Uncertainties in Stellar Evolution Models: Convective Overshoot

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Abstract In spite of the great effort made in the last decades to improve our understanding of stellar evolution, significant uncertainties remain due to our poor knowledge of some complex physical processes that require an empirical calibration, such as the efficiency of the interior mixing related to convective overshoot. Here we review the impact of convective overshoot on the evolution of stars during the main Hydrogen and Helium burning phases.

1 Introduction

Thanks to the efforts of many different groups in the last decades, stellar evolution has now reached a high degree of accuracy and completeness. Indeed, it can now account for a variety of internal physical processes, follow the most advanced phases and deal with different chemical compositions, so that one could in principle reproduce any stellar environment disclosed by the continuously advancing observational facilities. At the same time observations themselves have become more and more detailed, even providing direct access to star interiors, like in the case of asteroseismology, thus posing a real challenge to theory. In spite of these efforts, some physical processes, because of their complexity, still suffer of large uncertainties. These processes are crucial when dealing with advanced evolutionary phases, e.g. the Red Giant Branch (RGB) and the Asymptotic Giant Branch (AGB), and even more for stellar populations that are not well represented in the solar

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vicinity or in our Galaxy. From the theoretical point of view there are several long lasting questions that still lack a definitive answer, such as the issue of convective energy transport and mixing and that of the efficiency of the mass-loss phenomenon. This review deals mainly with one of such questions, the effect of convective mixing during the main phases of stellar evolution. We will summarise the current theoretical situation with emphasis on those phases where the uncertainties become more critical.

We may expect that adding new dimensions to the HR diagram, such as those provided by asteroseismology, could allow the biggest improvements just where the uncertainties are the largest.

2 The New Release of Stellar Evolutionary Tracks with PARSEC

We begin with a brief review of the new code developed in Padova, PARSEC (*P*adova T*R*ieste *S*tellar *E*volution *C*ode), with which we obtained many of the results presented here. A detailed description can be found in Bressan et al. (2012) and a few more recent updates in Bressan et al. (2013). The equation of state (EOS) is computed with the FreeEOS code developed and updated over the years by A.W. Irwin.[1] Opacities in the high-temperature regime, $4.2 \leq \log(T/\mathrm{K}) \leq 8.7$, are obtained from the Opacity Project At Livermore (OPAL) team (Iglesias and Rogers 1996) while, in the low-temperature regime, $3.2 \leq \log(T/\mathrm{K}) \leq 4.1$, we use opacities generated with our ÆSOPUS[2] code (Marigo and Aringer 2009). Conductive opacities are included following Itoh et al. (2008). The nuclear reaction network consists of the p–p chains, the CNO tri-cycle, the Ne–Na and Mg–Al chains and the most important α-capture reactions, including the α-n reactions. The reaction rates and the corresponding Q-values are taken from the recommended rates in the JINA reaclib database (Cyburt et al. 2010). Microscopic diffusion, applied to all the elements considered in the code in the approximations that they are all fully ionized, is included following Salasnich (1999) with diffusion coefficients calculated following Thoul et al. (1994). The energy transport in the convective regions is described according to the mixing-length theory of Böhm-Vitense (1958). The mixing length parameter is fixed by means of the solar model calibration and turns out to be $\alpha_{\mathrm{MLT}} = 1.74$. A remarkable difference with respect to other solar calibrations concern the partition of metals for which we assume the abundances taken from Grevesse and Sauval (1998) but for the species recently revised by Caffau et al. (2011). According to this abundance compilation, the present-day Sun's metallicity is $Z_{\odot} = 0.01524$, intermediate between the most recent estimates, e.g. $Z_{\odot} = 0.0141$ of Lodders et al. (2009) or $Z_{\odot} = 0.0134$ of Asplund et al. (2009),

[1] http://freeeos.sourceforge.net/.

[2] http://stev.oapd.inaf.it/aesopus.

and the previous value of $Z_{\odot} = 0.017$ by Grevesse and Sauval (1998). We remind here that the assumption of a different metallicity for the Sun affects directly the calibration of the MLT parameter.

3 Convective Overshoot on the Main Sequence

Besides the choice of the microscopic physics, the evolution during and after the main sequence is affected by mixing processes related to the efficiency of convective core overshoot, atomic diffusion and rotation. In PARSEC we adopt a maximum overshooting efficiency $\Lambda_{\max} = 0.5$, i.e. a moderate amount of overshooting (Bertelli et al. 1994; Girardi et al. 2000), corresponding to about $0.25\,H_P$ of overshoot region *above* the unstable region as commonly adopted by other authors. In the transition region between stars with radiative cores and those with convective cores, say between $M_{\mathrm{O1}} \leq M \leq M_{\mathrm{O2}}$, we assume that the overshooting efficiency Λ_{c} increases linearly with mass from zero to the maximum value. We define M_{O1} as the minimum stellar mass for which a convective core is still present even after its central hydrogen has decreased by a significant amount (X_{c} ~0.2) from the beginning of the main sequence. M_{O2} is set equal to $M_{\mathrm{O1}} + 0.3M_{\odot}$. This choice is supported by the modelling of the open cluster M 67 (see Bressan et al. 2012), which indicates an overshooting efficiency $\Lambda_{\mathrm{c}} \simeq 0.5$ already at masses of M$\sim 1.3\,M_{\odot}$ for solar-metallicity stars; and by the SMC cluster NGC 419 (Girardi et al. 2009; Kamath et al. 2010), in which the turn-off probes masses between $\sim$ 1.65 and $1.9\,M_{\odot}$. The run of the critical masses M_{O1} and M_{O2} as a function of the initial metallicity are shown in the left panel of Fig. 1. Constraints on these critical masses

