. Late Type Stars.

Mass-loss rates of the same order of those for early type stars are indicated by observations of stellar winds in luminous late type stars (Reimers, 1975, 1977; Sanner, 1976; Bernat, 1977; Hagen, 1978; van der Hucht et al., 1980; Merril, 1978). Complete surveys of the optical, infrared and radio studies are given by Reimers (1978), Merril (1978), Moran (1978), Cassinelli (1979), and Goldberg (1979). The most puzzling thing is that mass loss estimates by different authors may disagree by as much as two orders of magnitude. This fact makes hopeless any simple attempt to correlate the empirical rates with basic stellar parameters in order to distinguish among different mechanisms, and to serve as a guide for theoretical understanding. Through the analysis of observational data, Reimers (1975, 1977) identified several properties of winds from cool stars that led to his popular parametrization ($\dot{M} \propto L/gR$).
The theoretical understanding of the wind phenomenon from cool stars is even more unsettled than for the hot ones, al

though the growing amount of observational data makes discirnable the basic features of wind structures. Both radiative and coronal models have been proposed to explain the winds from this type of stars. As the merits and demerits of the various theories that have been suggested are thoroughly discussed by Cassinelli (1979) and Goldberg (1979), we will not go into any detail here. However, it is worthwise to mention the work of a few authors which has served as basis for evolutionary model computations.

Fusi-Pecci and Renzini (1975) supposed that the acoustic energy generated in the outer convective layers of cool stars powers their winds. Following this idea, the rate of mass loss was written as $\dot{M}=\eta\ La/gR$, a relationship very similar to the one given by Reimers (1975, 1977). In the above expression La is the total amount of acoustic energy generated in the convective regions, and η is an adjustable parameter. By imposing a number of astrophysical constraints not directly related to the wind mechanism itself but only to the total amount of mass that has to be lost by red giant stars, intermediate mass late type stars, and WR stars, Fusi-Pecci and Renzini (1975) found that η is the same in a wide range of circumstances and about 8×10^{-4}. The difficulties that make this theory questionable have been summarized by Goldberg (1979).

The fluctuation theory of mass loss by Andriesse (1979) can be also extended to cool stars for which in fact it was originally worked out. According to the revised formulation of Andriesse (1980) the rate of mass loss is written as $\dot{M}\propto f\ L^{1.5}(R/M)^{2.25}$, where f is a numerical factor of the order of 0.01, which takes into account the strong concentration of matter in the core of red giant and supergiant stars.

2.3. WR Stars.

Among early type stars the strongest winds are observed in WR objects for which mass loss rates of 10^{-5} to 10^{-4} $M_\odot$/yr and higher are commonly estimated. Recent mass loss rate determinations for WR stars are by Barlow et al. (1980). Average rates of mass loss for WN and WC types are about $\sim$3 10^{-5} $M_\odot$/yr and 5 10^{-5} $M_\odot$/yr respectively. These rates compared with those for evolved O type stars (Of and OI) turn out to be at least a factor of five to ten higher. According to Barlow et al. (1980), these rates appear to be too high for radiation pressure as the major source of their wind. Chiosi (1980a) tested the applicability of the relation $\dot{M}\propto L^{0.75}(R/M)^{2.5}$ to WR stars, assuming reasonable values for their mass, radius and luminosity. The $\dot{M}$ versus M_b relationship predicted for WR stars is shown in Fig. 2. On the base of the discussion of Barlow et al. (1980) and the results of Chiosi (1980a), one might conclude that the wind from WR stars is driven by some unknown mechanism perhaps seated in their interiors.

3. EVOLUTION OF MASSIVE STARS WITH MASS LOSS

The realization that such large rates of mass loss probably exist for the most luminous hot and cool stars has stimulated several independent studies of the effects of mass loss on model evolution (Chiosi and Nasi, 1974a; de Loore et al., 1977; Dearborn and Eggleton, 1977; Dearborn and Blake, 1979; Dearborn et al., 1978; de Loore et al., 1978; Chiosi et al., 1978, 1979a; Sreenivasan and Wilson, 1978; Stothers and Chin, 1978, 1979, 1980; Falk and Mitalas, 1979; Falk, 1979). Most of these computations are concerned with the earliest stages of evolution (core and shell H-burning phases). Although they have improved very much our understanding of stellar evolution with mass loss, it is worth saying that the fundaments of this subject were already known since the early paper by Tanaka (1966), who first pointed out the basic characteristics of models suffering mass loss at a given rate during their core H-burning phase.

As for cool stars, few fragmentary studies of post main sequence evolution with mass loss are available (Hartwick, 1967; Simon and Stothers, 1970; Bisnovatyi-Kogan and Nadezhin, 1974; Chiosi and Nasi, 1974a; Sreenivasan and Wilson, 1978; Chiosi et al., 1978; Stothers and Chin, 1978, 1979, 1980; Falk and Mitalas, 1979; Falk, 1979).

Before describing the model results in some detail, several considerations of general interest might be useful to understand correctly the validity of the available numerical computations.

Owing to the large uncertainties in both theories and observations of stellar winds, semiempirical formulations for the rate of mass loss are used, which are customarily calibrated on the observational data by means of one or more adjustable parameters. With the aid of this, sequences of models, whose mass simply decreases with time, are calculated, thus neglecting any dynamical treatment of mass outflow from stellar models. Such a procedure at least requires the consistency of the mass-loss rate with the evolutionary phase under consideration. If this task can be reasonably achieved in the case of red stars, which certainly are in post main sequence phases, this might not be the case of early type stars, as many types of object with profoundly different characteristics, like O, Of, OI and WR stars, crowd to the same area of the HR diagram. Finally, those studies make also evident that each evolutionary phase cannot be investigated separately, as mass loss may occur everywhere in the HR diagram. Therefore the amount and mode of mass loss in early (blue) phases will significantly affect all subsequent evolution, whereas the amount and mode of mass loss as intermediate to late type stars, may control the reappearance of the models as blue evolved objects.

