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THE EVOLUTION OF MASSIVE STARS IN THE LIGHT OF THE NEW OPACITY DATA

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RESUMEN

Basándose en modelos atómicos más detallados, Rogers & Iglesias han computado una nueva tabla de opacidades estelares. Estos valores de la opacidad son más grandes (hasta en un factor de 3) que en cómputos previos, especialmente en las condiciones presentes en la envoltura de estrellas masivas. Los modelos de la evolución de estos objetos se ven entonces modificados. Discutimos el estado actual de nuestro entendimiento de la evolución de las estrellas más masivas, incluyendo las modificaciones inducidas en los modelos por las nuevas opacidades y la necesidad de tener en cuenta la pérdida de masa y *overshooting*. Además, discutimos la comparación con las observaciones mostrando que el acuerdo de los modelos nuevos es mejor que en cálculos previos.

Finalmente, discutimos la plausibilidad física de la teoría de la convección empleada en los cálculos evolutivos.

ABSTRACT

Based on more detailed atomic models, Rogers & Iglesias have computed a new table of stellar opacities. These values of the opacity are larger (up to a factor of 3) than in previous calculations, specially in the conditions attained in the envelope of massive stars. Therefore the computed evolution of these objects is modified. We discuss the present status of our understanding of the evolution of the most massive stars, including the opacity-induced modifications of the models and the necessity of including mass loss and overshooting. We also address the comparison between the new evolutionary models with observations, showing that the agreement is better than in previous calculations. Finally, we review the physical plausibility of the theory of convection employed in the models of stellar evolution.

Key words: **ATOMIC DATA — CONVECTION — STARS: EARLY TYPE — STARS: EVOLUTION — STARS: MASS-LOSS**

1. INTRODUCTION

For a long time, it has been well known that the η Carinae region is particularly rich in massive stars. For this reason, it is very important to employ the valuable observational data we can collect from this region in order to make accurate comparisons with the predictions of the theory of stellar evolution, particularly for the massive stars.

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It is the aim of this talk, to give an overview of the present state of art of the models of the evolution of massive stars (hereafter EMS). In doing so, we shall pay particular attention to the recent improvements achieved in opacity calculations and experiments. Also, we shall give a brief discussion of the plausibility of the theory of convection currently employed in computing the models.

In § 2 we address the new opacity data; in § 3 we discuss the state of the art of the EMS. Section 4 is devoted to the plausibility of the theory of convection, and finally in § 5 we sketch our main conclusions.

2. THE NEW OPACITY DATA

As is widely known, the Rosseland mean opacity (hereafter κ_R) of the stellar material is one of the most important ingredients in determining the structure and evolution of the stellar models. From long time ago, it was only available by means of very complicated theoretical calculations. The first opacity tables suitable for computing stellar evolutionary models were provided by the Los Alamos group: (Cox & Stewart 1965) and further improved and extended by Cox & Stewart (1970a,b), Cox & Tabor (1976), and Huebner et al. (1977).

At that time, computers were small and not very powerful, thus in the above cited calculations it was unavoidable to introduce many approximations. For example, the equation of state of the mixture was computed as a mixture of ideal gases. Also, hydrogenoid photoionization cross sections were employed. Perhaps the main shortcoming was the impossibility to estimate the errors involved in these approximations.

In comparing resulting stellar models with observations, many researchers suggested that Los Alamos opacities may represent an underestimation of the actual κ_R. Among others, Simon (1982) arrived to this conclusion in fitting mass, luminosity and pulsation periods of Cepheid stars; also Stellingwerf (1978) proposed the same in order to energize the pulsation of β Cephei stars. These suggestions are now strongly supported by the work of Rogers, Iglesias and collaborators (Rogers & Iglesias 1992; Iglesias, Rogers, & Wilson 1992; Iglesias & Rogers 1993). They have performed a giant effort in improving the already available data introducing, by far, more details than in previous calculations, in producing the OPAL data.

