THE STRUCTURE AND EVOLUTION OF MASSIVE STARS

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1. INTRODUCTION

This review is restricted to the most recent studies of the structure of stars in the approximate range from 10 to 100 $M_\odot$, during the core H- and He-burning phases. Other recent major reviews on this subject are by Dallaporta (1971), Massevich and Tutukov (1974) and Iben (1974). The lower limit was chosen to be just above the transition from degeneracy to non-degeneracy in the core at carbon ignition (Schwarzschild and Härm 1958). The upper limit is very uncertain. The canonical value of about 60 $M_\odot$ for Pop I composition was set by Schwarzschild and Harm (1959), using linear pulsation theory. More recent non-linear dynamical calculations lift the limit above 100 $M_\odot$, and also show that mass loss by vibrational instability occurs at such a rate that stars in the range from 100 to 200 $M_\odot$ can survive for a time comparable to the total main sequence lifetime (Appenzeller 1970a, b, Ziebarth 1970, Talbot 1971a,b and Papaloizou and Taylor 1974).

2. SEMICONVECTION

Our understanding of massive stars in core H- and He-burning is still affected by the long-standing problem of the mixing of convectively unstable layers at the boundary of the convective core (semiconvection).

Excellent reviews are available on the basic ideas of semiconvection (Dallaporta 1971, Massevich and Tutukov 1974, and Iben 1974) and on the variety of structures of the intermediate layers which have been suggested since its discovery (Stothers 1970). We will review only the controversy over which criterion

A. G. Davis Philip and D. S. Hayes (eds.), The HR Diagram, 357-368. All Rights Reserved.

to use for stability against convection in regions with a gradient of molecular weight. Two approaches have been suggested. Schwarzschild and Härm suggested that the composition in these layers is modified such that the temperature gradient is equalized to the adiabatic value to maintain a neutrality condition ($\nabla_T = \nabla_{Ta}$, hereafter called Eqn. 1). In the second case, due originally to Ledoux (1947), the density gradient is equalized to the adiabatic value ($\nabla_\rho = \nabla_{\rho a}$, hereafter called Eqn. 2).

It is evident that whereas Eqn. 1 implies a layer which is dynamically stable, Eqn. 2 implies a layer on the verge of dynamical instability. It is therefore likely that complete mixing could take place.

The basic mechanism for mixing is unknown in both cases. Kato (1966) pointed out that Eqn. 2 must be applied in a medium with a gradient of molecular weight when thermal dissipation is neglected. If, however, it is included, one ends up with Eqn. 2. In Kato's picture the mixing mechanism is thought to rely on the vibrational instability of the gravity modes of non-radial oscillations. Since the instability sets in as soon as $\nabla_T > \nabla_{Ta}$, mixing would take place in such a way that Eqn. 1 is satisfied. But Kato's analysis is a local one, based only on the intermediate layers themselves. This approximation is very drastic, and it is valid only for eigenfunctions with very large amplitudes in the destabilizing region and small amplitudes everywhere else. Moreover the onset of vibrational instability is known to involve the whole star, so a careful analysis is necessary. This problem was investigated by Gabriel (1969) and Aure (1971) using approximate stellar models and eigenfunctions, and no instability was found. Gabriel and Noels (1976) reconsidered this problem, analyzing the vibrational instability of gravity modes for a 30 $M_\odot$ stars, when no prescription for semiconvection is adopted in the intermediate layers. The result is that a large number (increasing as evolution proceeds) of eigenfunctions, with large values of the surface spherical harmonic ℓ, are trapped in the region with a gradient of molecular weight. Most of the eigenfunctions are vibrationally unstable with a time scale on the order of 10^3 to 10^4 years. The idea is that these unstable gravity modes are able to reduce the temperature gradient to a value very close to the adiabatic one.

This result, if confirmed by non-linear analysis, would allow us to disregard models with layers obeying Eqn. 2 in favor of those obeying Eqn. 1.

3. EVOLUTIONARY RESULTS

Numerous calculations have shown that semiconvective mixing does not play a significant role (whatever the adopted stability criterion) on the main sequence. However, H shell burning and especially He core burning are, on the contrary, completely dominated both by any small difference resulting from the choice of stability criterion and by secondary details of the input physics (opacity, nuclear reaction rates, chemical composition, and mixing length ratio).