The recent reviews by de Loore (1979, 1980) on the evolution of massive stars undergoing mass loss by stellar wind during

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core and shell H-burning phases make superflous here a detailed description of those results. Therefore we will be only concerned with the most recent advancements, yet the main results on the subject will be also outlined.

3.1. Core and Shell H-Burning Phases.
Evolutionary models in core and shell H-burning phases have been calculated with four or five different relationships for the rate of mass loss. The major difference among them is whether the mass-loss rate depends on the luminosity only, or other variables are taken into account. (See de Loore (1979, 1980) for a complete list of the most popular relationships used in model computations).
The main results can be summarized as follows:
i) The main sequence band widens at lower mass ranges, and shrinks at the highest range, if the mass loss rate is sufficiently high. For very high mass loss rates ($\dot{M}\simeq10^{-5}$ $M_\odot$/yr) the most massive stars may even cross the zero age main sequence before exhausting hydrogen in the core.
ii) Losing mass models run at lower luminosity compared with the constant mass case, the decrease in luminosity being proportional to the rate of mass loss. Those models are however always overluminous for their mass compared to the conservative ones in the same evolutionary stage.
iii) The occurrence of mass loss drastically reduces the mass size of semiconvective and intermediate fully convective zones, the extent of reduction being proportional to the rate of mass loss. This fact somewhat alleviates the long lasting uncertainty in models of massive stars due to the adoption of one of the two stability criteria against intermediate convection. Nevertheless, an accurate treatment of this intermediate instability, whichever criterium is adopted, is still necessary. In fact, as is well known, one of the leading parameters that control the location in the HR diagram of models in post main sequence phases is the chemical profile in their intermediate layers.
iv) The main sequence lifetime is also affected by mass loss. Two competing effects can be outlined: losing mass models have smaller convective cores, no semiconvective feeding and therefore less fuel to burn, which would shorten the core H-burning lifetime. This trend is overwhelmed by the decrease in luminosity, leading to the net result that the main sequence lifetime increases with average mass loss rate.
v) The masses of the remnants at the end of core H-burning phase depend on the average mass loss rate.
vi) The helium core that is left in these models at the end of core H-burning is smaller in mass compared to the conservative case, the decrease being proportional to the mean rate of mass loss. This has the interesting consequence of affecting the chemical enrichment of the interstellar medium at the end of the star life in the way pointed out by Chiosi

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and Caimmi (1979). Furthermore, since those models have significantly decreased their mass, the fractionary mass of the helium core turns out to be greater than for conservative models. As pointed out by Chiosi et al. (1978, 1980) and Falk (1979) this fact will play a role in locating core He-burning models in the HR diagram.

vii) In presence of a substantial mass removal (high rates and/or long lifetimes), CNO processed material is exposed at the surface before central hydrogen is exhausted. The initial mass above which this effect may occur lowers from 100 $M_{\odot}$ to 60 $M_{\odot}$ for rates of mass loss increasing by about a factor of two.

viii) After core H-exhaustion, all computed tracks run at constant luminosity towards cooler effective temperatures, in that similar to the conservative ones. With the adopted mass loss rates (ranging from 10^{-7} to 10^{-5} $M_{\odot}$/yr for initial masses increasing from 20 to 100 $M_{\odot}$), the models do not lose enough mass to avoid this phase at low effective temperatures. Very little mass is lost during the rapid expansion of the outer envelope due to the very short lifetime of this phase.

As in all these models the rate of mass loss was dependent only on a weak power of the luminosity, it did not vary along the evolutionary tracks. On the contrary, if the new formulations of Andriesse (1979) or Chiosi (1980a,b) are adopted, the rate of mass loss may increase by more than an order of magnitude from the main sequence to the beginning of the shell H-burning phase. However, very little mass is lost during the main sequence phase due to the fact that the rate of mass loss starts small and increases to high values, comparable to those of the previous evolutionary calculations, only at the very final stages (Chiosi, 1980a; Andriesse et al., 1980; and Lamers, 1980). In this case the evolutionary tracks are again very similar to those with constant mass and some difficulties will arise in interpreting the observational data, as will be discussed later on.

Finally, it is worth mentioning that to more readily understand the results of numerical calculations with a variety of mass-loss rates, simple analytical formulations in terms of some basic quantities have been worked out by Dearborn et al. (1978) and Falk (1979). According to Dearborn et al. (1978) the numerical results for core H-burning models can be organized in a simple scheme described by the mass loss parameter $\zeta=\tau_{ms}|\dot{M}|/M$, where τ_{ms} is the main sequence lifetime. Until ζ is below some critical value, the inclusion of mass loss does not change too drastically the behaviour of evolutionary models compared with those at constant mass, and the scheme we have illustrated above holds for a large range of rates. If ζ is greater than the critical value, the models at the end of the main sequence phase consist of an almost stripped helium core still embedded in a very thin

H-deficient envelope. Mass loss prevents these models from further expanding their envelopes so that they remain forever at high effective temperatures. As very large rates of mass loss ($\dot{M}>4\ 10^{-5}\ M_\odot/yr$ for an initial 100 $M_\odot$ or $\dot{M}>8\ 10^{-6}\ M_\odot/yr$ for an initial 20 $M_\odot$) are required, it is very unlikely that this case may exist.