They used the method of parametric potentials, in which a Yukawa- like potential of the form

$$V(r) = \frac{2}{r}(1 + Q + \sum_n N_n \exp(-\alpha_n/r)) \quad , \tag{1}$$

(where Q is the total charge of the nucleus, N_n is the number of electrons in the shell with principal quantum number n and α_n are free parameters) is proposed, and then, the Dirac equation is iteratively solved to get the α_n adjusting the experimentally measured energy levels, oscillator strengths and photoionization cross-sections. This was done considering valence as well as internal electrons.

In their first work, Rogers & Iglesias (1992) assumed the Anders & Grevesse (1989) abundances and neglected the effect of molecules. This imposed a lower limit for the range of temperatures for which OPAL tables are applicable. Also they considered up to 10^4 spectral lines and **L.S** coupling.

The authors of OPAL data have chosen to tabulate the opacities as a function of the logarithm of temperature $\log(T)$ vs. $\log(R)$, where R is defined as $R = \rho\ T_6^{-3}$, where T_6 is the temperature in units of $10^{6o}K$. In the stellar interior $\log(R)$ is better behaved than ρ which was the variable used by the Los Alamos group. For this reason, the interpolation procedures are easier to perform with the OPAL data.

The ranges for which κ_R has been tabulated is: $\log(T_6) = 0.006$ to 0.04 and $\log(R) = -5$ to 1; and $\log(T_6) = 0.04$ to 100 and $\log(R) = -5$ to -1 for $x > 0$; or $\log(T_6) = 0.006$ to 100 and $\log(R) = -5$ to -1 for $x = 0$; and $X = 0.70; 0.35; 0.00$; $Z = 0, 0.0001, 0.0003, 0.001, 0.002, 0.004, 0.01, 0.02, 0.03$

As a result, many differences were revealed when comparing the new opacity data with the previous ones. The most important is that the expected increase in κ_R is real and arises as a natural consequence of the much improved atomic data. Also, it was shown that one of the most important sources in κ_R is the Fe, mainly in transitions in the M shell ($n = 3$) with $\Delta n = 0$. This fact revealed us that, to get κ_R, we must know not only the heavy elements fraction Z (as expected in the past) but also the Fe abundance with high accuracy.

In a further work Iglesias et al. (1992) relaxed the **L.S** coupling approximation and allowed for intermediate coupling and up to 5×10^4 lines. This should be more accurate in the case of heavy ions like Fe that are just the ones that dominate the κ_R. The effect of the intermediate coupling is to split the energy levels of Fe allowing for the appearance of more spectral lines, thus increasing the κ_R values (see Figs. 8 of Iglesias et al. 1992). They also changed the abundances according to the Grevesse et al. (1991) data that includes a 30% lower fraction of

Fe than before. These two changes have an opposite effect on the value of κ_R, but the net effect is to increase it. For the sake of comparison between OPAL and Cox & Tabor (1976) data see Figs. 2-5, and for the effects of changing from the former to the now assumed heavy elements abundances see Fig. 10a,b of Iglesias et al. (1992) respectively. These tables have been extensively employed in computing EMS by several groups (see § 3).

In the above described works, the assumed chemical composition of the mixtures is adequate to describe the structure of stars in the H-burning stages but not beyond. To overcome this limitation Iglesias & Rogers (1993) have recently computed κ_R for carbon- and oxygen-rich mixtures and devised an interpolation scheme to be employed in evolutionary calculations. With this new data it is possible to recompute the two longest stages of stellar evolution (H - and He - burning), a work that will certainly appear in the near future.

Up to the near past, κ_R was available only by means of theoretical calculation but this situation has just dramatically changed. Using a powerful laser, Da Silva et al. (1992) have been able to show experimentally that the transitions in the M shell of Fe ($n = 3$) with $\Delta n = 0$ are indeed very important. More recently Springer et al. (1992) performed the *first* experimental measurement of the κ_R of Fe. They got a Fe plasma at $\rho = 10^{-2}$ g cm^{-3} and $T = 6 \times 10^{5o}$K and measured a value of $\kappa_R = 4400 \pm 600$ cm^2 gr^{-1}, meanwhile the OPAL code gives $\kappa_R = 4255$ cm^2 gr^{-1}. This spectacular result make us to feel that Rogers, Iglesias and their group have performed a landmark advance in our knowledge of stellar opacities.