3.1 Helium Ignition

Because of the large body of literature on this subject, only a few references will be quoted here. For further details see Stothers and Chin (1975, 1976). The lower limit of the mass, for Pop I composition, at which the choice of stability criterion produces a significant difference in the evolutionary behavior was estimated by Barbaro, et al. (1972) to be around 13 $M_\odot$. The adoption of Eqn. 2 in computing stellar models results in the devlopment of a shallow gradient of chemical composition. The onset of an H-burning shell does not modify this structure, and no matter where core He-burning is initiated, whether at high or low T_{eff}, thermal equilibrium is first partially achieved in the red supergiant phase. Further evolution either takes place entirely at low T_{eff}, or with more or less wide loops in the HR diagram. Several causes of the loops are discussed next.

The adoption of Eqn. 1 leads to a more intriguing situation. The onset of an H-burning shell causes the development of a fully convective shell in the region of intermediate instability, which drastically changes the H-profile throught the zone. Models of this type were first computed by Chiosi and Summa (1970) and by Simpson (1971), who also pointed out the main reasons for this transition from semiconvection into full convection.

In the mass range from 13 to 40 $M_\odot$ (these values are only estimates, as they depend upon several parameters, mostly the composition), due to the occurrence of the fully convective zone, or more precisely, the plateau-shaped H-profile, core He-burning takes place either entirely in the blue supergiant region or partly in the blue and partly in the red supergiant region. This is no longer true, though for different causes, for both lower and higher masses. In fact, models around 11 $M_\odot$, which use Eqn. 1 and which have a plateau-shaped H-profile, start core He-burning as red supergiants and perform a loop in the HR diagram (Barbaro, et al. 1972). Two sequences at 12 $M_\odot$, by Robertson (1972), are exceptions, having the entire He-burning phase in the red supergiant region without a loop. On the other hand, stars with mass greater than about 40 $M_\odot$ spend either their entire He-burning phase, or a time comparable to the total time of He-burning as red supergiants (Barbaro, et al. 1971, Varshansky and Tutukov 1973, and Stothers and Chin 1976). Barbaro, et al. (1971) suggested a possible qualitative interpretation of this behavior for both types of models. In studying the influence of the H-profile on the core He-burning phase, they introduced two characteristic time scales which describe the pre-He-ignition phase: the time T_{sh} at which the H-burning shell advances through the H-profile, and the time T_d of diffusion of radiation from the shell to the surface. When $T_{sh} < T_d$ (low H-content) the models are not in thermal equilibrium because the outer layers cannot readjust to the rapid changes in the interior. If the H-content in the shell is high then T_{sh} becomes greater than T_d, and thermal equilibrium can be restored. Moreover, T_d becomes quite small in the presence of extended convective zones in the outer envelope. It is also easy to understand the relation between T_{sh} and the H-profile resulting from the choice of different stability criteria. Models in the intermediate mass range ($13 < M/M_\odot < 40$) using Eqn. 1 have the merger of the H-burning shell with the inner edge of the H-plateau, formed by the convective shell, occurring at high T_{eff}, so that $T_{sh} > T_d$ and thermal equilibrium is restored. At lower mass ($M < 13\ M_\odot$), however, as the inner extension of the convective shell is smaller, an extended zone with low H content is left between the He-core and the H-plateau; the models reach the Hayashi line before the H-burning shell has reached the H-plateau. In the higher mass ($M > 40\ M_\odot$) range, even though T_{sh} is quite soon equal to or greater than T_d, the additional effect of the high L/M makes the models red (Stothers and Chin 1976). Models constructed with Eqn. 2, owing to their shallow H-profile ($T_{sh} < T_d$), must undergo a preliminary red phase before partially restoring thermal equilibrium.

Subsequent evolutionary behavior, after the star has reached the Hayashi line in the early phases of core He-burning, is not well understood. In particular, whether these stars become blue supergiants while performing a loop in the HR diagram, or whether they remain red supergiants until core He-depletion, is not yet well established.

3.2 Loop Formation

A general view of the variety of models obtained by many authors gives the impression of contradictory and rather erratic results. It was not until the work of Ziolkowski (1972), though the result had been predicted by Paczynski (1970), that the crucial effect of small changes of the depth of the convective envelope at the tip of the red giant branch on the loop formation was shown. The critical point is whether the H-burning shell is able or not to approach, before the core He-depletion stage, the discontinuity in the composition profile previously produced by the penetration of the outer convection zone. The numerical computations show that, once the H-burning shell passes the composition discontinuity, the models rapidly shift into the region of high T_{eff}, producing a loop.