3.2. Core He-Burning Phase.

The effects of main sequence mass loss are of great importance in the core He-burning phase, which is considered to begin when a convective core breaks out due to nuclear energy generation via the 3α process.

Looking at the models calculated taking into account mass loss in this phase, a picture even more intrigued than for the conservative case seems to arise (Chiosi et al., 1978; Sreenivasan and Wilson, 1978; Stothers and Chin, 1978, 1979, 1980; Chiosi et al., 1980; Maeder, 1980). Evolutionary sequences have been computed with various assumptions for the rate and mode of mass loss: a combination of radiation pressure and acoustic flux driven winds at high and low effective temperatures respectively by Chiosi et al. (1978, 1980), and Sreenivasan and Wilson (1978); the mass loss rate of Mc Crea (1962) ($\dot{M}\propto L/v^2_{es}$) throughout the entire HR diagram, or sudden mass loss below some critical effective temperature (the latter somehow mimics the acoustic flux driven wind relationship) by Stothers and Chin (1978, 1979, 1980); the Barlow and Cohen (1977) relation ($\dot{M}\propto L^a$) by Maeder (1980). The available numerical results can be tentatively organized in the following scheme:

i) Models calculated with the Schwarzschild-Härm neutrality condition, which suffered moderate mass loss during the core H-burning phase, ignite and burn helium in the core as blue supergiants and eventually become red supergiants, if their original mass was in the range 15 $M_\odot$ to 50 $M_\odot$. The stages of stationary nuclear burning are however redder and covering a larger range of effective temperatures than for conservative models. On the contrary, models of higher initial mass ignite core He-burning as red supergiants. Whether they will loop back toward high effective temperatures at later stages, or will remain forever as red objects, it depends on mass loss in the red region and details of their internal structure.

ii) Models calculated with the Ledoux criterium start burning helium in the core as red supergiants, independently of their initial mass and for any reasonable amount of mass loss in the previous stages. Whether a loop can be started or not depends on factors which cannot be easily identified a priori.

In order to understand the apparently erratic behaviour of the models, both semianalytical and numerical experiments have been performed (Falk, 1979; Chiosi et al., 1980), which enable us to foresee the model response at varying basic parameters in a broad range of cases. A criterium for reversal of the evolution in the HR diagram was derived by Falk (1979) and Chiosi et al. (1980). According to Chiosi's et al. (1980) formulation the stellar radius R can be expressed as a function of M_c, ρ_c and M, where M_c and ρ_c (mass and density, respectively) refer to a characteristic mass point in the H-burning shell above which a polytropic pressure-density relationship can be used (M stands for the current total mass). The time derivative of R is written as

$$\frac{\dot{R}}{R} = \left(\frac{\partial \ln R}{\partial M_c}\right)_{\rho_c, M} \dot{M}_c + \left(\frac{\partial \ln R}{\partial \rho_c}\right)_{M_c, M} \dot{\rho}_c + \left(\frac{\partial \ln R}{\partial M}\right)_{M_c, \rho_c} \dot{M} \qquad (1)$$

where the partial derivatives are estimated by integrating mass and momentum conservation equations with the use of the polytropic relationship between pressure and density. A network of solutions is calculated varying M_c, M and ρ_c, from which it follows that:

i) $(\partial \ln R/\partial M_c)_{M,\rho_c}$ is positive as long as M_c/M is below some critical value, which turns out to be about 0.6, in agreement with the equilibrium model analysis of Giannone (1967).

ii) $(\partial \ln R/\partial M)_{M_c,\rho_c}$ and $(\partial \ln R/\partial \rho_c)_{M_c,M}$ are always positive and negative respectively.

The time derivatives $\dot{M}_c$, $\dot{\rho}_c$ and $\dot{M}$ are determined by the outward movement of the H-burning shell, the physical response of the outer border of the core to central gravitational contraction in presence of a burning shell, and mass loss in the order. The time variation of ρ_c is known to be very small until the central He content falls below some critical value, so that it can be neglected during most of core He-burning. Therefore the condition for a redward movement of the models in the HR diagram becomes

$$\tau_{sh} < \tau_{\dot{M}} \left[\left(\frac{\partial \ln R}{\partial \ln M_c}\right)_{M,\rho_c} \left(\frac{\partial \ln M}{\partial \ln R}\right)_{M_c,\rho_c}\right] \qquad (2)$$

where τ_{sh} and $\tau_{\dot{M}}$ are two time scales defined as

$$\tau_{sh} = M_c/\dot{M}_c \quad , \quad \tau_{\dot{M}} = M/|\dot{M}| \quad . \qquad (3)$$

Whenever condition (2) is violated a blueward movement of the models will occur. Relation (2) recovers the analytical prediction of Falk (1979), however being of more general validity. A detailed discussion about the applicability of relation (2) to existing numerical evolutionary sequences can be found in Chiosi et al. (1980). It is worth pointing out that the competition between mass loss and H-burning shell evolution will determine the location of models in the HR diagram.

4. COMPARISON WITH THE OBSERVATIONS

The effects of mass loss at various rates on the mass-luminosity relationship for main sequence and early type supergiant stars, on the problem of mass determination and on the age of young clusters, can be found in de Loore (1979, 1980) and Chiosi et al. (1979a). Since the situation has not been changed by more recent results, we will not deal here with those subjects.