Regarding the modifications in stellar evolutionary models, it is worth to note that the difficulties with pulsating stars have been largely removed by these new opacities (Cox 1991). We leave the modifications induced in the massive stars' context for the following section.

3. THE EVOLUTION OF MASSIVE STARS: THE PRESENT STATUS

The EMS is one of the most important phenomena for the evolution of the whole Universe, because e.g., they are thought to be the main source of the heavy elements present in Nature and the supernova explosion progenitors. For a review of the early work on this topic see Chiosi & Maeder 1986). We shall only review the main characteristics of the EMS models paying special attention to the opacity-induced modifications.

It is well known that massive stars shed mass at appreciable rates, that are able to modify their evolution in a sizeable way. The rates range from negligible up to $\dot{M} \approx 10^{-5} M_\odot$ y^{-1} for O stars to $\dot{M} \approx 10^{-4} M_\odot$ y^{-1} for Wolf-Rayet (hereafter WR) stars.

From sometime ago, mass loss has been incorporated in the computation of EMS assuming that the outer layers of the star flow apart at the observed rate. The calculations (e.g., Maeder 1981) have shown that, compared with constant mass evolutionary models, in the mass losing models:

i) L is lower but the object is overluminous for a given M;

ii) because L is lower, MS lifetime is larger;

iii) T_c increases at slower rate and M_{core} is larger;

iv) MS is moderately widened if $\dot{M}$ is not very large.

All these effects imply that:

v) evolutionary tracks and isochrones in the HR diagram are deeply modified;

vi) $\dot{M} \neq 0$ is needed to account for the observed lack of RSG at $M_{bol} \leq -9.5$ (Humphreys & Davidson 1979) limit;

vii) mass loss can be strong enough to make the star lose its H-rich envelope turning it into a WR object.

In comparing the theoretical and observed MS it was found that many stars appear located outside the theoretical MS but near the TAMS. This was assumed by some authors (e.g., Maeder 1975; Stothers & Chin 1985) as an indication of problems in the treatment of convection and invoked the presence of overshooting (hereafter OV). OV is the effect by which eddies go upwards beyond the classical "Schwarzschild edge" (defined by $\nabla_{rad} = \nabla_{ad}$) of the convective core because they arrive there with $\dot{v} = 0$ (zero buoyancy force) *but* $v \neq 0$. The extent l_{OV} of the OV zone is parametrized as $l_{OV} = \Lambda_{OV} H_P$ where H_P is the scale of pressure height and Λ_{OV} is a free parameter.

Convective OV produces:

i) larger M_{core}; ii) higher L but because the increase in M_{core} dominates, MS lifetime is longer; iii) much wider MS; iv) He burning is not much affected, but loops are smaller.

It should be noted that because M_{core} is larger, OV also deposits nuclearly-processed matter closer to the stellar surface, thus (as $\dot{M} \neq 0$ does) making it easier for a star to show enriched material at the surface, providing an interesting test for the theory of EMS (see e.g., Figs. 10-12 of Bressan et al. 1993 and Figs. 13 and 14 of Maeder & Meynet 1987; for more details on the structure of stars including OV see e.g., Stothers & Chin 1985). Since the review article of Chiosi & Maeder (1986) some EMS models with mass loss and OV have been published: Maeder & Meynet (1987; 1989); Maeder (1990); Chin & Stothers (1985) and Alogni et al. (1993). All these models used the old opacity data, therefore we shall not discuss them here.