A deeper analysis of this problem shows that the loop phenomenon is ultimately related to the composition profile throughout the star. It was shown by Lauterborn, et al. (1971a, b), Kozlowski (1971) and Fricke and Strittmatter (1972) that thermally stable models in the core He-burning phase with a rectangular H-profile can exist only in the region of high T_{eff}. In this context it is evident that any mixing that contributes to the formation of a discontinuous H-profile, due to convection either in internal layers or in the outer envelope, plays a very important role. Models reaching the Hayashi line with a shallow H-profile must stay there until the H-burning shell reaches the discontinuity in composition produced by the outer convection zone. A significant fraction of the core He can be burnt during this stage. Some models may even have the entire core He-burning as red supergiants. On the other hand, those models which suffered an intermediate homogenization while crossing the HR diagram prior to core He-ignition, quite soon build up a quasi-rectangular profile and go back into the region of high T_{eff}. A negligible fraction of the core He is burnt in this case. It is also easy to see that a number of parameters, such as the opacity source, the nuclear reaction rates and the mixing length ratio may significantly affect this picture (Stothers and Chin 1975, 1976).

3.3. Stationary He-burning

Models without a pre-He-burning red phase (Chiosi and Summa 1970, Simpson 1971, Stothers and Chin 1976), or models that did not undergo any significant He-depletion before the loop formation (Chiosi and Summa 1970, case A, Barbaro, et al. 1972), have their major stage of core He-burning as blue supergiants, with the remainder as red supergiants. The two subphases are separated by an intermediate yellow phase with a thermal time scale. Over an extended mass range Lauterborn, et al. (1971a, b), Fricke and Strittmatter (1972), and Barbaro, et al. (1973) suggested that the two stages could be described in terms of the fractional mass in the He core, q_{He}, and the central He-content Y_c. The parameters q_{He} and Y_c are found to control the blue and red stages, respectively. The existence of the thermally unstable yellow region is also confirmed by the sequences of equilibrium models by Barbaro, et al. (1973) and Lauterborn, et al. (1971b). The ratio $(T_B/T_R)_{He}$ of the lifetimes of the blue and red stages is not uniquely correlated with the stellar mass, but is also affected by a number of other factors. It increases with Z, Y, ε_{C+DC} and decreases with $\varepsilon_{3\alpha}$. On the other hand, models whose lifetime in the red supergiant region is long enough to significantly deplete the core He-content, and models which spend their entire core He-burning lifetime as red supergiants, do not fit this picture. In particular, the former exhaust the remaining core He as blue supergiants only (Ziolkowski 1972, Stothers and Chin 1975). In any case, the lifetime ratios $(T_B/T_R)_{He}$ are always quite small.

3.4 Multiple Solutions

The possibility that multiple solutions may exist for models of the same mass and distribution of composition was first suggested by Paczynski (1970). His suggestion was confirmed by Lauterborn, et al. (1971a, b), Kozlowski (1971), and Fricke and Strittmatter (1972). They showed the existence of three different models (blue, yellow and red) of a star with a given mass and composition profile in a certain range of the mass of the He core.

The same authors demonstrated the occurrence of secular instabilities, associated with the yellow solutions, during the loop phase. These apparent violations of the Vogt-Russell theorem were discussed by Kähler (1972) and further investigated by Paczynski (1972), who developed the concept of the similarity between a sequence of static models and the linear series of Poincaré. The relationship between multiple solutions, the sign of the Henyey determinant, and thermal stability was also clarified. Moreover, the possibility of multiple branches in the linear series also accounts for the multiplicity in the solutions found by numerical computations. The most salient advantage of these studies is that they not only give a systematic interpretation of the basic evolutionary features, but also foresee the response to variations in the input parameters.

4. CARSON'S OPACITIES

The results we have just outlined are mostly based on the use of the radiative opacities calculated by Cox and Stewart (1965, 1970) using the hydrogenic model of the atom. On the other hand, the new radiative opacities of Carson (1974) are based on the hot "Thomas Fermi" model of the atom for all elements heavier than He. The largest difference between the new and old opacities is the bump (absent in the old ones) due to the ultimate ionization of the CNO group of elements at moderate temperatures and low densities. Evolutionary models by Stothers (1977), for the mass range from 7 to 60 $M_{\odot}$ and Pop I composition, show that the new feature of Carson's opacity becomes important for masses greater than 10 $M_{\odot}$. As a consequence of it, a fraction of the envelope, growing with mass and proceeding evolution, becomes convective even at high T_{eff}. This result broadens the main sequence band. The main features of semiconvection and its dependence upon the stability criteria are still preserved under the new opacities. However, for masses above some value, about 20 - 30 $M_{\odot}$, the intermdiate instability is suppressed when the outer layers expand to very large radii, or when the outer convection zone penetrates inwards very deeply. Moreover, the present computations seem to indicate that stars of the highest mass (around 60 $M_{\odot}$) could spend a large fraction of the core H-burning phase itself as red supergiants. According to this interpretation the upper main sequence could extend across the whole HR diagram. In addition, the results indicate that no static red supergiant models can exist for masses greater than 30 $M_\odot$. Stothers (1977) speculates that, as a plausible consequence of it, mass loss in the red region would occur.