4.1. The Boundary to the Luminosity of OB Stars.

The dependence of the coolest edge of the main sequence band on the mass loss rate, originally pointed out by Chiosi et al. (1978) and since then taken as a constraint on the average mass-loss rate during core H-burning phase (Chiosi et al. (1979a), Lamers et al. (1980), and Maeder (1980), might suggest an explanation of the upper boundary to the luminosity of OB stars pointed out by Humphreys and Davidson (1979).The confrontation of model location with observational data seems to indicate that models losing mass at rates intermediate between those with α=0.83 and α=0.90 in the Chiosi et al. (1978) notation match the observational situation.
It is worth noticing that two assumptions are implicit in the above comparison and conclusion, namely the rate of mass loss is proportional to the luminosity only, and all stars in the area are burning hydrogen in the core. On the contrary, if the rate of mass loss has the dependence suggested by the most recent data (Conti and Garmany, 1980a,b; Gathier et al., 1980) and theoretical studies (Andriesse, 1979, 1980; Chiosi, 1980a,b; Lamers, 1980) the agreement is very poor, as the main sequence band is expected to widen at the highest luminosities Chiosi(1980a).This problem was studied by Chiosi and Greggio (1980), who argued that the observed luminosity limit might be mostly due to the stochastic nature of the initial mass function for massive stars, and to the coarse number of stars in the sample of Humphreys and Davidson (1979). In such a case the upper luminosity boundary can not be safely used to set a limit to the average rate of mass loss from O type stars.

4.2. Blue-Yellow-Red Supergiants.

With the aid of models evolved in occurrence of mass loss, we discuss here those basic features of the HR diagram of young luminous stars (Fig. 1) that could not be explained by conservative models, namely the crowding of stars in the Kelvin Heltmoz gap and large spread of blue supergiants in the range of effective temperature $4.3>\mathrm{Log}T_e>3.90$, the lack of very luminous red supergiants, the steady decline of the limit luminosity with decreasing spectral type passing from early OB to late M stars.
Theory predicts the existence of a zone in the HR diagram where stars are expected to evolve rapidly between the last

stages of core H-burning and beginning of stationary core He-burning. However, no gap of this type exists among stars more massive than 15 $M_\odot$ on the main sequence.
Can the combined effect of mass loss in both H and He-burning phases populate this area, and reproduce all other features at the same time? From the available computations we see that the location in the HR diagram of both core H-burning and core He-burning (blue and red) models is affected by mass loss. For the sake of simplicity, it is worth considering separately the two cases of intermediate (about from 15 to 50 $M_\odot$) and high (above 50 $M_\odot$) initial mass. The boundary of 50 $M_\odot$ is chosen because the average luminosity of this star roughly corresponds to the luminosity limit of red supergiants, and because the models of very massive stars were seen to behave differently compared to those of smaller mass.
In the range of intermediate mass stars, mass loss by stellar wind may widen the main sequence band, however the Kelvin-Heltmoz gap is also widened, although at the same time the blue portion of stationary He-burning is spread over a much larger range of effective temperatures. The red supergiant area can be populated by models in either early stages of core He-burning or later ones according to whether Ledoux or Schwarzschild-Härm criterium is adopted, and the rate of mass loss is high or low. Extended loops towards high effective temperatures during early to intermediate stages of core He-burning may also occur under suitable circumstances. A large variety of possible combinations exists according to different authors (Chiosi et al., 1978; Sreenivasan and Wilson, 1978; Stothers and Chin, 1978, 1979, 1980; Maeder, 1980). On the basis of those models we may suggest that a suitable tune up of the mass loss rate in both core H and He-burning could perhaps give the required spread of models in the blue, yellow, and red supergiant area. The Kelvin-Helmotz gap could therefore be populated by stars in latest stages of central H-burning, early stages of core He-burning and latest stages of it. If the goal can be achieved in terms of model location, still the relative percentages of blue, yellow, red supergiants, compared with the main sequence stars, cannot be reproduced by those models. In fact too many stars are observed in the gap for being in those quite rapid stages of evolution. Therefore the existence of these stars seems to be at variance with standard models of massive stars even in occurrence of mass loss.
As for stars initially more massive than about 50 $M_\odot$, the main sequence band may either widen, as in the case of lower mass stars, or shrink, depending on the average mass-loss rate. However for the arguments brought by Chiosi and Greggio (1980) this will not have significant observable consequences. The core He-burning phase of these stars is expected to occur at high effective temperatures, possibly merging the main sequence band, for suitable combinations of total mass

removal during the core H-burning phase and rate of mass loss during the He-burning phase. The expected location of central He-burning for the two ranges of mass is shown in Fig. 3.

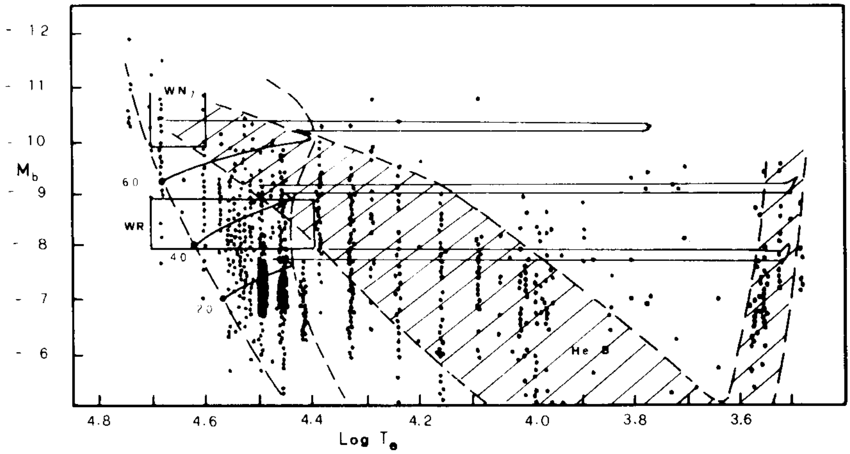

Fig. 3 - Observational and predicted theoretical HR diagrams.