The first in applying OPAL data to EMS were Stothers & Chin (1991) who show that MS moves to lower T_{eff}; the ZAMS agrees much better with the observed young open cluster data (up to $M_{bol} \approx -8$ which corresponds to $\approx 30 M_{\odot}$ objects) as do the TAMS *without* OV. Based on this kind of comparison they stated an upper limit for Λ_{OV}: $\Lambda_{OV} \leq 0.20$ (see Fig. 2 of Stothers & Chin 1991). Even if other authors do not share this point of view, they agree that OV should be moderated. The "tendency" of models with OPAL data to give lower Λ_{OV} is one of the most important consequences of the new opacities, as well as the fact that they provide a MS widening.

Since OPAL data became available, the Geneva and Padova groups started to produce large sets of stellar evolutionary models for stars of masses from a few tenths of $M_{\odot}$ to 120 $M_{\odot}$ and for different heavy element content (Schaerer et al. 1993b for $Z = 0.04$; Schaller et al. 1992 for $Z = 0.02$ and $Z = 0.001$; Schaerer et al. 1993a for $Z = 0.008$; Charbonnel et al. 1993 for $Z = 0.004$ and Bressan et al. 1993 for $Z = 0.02$ respectively). These evolutionary models have updated:

i) opacities;

ii) mass loss rates;

iii) OV in the core with $\Lambda_{OV} = 0.20$;

iv) the mixing length theory parameter Λ_{MLT} was assumed to be $\Lambda_{MLT} = 1.6$ fitted to solar data (see below);

v) partial ionizations of H, He, C, O, Ne and Mg in the equation of state;

vi) reaction $^{12}C(\alpha, \gamma)^{16}O$ rate;

vii) neutrino loss rates.

The Geneva group also included:

viii) a new algorithm to calculate $X_i(t)$

and

ix) thick winds corrections for WR stars;

meanwhile the Padova group included:

x) downwards envelope OV with $\Lambda_{OV}^{env} = 0.7$.

In these models it has been assumed that $\dot{M} \propto (Z/Z_{\odot})^{1/2}$ and Λ_{OV} has been taken to get the best fitting to the observational data.

The most important characteristics of these sets of models for the case of massive stars are summarized in Fig. 3 ($Z = 0.04$) of Schaerer et al. (1993b); Fig. 5 ($Z = 0.02$) and Fig. 6 ($Z = 0.001$) of Schaller et al. (1992); Fig. 3 ($Z = 0.008$) of Schaerer et al. (1993a); Fig. 3 ($Z = 0.004$) of Charbonnel et al. (1993a); and Fig. 7 ($Z = 0.02$) of Bressan et al. (1993a) which describe the high luminosity part of the HR diagram. From them it can be realized that:

i) the MS becomes bluer at lower Z values;

ii) because of the assumed relationship $\dot{M} = \dot{M}(Z)$, for stars with $M \leq 25\, M_{\odot}$, the lower the Z the higher the T_{eff} in the He burning stage. For stars with $M > 25\ M_{\odot}$ the opposite effect is predicted, mainly because these stars quickly lose their H-rich envelope precluding any motion to the red part of the HR diagram. It is worth to note that for the cases of $Z = 0.004$ and $Z = 0.001$ an appreciable part of the He burning stage is spent in the forbidden region, beyond the Humphreys & Davidson limit.

iii) the width of MS is maximum at a L that decreases with Z. The Geneva group predicts it to be located at $\log(L/L_{\odot}) = 5.75, 6, 6.25, 6.25$ and > 6.5 for $Z = 0.04, 0.02, 0.008, 0.004$ and 0.001 respectively; while for $Z = 0.02$ the Padova group predicts it to occur at $\log(L/L_{\odot}) = 5.5$. In all cases MS reaches $T_{eff} \approx 4.0$ at these points.

iv) because of the low $\dot{M}$ for low Z, high Z population reaches the WR stage more easily.

Regarding point iv) for example at $Z = 0.02$, stars with $M \geq 32\, M_{\odot}$ become WR (WN and WC) while at $Z = 0.001$ only the WN stage is reached by stars of $M \geq 85\, M_{\odot}$. For stars of $M \approx 60\, M_{\odot}$, the MS is much wider than with old opacities (Schaller et al. 1992), but other large changes we would have expected are smaller because of the change in the assumed Λ_{OV}.