The advantages and improvements in the comparison with observations have been extensively discussed by Stothers (1976b) and references quoted therein. However, a number of serious difficulties are still present, such as the observed rarity of very luminous M supergiants, and the presence of intermediate spectral type stars (B2-A5), which do not have a theoretical counterpart in the proposed scenario (Stothers 1977).

5. MASS LOSS

In the spectra of OB supergiants, the presence of displaced ultraviolet resonance lines, similar effects in the visible region, $H\alpha$ emission, and radial velocity gradients are commonly interpreted as an indicator of mass outflow (Hutchings 1976, Conti 1976, and Snow and Morton 1976). The mass loss rates are estimated to be from 10^{-7} to 10^{-5} $M_\odot$/yr. A further indication of mass loss in OB supergiants is provided indirectly by the upper limit of the luminosity of hot supergiants, which decreases from $M_{bol}=-10^{m}.5$ at log $T_{eff}=4.5$ to $M_{bol}=-8^{m}.5$ at log $T_{eff}=4.3$ (Hutchings 1976). Moreover, anomalies in the surface abundances of some OB stars, which appear to be carbon or nitrogen rich (OBC, OBN), seem also to imply that mass loss occurs (Dearborn and Eggleton 1977). The observational evidence of mass loss from red giants and supergiants is discussed by several authors (Weyman 1963 and Reimers 1975). The mass loss rate ranges from 10^{-9} to 10^{-5} $M_\odot$/yr. with an uncertainty on the order of a factor of two either way, according to Reimers (1975). For red supergiants with masses greater than 3 $M_\odot$, Reimers (1975) also suggests either an additional previous phase of mass loss, or an increase in the rate by a factor of three. No accurate estimate exists for the most luminous red supergiants.

Theoretical investigations of mass outflow from red supergiants offer two possible pictures, either radiation pressure on grains (Lucy 1976), or stellar wind from a hot corona due to non-thermal processes in the convective envelope (Fusi-Pecci and Renzini 1975, and references quoted therein).

Evolutionary sequences incorporating the mass loss phenomena, for the mass range 20 - 100 $M_\odot$ during the H and He core burning phases, have been calculated by Chiosi, et al. (1977) and de Loore, et al. (1977a, b). Because of several uncertainties in our theoretical understanding of mass loss, both of these attempts use one or two parameters to reproduce the observational data. Core H-burning sequences with mass loss evolve at lower luminosity and T_{eff}, thus broadening the main sequence. However, if the mass loss rate is high, the most massive stars (60 - 100 $M_\odot$, the limits depending upon the average mass loss rate) invert their path in the HR diagram long before core H-exhaustion and shrink towards the main sequence, eventually crossing it. This behavior leads to a plausible interpretation of the upper luminosity boundary of OB supergiants if the mass loss rate ranges from 2×10^{-6} $M_\odot$/yr., for an initial mass of 20 $M_\odot$, to 2×10^{-5} $M_\odot$/yr., for an initial mass of 100 $M_\odot$. Semiconvective instability is suppressed during the entire core H-burning phase. At the onset of an H-burning shell, a convective layer appears above it, as is usual when the Schwarzschild criterion is used. However, its extension in mass is much smaller than in the case of conservative evolution. Stars in the upper range of mass, roughly from 60 to 80 $M_\odot$ with a sufficiently high mass loss rate, may lose as much as 40 to 50% of their mass during the main sequence phase. Layers of the original convective core are brought to the surface, with the result that the surface He abundance is increased by almost a factor of two at the end of core H-burning, and the H abundance is correspondingly decreased. Since CNO processed material is brought to the surface, enhancements of ^{14}N and ^{13}C relative to ^{12}C and ^{17}O relative to ^{18}O are expected. Following Dearborn and Eggleton (1977), mass loss and these anomalies in the surface composition may be clues to the interpretation of OBN stars. On the basis of the quite low N(H)/N(He) ratios (1-2) predicted theoretically for the last stages of core H-burning in very massive stars (roughly 80 and 100 $M_\odot$), de Loore, et al. (1977b) suggested that single WN7-WN8 stars were still burning H in their cores. An alternative suggestion was made by Chiosi, et al. (1977), who preferred the idea that WN7-WN8 stars are in advanced stages of core He burning. In this case the WN7's and WN8's would be the result of mass loss in both the blue and red stages. Thus, an attempt was made by Chiosi, et al. (1977) to follow evolutionary sequences, with mass loss given by the acoustic flux mechanism, through both the blue and red stages and up to the intermediate core He-burning phase. As a result of this study we may suggest the following scenario. Stars with an initial mass smaller than ∿15 $M_\odot$ reach the Hayashi line and undergo moderate mass loss by a wind driven by the acoustic flux. Their evolution is similar to the classic scheme. Stars with an initial mass in the range from ∿15 to ∿35 $M_\odot$ reach the Hayashi line but suffer a significant mass loss so that their subsequent evolution is greatly modified. In fact, the core He-burning takes place after the red phase, while the star is slowly moving towards higher T_{eff}'s. The area in the HR diagram which is occupied is similar to the one resulting from the use of the Ledoux criterion, but covers a broader strip, giving better agreement with the observations.