In this scenario the systematic increase of the luminosity of the brightest stars in the HR diagram (Fig. 1) with increasing effective temperature, and lack of very luminous red stars, may find a natural explanation. In particular, the luminosity boundary for OB stars should be determined by the reddest edge of stationary core He-burning instead of the reddest edge of core H-burning as suggested in the past. Hopefully, these two observational facts could be used to set constraints on the average mass-loss rate during the lifetime of massive stars.

In addition to this, since in the left upper part of the HR diagram models of substantially different internal structure, and surface chemical composition, are expected to exist, one could find reasonable evolutionary links among O, Of and WR stars.

4.3. The Of Stars.

Of stars are commonly assumed to be in the latest stages of core H-burning. This assumption is in fact implicit in the procedures used by Chiosi (1980a,b) and Lamers (1980) to derive empirical formulations for the rate of mass loss from O type stars. However Of stars are located in the same area of the HR diagram occupied by OV stars. More specifically, the majority of the brightest O type stars is constituted by Of stars. This means that either the mass loss rate suddenly increases as a massive star starts evolving from the zero age main sequence, in such a case we would recover the old simple formulations for the mass loss rate, or those stars are in a different evolutionary stage.

Plausibly one cannot exclude the possibility that Of stars

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are in the core He-burning phase, in those stages that presumably preceed the WR stages. Current observational data and theoretical evolutionary models cannot enable us to reach any firm conclusion about this point.

5. EVOLUTIONARY SCENARIO FOR WR STARS

The occurrence of stellar winds during core H and He-burning stages has the consequence that a variety of stellar remnants are produced, which hopefully should be located near the zero age main sequence, and which should be observed as overluminous, He-rich and N-rich stars. As is well known, WR stars are believed to show such characteristics. In fact, WR stars are in general H-poor and He-rich, and in particular H is extremely poor in early type WN's and WC's, and more abundant in late WN's. Nevertheless, few exceptions exist which somehow invalidate this simple schematization. As pointed out by Massey (1980), the WN5 stars HD 193077 and HD 9974 show in fact convincing evidence of H in the envelope, whereas the WN8 star HD 17230, which is expected to show H at the surface, does not (Massey and Conti, 1980). It appears also that WN stars have more nitrogen, whereas WC stars seem to have more carbon and oxygen at the surface. According to a theoretical suggestion of Paczynski (1973) and the work of Willis and Wilson (1978), WN stars should expose at the surface CNO processed material, which could easily account for the N overabundance, whereas the WC stars should expose 3α processed matter, in which carbon and oxygen are abundant. As a consequence of this,WC stars should be more evolved than WN stars (Paczynski, 1973).

The position of WR stars in the HR diagram, summarized by Conti (1976a), is still rather uncertain. According to Conti's (1976a) analysis the majority of WR stars fall in a narrow range of luminosities and effective temperatures, with the exception of the WN7 type for which significantly higher luminosities and a narrower range of effective temperatures are given. However, if the discussion of Conti (1979) is taken into account, also WN7 stars may shift to cooler effective temperatures and lower luminosities. Recent contribution to the subject is by Barlow et al. (1980) who derived the bolometric magnitudes and black body temperatures for a sample of WR stars. If the black body temperature can be taken as an approximate indicator of the effective temperature, the WR stars appear to populate a well defined band in the HR diagram.

The most important question concerning WR stars is whether all of them are members of binary systems or truly single objects may also exist. This problem has been revised recently by Vanbeveren and Conti (1980), who suggest that about 40% of the WR stars are binaries with an OB companion, and an equal number of WR stars could exist with a compact companion. Some 20% of the WR stars are therefore expected to be truly single objects. The previous larger frequency, 73%, of binary WR stars with respect of the single ones found by Kuhi (1973) is thus significantly lowered by this recent study, and made comparable to that of OB binaries (about 50 to 60%) quoted by Conti (1976b).

The mass of WR stars is still poorly known. For those WR's that are members of binary systems, a study of these stars reveals that the average mass is about 20,ranging from 10 to 50 $M_{\odot}$ (Massey, 1981). No plausible information can be derived for the mass of single WR stars.

Another important question to be clarified before the WR stars can be fitted into an evolutionary scheme concerns the statistics of WR stars compared to their progenitors, very conceivably the OB stars. According to Smith (1973), and Moffat and Seggewiss (1978) for the particular case of the latest type WN's, the occurrence of the WR phenomenon far from being rare, is to be considered normal among massive OB stars.

Finally the very crucial aspect of the WR phenomenon is the correlation between the spectral classification and evolutionary status. In other words, are late WN's and WC's progenitors of the early ones, and WN's preceed WC's in their evolutionary history or not? or a more complicated scheme has to be devised? The interpretation of binary WR stars has been the subject of a great deal of theoretical work. As is well known, the mass exchange, and more recently a combination of mass exchange and mass loss by stellar wind, offers an easy and straightforward scenario for the production of WR stars in binary systems. The situation has been recently reviewed by de Loore (1979, 1980, this conference). On the contrary, the possibility that mass loss by stellar wind may transform a single O type star into a WR star, as suggested some time ago by Conti (1976a), is still an unsettled question.