Finally, we note that the present models do not account for the position of the pre-SN 1987A star, because in Schaerer et al. (1993a) stars of 20 $M_{\odot}$ with the chemical composition of the LMC are just beginning to burn He at arriving to $\log(L/L_{\odot}) = 5.$ and $T_{eff} = 4.2$. This is in strong conflict with observations. For possible solutions on this important problem see Langer, El Eid, & Baraffe (1989).

4. ON THE PLAUSIBILITY OF THE THEORY OF CONVECTION

We have discussed above the results of stellar models based upon data from several sources, many of which rely on laboratory experiments. However, this is *not* the case for stellar convection included in the models.

The employed "theories" are two: the mixing length theory (MLT) and OV. MLT assumes only the motion of large eddies and involves an unknown quantity, the mixing lenght Λ_{MLT}, which is usually fitted in order to reproduce the Solar data. Then, the same Λ_{MLT} is applied to different stars, a procedure of doubtful validity.

Recently Canuto & Mazzitelli (1991) (see also Canuto & Mazzitelli 1992) have criticized this approach and shown that MLT is useful only for the case of viscous fluids. However, stellar interiors are almost inviscid environments, therefore the basic MLT approximation is not valid. For example, Canuto & Mazzitelli (1991) have shown also that, the ratio of the largest to the smallest present eddy is $\approx 10^6$ and not ≈ 1 as assumed by MLT. These eddies are capable to carry much more energy than in the MLT, and thus their velocity is ≈ 10 times lower, and also MLT underestimates the overadiabaticity in the stellar envelope again in ≈ 10 times. Notably Canuto & Mazzitelli (1991) have been successful in studying the structure of the outer layers of the Sun, because they predicted a density bump that improves the agreement of theoretical helioseismology with observations; also $L_{\odot}$; $(T_{eff})_{\odot}$ and the solar age are accounted for within 0.5% with no adjustable parameters.

From an hydrodynamical point of view, the main motivation for invoking OV is just that, by Schwarzschild criterion, the eddies arrive to the edge of the convective core with zero buoyancy force but their upwards velocity is still different from zero. It is obvious that the Canuto & Mazzitelli (1991) theory should make weaker this argument, but unfortunately, this is a local theory, therefore it is not applicable to the problem of OV.

To overcome the OV problem, Canuto (1992; 1993) has advanced a theory of convection (based on the Reynolds Stress Approach) including OV. This theory still has not been applied in the stellar interior environment. It would be a large improvement to the present state of art of the EMS models, because this theory not only has no free parameters neither for convective nor for OV zones, but also it naturally provides a criterium for the stability of the stellar layers. Using this approach we would be able to remove the long standing uncertainties in the treatment of OV.

5. CONCLUSIONS

As stated above, many of the ingredients we need in constructing EMS models are at present quite accurately known. Specially our knowledge of the stellar opacities has improved spectacularly, allowing substantially improved stellar models to become available. Nevertheless, we are still using a poor theory of convection. We usually employ MLT and OV that, as quoted in the preceding section, introduce two free parameters that are fitted to observational data in a physically doubtful way. This kind of procedures makes the theory unable to produce accurate predictions. Despite of the many claims in the literature that the agreement between theory and observations is pretty good (e.g., Meynet, Mermilliod, & Maeder 1993), it is possible that in tuning the free parameters we are, as a matter of fact, still hiding our ignorance of many important phenomena present in stars (e.g., rotation, rotationally induced mixing, diffusion, hydrodynamic instabilities, etc.). It seems that the way out of this uncomfortable situation may be to change to more physical theories of convection like the one quoted above. Probably the main progress we may reach in the near future in modelling the EMS is related to this ingredient of the models. Also, accurate measurements of Fe abundance are quite important due to the sensitivity of the opacity upon this quantity. Another point that should deserve more careful treatment is the optically thick winds corrections to WR stars.

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