Stars with higher initial masses ($M > 40$-50 $M_\odot$) do not reach the Hayashi line because of their high mass loss rate. Nevertheless, their subsequent evolution is similar to that of intermediate-mass stars. Within this framework, Chiosi, *et al.* (1977) suggested that single WN7 and WN8 stars originate from stars of the highest mass and are in the late stages of core He-burning. Moreover, single WN's and WC's should have progenitors in the mass range from 20 to 40 $M_\odot$ (or, better, from 30 to 50 $M_\odot$) which reached the Hayashi line but also suffered extensive mass loss. WN's and WC's, then, may be in advanced stages of central He burning. The numerical results seem also to indicate that stars in the latter mass range may lose their entire H-rich envelope, before the completion of core He-burning, as blue stars. Then the WC's should correspond to that fraction of the core He-burning phase which occurs after the removal of the H-rich envelope and before He-exhaustion. However, because of the many uncertainties prsent in this picture, more work is necessary to achieve a deeper insight into the problem.

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DISCUSSION

KÄHLER: I have a comment and a question. First the comment: You discussed the first loop which depends on details of the chemical profile. We have investigated the second loop for a star with $9M_{\odot}$. It turns out that the occurrence of the second loop depends critically on the mass of the burnt-out C-core but is nearly independent of the chemical profile. My question: Do you prefer the new opacities or the old ones?

CHIOSI: The results I have just described refer only to massive stars ($M > 10\ M_{\odot}$) and in the central He-burning phase. It is generally accepted that the chemical profile throughout the models is the leading parameter for the occurrence of a loop, although other factors may strongly affect its features. Moreover, as far as I know, in this range of masses, phases subsequent to the central He exhaustion occur only along the Hayashi line, so a second loop does not occur. However, I agree with you that in the case of lower mass stars the leading parameter for the loop formation in the double shell-burning phase is the mass of the carbon core. As far as your second point is concerned, I don't have an easy answer. The results by Stothers, using the new radiative opacities, give a rather embarassing picture for the evolution of most massive stars even in the core H-burning phase. Very recently, Stothers has discussed possible improvements achieved by the use of the new radiative opacities. However, the new opacities also give a number of serious problems when the theoretical results are compared with observations. For instance, they do not account for the occurrence of intermediate spectral type supergiants and the lack of very luminous red supergiants (mass-loss in the case is absolutely necessary). My personal opinion is still in favor of the old radiative opacities. In any case more work is necessary to cast light on this problem.

FLOWER: I would like to comment on the Carson opacities. The group calculating stellar opacities at Los Alamos under the direction of Al Mertz has not been able to reproduce these opacities using the same atomic model as Carson. Therefore, evolutionary calculations using these opacities may be very suspect.

CONTI: Stothers' models using Carson's opacities do have what I consider a serious problem. The temperature of the most massive, O-type stars is predicted not to be greater than 35000 K or so. This is in conflict with what I feel is the well determined temperature scale based upon the observed ionization equilibrium of helium. We observe normal O-type stars with temperatures up to 50000 K. This is in conflict with Stothers' models using Carson's opacities.

CHIOSI: I agree.