In Conti's (1976a) suggestion, single massive O stars would become Of's if substantial wind were to exist. With increasing rate of mass loss, Of stars would transform into latest type WN's ("transition" WR's), which in turn would evolve into classical WR's if further mass loss were to occur. This straightforward scheme was reelaborated by Chiosi et al. (1978), who distinguished two different ranges of initial mass, and considered the overall effect of mass loss during core H and He-burning phases. Chiosi's et al. (1978) scenario rests on the basic idea that all WR stars (single included) are in the core He-burning phase, and the different chemical abundances at the surface are determined by the amount of peeled off material, which in turn depends on the initial mass and average rate of mass loss. In brief, the most luminous WR stars (the H-rich late type WN's) have evolved from the most massive O stars, whereas the progenitors of the higher excitation WN's (from WN3 to WN6) would be O stars with original mass in the range 25 to 50 $M_{\odot}$, which become WN's during core He-burning, when surface layers are stripped away.

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The WC's should be the descendents of these latter WN's. The ultimate reason for the distinction between two ranges of initial mass is the competition between the core He-burning lifetime, which decreases with increasing initial mass, and the time scale for removal of the H-rich envelope, which depends on mass loss during core H-burning and current rate of mass loss during core He-burning.

At the base of that evolutionary scenario for single WR stars were the models of Chiosi et al. (1978) computed with a rate of mass loss dependent on a weak power of the luminosity alone, and therefore practically constant. This fact hindered those authors from fully matching some properties of WR stars, like the high rate of mass loss and low H content at the surface.

It appears nowadays as very likely that the rate of mass loss may vary by more than one order of magnitude in the course of evolution of massive stars, as indicated by the formulations of Andriesse (1979, 1980), Chiosi (1980a,b) and Lamers (1980). Therefore it seems worth refining that scenario at the light of the most recent observational facts. The aim of the following considerations is to elaborate a scheme in which WR stars can be fitted independently of their binary or single nature. In fact, mass loss by stellar wind and mass removal by Roche lobe overflow have similar, though not quantitatively equal effects on the structure of the remnants, and represent two different alternatives for producing WR stars.

The available gross characteristics of WN and WC stars can be tentatively organized as shown in Fig. 4, where in addition to the location in the HR diagram few other basic parameters are also indicated. The area assigned to each subtype is quite arbitrary and must be taken only as an indication of the suspected spread of masses and luminosities. Finally, it must be emphasized that the proposed scheme is not to be intended as a definitive interpretation of the evolu

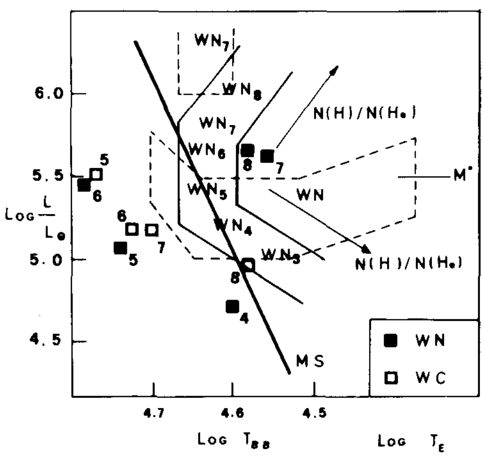

Fig. 4 - Location of WR stars in the HR diagram.

tionary history of WR stars, but is simply offered as a starting point for future implementation. The leading idea of this suggestion is that WR stars neither form an unique sequence, in the sense that any star moves from WN9 to WN3 and from WC9 to WC3 independently of their initial mass and mode of mass loss, nor a sequence of remnant masses, each of which corresponds to a specific initial mass. Rather a combination of the two aspects. This point of view is also somehow supported by the recent study of Niemela (1980).

i) Stars with initial mass smaller than some critical value M^* lose very little mass during core H-burning phase, and evolve redwards in the HR diagram with rapidly increasing mass loss rate. Whether stationary He-burning takes place without a blue loop or not cannot be still foreseen a priori. However, as the rate of mass loss is expected to increase with both increasing radius and decreasing mass, this fact should favour the possibility that a fraction of the latest stages of central He-burning might be spent as WR stars of early type, running at least part of the sequence WN3 to WN5. It is obvious that the percentage of such single WR stars is expected to be very low compared to that of binaries, owing to the by far more efficient mechanism of mass exchange. The extreme case would be that none of these lower luminosity WR's is single, but all are binaries. In this case the modality of mass exchange will determine the initial type of the WR sequence for the core He-burning remnant, and the competition between further mass loss and core He-burning lifetime will determine through how many WN and possibly WC types the remnant can evolve.

ii) Stars of initial mass above M^* also lose very little mass during core H-burning, but owing to the fast increase of the mass-loss rate as they start moving redwards, and the larger fractionary mass of the He-core, these stars cannot spend any appreciable fraction of their lifetime at low effective temperatures. The whole core He-burning phase is expected to occur near the zero age main sequence. We speculate that when H-poor layers are brought to the surface ($N(H)/N(He)$ being about 2), they should appear as late type WN's. Further mass loss make them run at least part of the sequence WN9 to WN6. However,owing to the very short core He-burning lifetime for these very massive stars (about $0.2\ 10^6$ ys), they will unlikely lose the whole H-rich envelope, and evolve through more than one spectral type, even in presence of the high rates quoted by Barlow et al. (1980). WC stars are expected to be hardly produced by these single late type WN's. Although the evolutionary computations carried out so far with the new formulations for the mass-loss rate are very preliminary, they seem to support the above suggestion.

The same arguments can be also applied to massive progenitor WR stars in binary systems. However due to the more favourable circumstances (mass exchange and stellar wind) the core

He-burning remnants may evolve through one or more subtypes, and also WC stars might be eventually generated.
Since stellar wind is competing with mass exchange in this range of initial mass, we expect the duplicity to be about normal among these most luminous WR stars, as indicated by Moffat and Seggewiss (1979).

6. MASS LOSS FROM YOUNG STARS IN LMC AND SMC

Recent observations on stellar winds from O, Of and OB stars in LMC and SMC (Hutchings,1980b) seem to indicate the existence of systematic differences in wind properties, which might suggest that those stars are losing mass at lower rates than their galactic counterpart.
The HR diagrams of supergiant stars in LMC and SMC also show systematic differences compared with the HR diagram of galactic supergiants. In fact the red supergiant stars are systematically bluer (Humphreys, 1979), and the highest luminosity limit for early to intermediate spectral type supergiants is systematically lower (Chiosi et al., 1980), passing from the Galaxy to SMC. The ratio NH/NHe of core H-burning to core He-burning supergiant stars studied by Bisiacchi and Firmani (1980) is found to vary from SMC to the Galaxy. In addition to this, Vanbeveren and Conti (1980) studied the frequency distribution of single and binary WR stars as a function of the spectral type in the Galaxy, LMC and SMC. While galactic WR's seem to equally populate each subtype, late WC's are absent in LMC, and an almost complete lack of WC stars is observed in SMC. A clear correlation between the mass ratio and spectral subtype for either WN or WC stars in the three galaxies is found by Moffat (1980). Finally, Maeder et al. (1980), comparing the number of red supergiant to WR stars across the galactic disk and in LMC and SMC, found that the ratio N_R/N_{WR} varies with galactocentric distance and among the three galaxies. Similar analysis is also made by Bisiacchi and Firmani (1980), who compare the number of WC to WN stars, and WR's to yellow supergiants in the Galaxy with the ones in the Magellanic Clouds.
Since the three galaxies differ from one to another in the mean metallicity, which systematically increases from SMC to LMC and Galaxy, the most straightforward interpretation of the above observational facts is sought in terms of different metal content. To this aim,both evolutionary computations of massive stars with low metal content, and various assumptions for the mass loss rate dependence on the metallicity (Chiosi et al., 1979b, 1980; Hellings and Vanbeveren, 1980; Maeder, 1980) are carried out, and semiempirical analyses performed.
Although preliminary, those studies enable us to derive several indicative results and conclusions:
i) Once more, the lack of red supergiants in LMC and SMC brighter than M_b=-9.5 can be reproduced with models of mas

sive stars suffering mass loss at substantial rate as in the galactic case (Chiosi et al., 1980).

ii) The shift of red supergiants in SMC, and to a lower extent also in LMC, to effective temperatures higher than for galactic red supergiants can be easily understood in terms of increasing metallicity from SMC to Galaxy (Chiosi et al., 1980).

iii) The distribution of blue supergiant stars in SMC cannot be reproduced by standard models calculated with metallicity holding for SMC (estimated in the range 0.001 to 0.003). In fact,the predicted band of stationary He-burning for intermediate mass stars, 15 to 50 $M_{\odot}$, is much narrower and bluer than for galactic stars, without any appreciable lifetime spent at low effective temperatures, contrary to the observational evidence of red supergiants in the range of luminosities pertinent to the above range of mass (Chiosi and Nasi, 1974b; Chiosi et al., 1980). In the same spirit of the galactic case, mass loss by stellar wind during both core H and He-burning phases is supposed to take place, thus reaching a much better agreement between theory and observations (Chiosi et al., 1980; Maeder, 1980). With the adopted formulations for the rate of mass loss (proportional to the luminosity in Hellings and Vanbeveren (1980), and Maeder (1980); radiation pressure mechanism of Castor et al. (1975) in Chiosi et al. (1980)), the effect of a lower metallicity on the rate of mass loss is however quite marginal, and the model differences are mostly due to the different chemical composition.

iv) The increase of the limit luminosity for early and intermediate spectral type supergiant stars, passing from SMC to the Galaxy, can be hardly understood even in terms of losing mass models with different chemical composition. Moreover it appears to be at variance with the suspected dependence of the mass loss rate on the metal content. Perhaps systematic variations of the initial mass function for massive stars (Peimbert and Serrano, 1980; Chiosi and Matteucci, 1980) might remove the above difficulty.

v) With the aid of mass losing models of Chiosi et al. (1978) and Chiosi (1980a), Bisiacchi and Firmani (1980) interpreted the variation of N_H/N_{He} as due to metal content and mass loss rate variations. In particular an increase of the mass-loss rate by a factor of five passing from SMC to Galaxy seems to be required.

vi) The variation of the N_R/N_{WR} ratio is attributed to the combined effect of abundances of heavy elements and amount of mass loss both in the main sequence and red supergiant phase (Maeder et al., 1980). The same conclusion is advanced by Bisiacchi and Firmani (1980) to interpret the variation of number of WC to WN stars and WR's to yellow supergiants

vii) The different distribution of WR stars among spectral subtypes observed in SMC, LMC and Galaxy can be perhaps also interpreted in terms of mass loss and chemical composition parameters (Chiosi et al., 1979c; Vanbeveren and Conti, 1980; Hellings and Vanbeveren, 1980), even though a quantitative analysis of this problem is still lacking.

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DISCUSSION

SERRANO: I want to make two comments about the comparison with observations. First as Lequeux et al. (1979) have shown, the heavy element abundance in irregular and blue compact galaxies can only be explained if mass loss as you have described takes place in massive stars. Models with constant mass evolution definitely do not fit observations. On the other hand, the helium to heavy element abundance ratio $\Delta Y/\Delta Z$ needs also evolution with stellar mass loss as I will mention later. Our understanding of mass loss is clearly inadequate, but you cannot change models much without violating these observed facts.

CHIOSI: As well known, the occurence of mass loss during core H- and He burning phases, by effecting the mass size of the core, will also effect the yield of heavy elements from massive stars (Chiosi and Caimmi, 1979 Astron. Astrophysics 80, 234). Since much lower yields are predicted with mass loss, the heavy element abundances in irregular and blue compact galaxies can be reproduced. I wonder however if this is the only possible explanation, because if one uses the same yields in modelling the solar vicinity too, a low metallicity is predicted at the present time. This same difficulty arises when, in order to explain the observed $\Delta Y/\Delta Z$ ratio yields with mass loss are adopted.

IBEN: You have emphasized that the location in the HR diagram of a massive star during core helium burning is extremely sensitive to the rate of mass loss. Can you state quantitatively what this sensitivity is and whether or not it is conceivable that a star oscillates back and forth in the HR diagram solely as a consequence of modest fluctuations in the mass loss rate.

CHIOSI: I cannot answer with simple arguments to the second point of your question. However on the basis of a few numerical computations that are available the location of models in the HR diagram may depend on the rate. As an example of it, an original 60 $M_\odot$ ($X = 0.7, Z = 0.001$) suffering mass loss at the rate of $1.97\ 10^{-5}\ M_\odot/y$ spent the entire core He-burning lifetime as red supergiant, whereas with slightly higher rate ($\dot{M} = 2.06\ 10^{-5}\ M_\odot/yrs$) a blue loop occurred.

VANBEVEREN: I still doubt whether or not the T_{eff} and radius variation for massive stars resulting from evolutionary computations can represent reality. As has been discussed by K. Andriesse yesterday in most of the stars one can expect subphotospherical instabilities and at present no computations are available to investigate the effect of these instabilities on the T_{eff} and radius variation. A first attempt to include instability effects in evolutionary calculations has been made by Appenzeller (1970) for stars more massive than 100 $M_{\odot}$ and he found a radius increase of about a factor 4 compared to ordinary evolutionary calculations.

CHIOSI: Appenzeller's (1970) analysis of vibrational instability applied as you said, to stars more massive than 100 $M_{\odot}$, whereas in discussing the comparison between theoretical models and observations, I referred to stars of smaller mass, the latter being even smaller in the domain of intermediate type supergiants. Although I quantitatively agree with you on the existence of such a problem, I do not know whether or not it can be simplified in the way you are suggesting.

DE LOORE: I can make clear what D. Vanbeveren is saying by showing the next figure. In the figure are indicated the ZAMS (full line) and the TAMS (dashed straight line) and some lines of O type stars. A large part of these stars are outside the core hydrogen burning region. Appenzeller (1970) (Astron. Astrophys. 5, 355; 9, 216) has studied the effect of vibrational instabilities on the stellar structure for massive stars and concludes that the radii of such stars increase with about a factor 4. This implies, if we assume that the luminosity is not affected, that the effective temperature is diminished with 0.3 in the logarithm. I have expanded on evolutionary models (N = 300), and so the evolutionary tracks reach further into the red. The new TAMS is indicated as $TAMS^1$. Now you see that all the O stars fall in the newly defined core hydrogen burning region. One of our collaborators at the Astrophys. Institute, Brussels, Hellings is investigating this effect in detail, and is computing stellar models and evolutionary series.

MAEDER: You have shown an analytical relation expressing the change of radius in function of core mass, density at well chosen level and total mass. How are you sure that this relation is the most physically meaningful?

CHIOSI: An inspection of the numerical model reveals that a politropic relationship between pressure and density holds for a large variety of envelope structures. Therefore the mass of the core and density at the inner boundary of the envelope, together with total envelope mass may be used to investigate the envelope structure. Although we cannot say that this approach is the most complete, the validity of our analysis is supported by the agreement with detailed numerical calculations and the semi analytical formulation of Falk (1979).

SAHADE: My comment is in regard to what has been said about WR stars. Again we are considering as an established fact the very attractive scenario proposed by Conti in 1975. Let me remark that I do not think we can talk about H/He ratio in WR stars. We do not see photospheric lines in WR stars except in a few cases, so far - and even then we have not enough information to tell about H/He ratio. And if we want to derive that ratio from the features that arise in the extended envelope, I would repeat what I said yesterday, in the sense that we cannot talk about abundance without being able to describe the physical conditions of the layers involved. Let me also remind you that earlier it was believed that a typical WR mass was 10 $M_{\odot}$ and no H had been found in these objects (except for L. Smith's observations presented in the Buenos Aires Symposium). Everybody was happy and could explain WR stars evolutionary-wise. Now we have found larger masses and H in some WR stars and other exceptions. I suggest that we have reached a stage in which we need more observations and we need to look more thoroughly at the available and forthcoming information.

CHIOSI: I agree. More observations, theoretical understanding of the WR phenomenon and an open mind in facing this problem are most welcome. Nevertheless, I think that at the present time it might be still worthwise to explore to some extent Conti's scenario.

CARRASCO: A general warning concerning the problem of comparing theoretical tracks for massive stars with observational H-R diagrams: One must be aware of the fact that the O-type stars are a mixture of extreme PopI. and Old Disk Population objects. The latter group represent at least 10% and probably up to 40% of the O-type stars, and they are likely low mass highly evolved objects and hence subject to different evolutionary time scales.