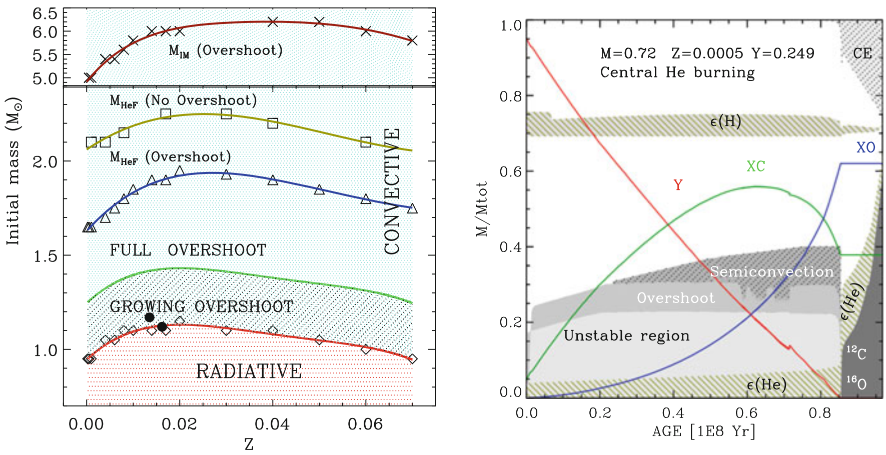

Fig. 1 *Left*: critical masses as a function of the metallicity. The *filled dots* represent the two models that best reproduce the asteroseismic data of Dushera (Silva Aguirre et al. 2013). *Right*: overshooting and semiconvective regions, during central He burning

are being set by asteroseismology. Indeed while earlier observations of α Cen A suggest negligible overshooting in solar-metallicity stars of mass $\sim 1.1\,M_{\odot}$ (de Meulenaer et al. 2010), recent studies of the nearby old low-mass star HD 203608, with $[Z/X] \simeq -0.5$, support the existence of sizable overshoot ($\alpha_{\rm ov} = 0.17$ corresponding to $\alpha_{\rm ov} \simeq 0.32$ in our formalism) at masses as low as $0.95\,M_{\odot}$, which is probably just slightly above the $M_{\rm O1}$ limit at the corresponding metallicity (Deheuvels et al. 2010). The full dots near $M_{\rm O1}$ at Z$\sim$0.015 represent the location of the two models that best reproduce the asteroseismic data of Dushera (Silva Aguirre et al. 2013), both requiring a sizeable overshoot ($\sim 0.2\,H_P$). Effects of core overshoot during the evolution on the main sequence, already thoroughly described in literature, are being used to obtain indirect calibrations of this process. Among them it is important to remind the difference between the threshold initial mass for undergoing helium flash between models with and without overshoot. The critical threshold as a function of the metallicity, M_{HeF}, decreases significantly with overshoot, as indicated in Fig. 1. The difference in mass between the two cases is significant and is certainly larger than the accuracy of the most recent determination of the mass with asteroseismic observations of evolved stars. Indeed, recent detailed studies of the evolutionary properties of He burning stars suggest to use the morphology of the red clump to trace stars with the mass around this critical transition (Girardi et al. 2013). Clearly, asteroseismology is opening a new window to constrain the mixing efficiency in the transition region from $M_{\rm O1}$ to $M_{\rm O2}$.

4 Overshoot and Mixing During the He Burning Phase

The presence of mixing beyond the unstable region in the core of He burning stars has been suspected since about fifty years.

Local Overshoot. As helium is converted into carbon in the convective core of He burning stars, the free-free opacity increases and so the radiative temperature gradient. This produces a discontinuity in the radiative temperature gradient just at the border of the convective core. It has been shown that this condition is unstable because the pollution with carbon rich material due to possible perturbations of any kind, renders the surrounding radiative layers irreversibly unstable to convection (Castellani et al. 1971). Thus, if these perturbations are allowed to occur by means of some artificial description of this kind of mixing, then the unstable region tend to grow during the evolution. This effect, known as *local* overshoot, increases the central He-burning lifetime almost proportionally to the growth of the core mass.

Semi-convection. In the more advanced stages, the star develops an intermediate zone, just above the convective core, which is marginally unstable to convection. This instability, known as semi-convection, gives rise to a smooth chemical profile maintaining the neutrality of the medium against convection. This mechanism is similar to the semi-convection that appears during hydrogen burning phase of massive stars though, in that case, it is due to the dependence of the electron scattering opacity on the hydrogen fraction (Schwarzschild and Härm 1958).

Notice that, in spite of the presence of a gradient in mean molecular weight, the Schwarzschild criterion should be preferred to the Ledoux one (Kato 1966; Spiegel 1969). Semi-convection contributes to the mixing in the central regions and gives rise to a further increase of the central helium exhausted core.

Breathing Pulses. Towards the end of central helium burning the star may undergo one or more breathing pulses of convection. This kind of instability is due to the luminosity feedback produced by the increase of the central He content that follows the growth of the mixed region when it enters a steep composition profile (Castellani et al. 1985). A further growth of the He exhausted core is produced by this mechanism which, in the HR diagram of intermediate mass stars, can be recognized by the presence of secondary blue loops toward central He exhaustion.

Non local overshoot. In presence of sizable *non local* overshoot, the discontinuity of the temperature gradient shifts well within the radiative stable regions where the radiative gradient is well below the adiabatic one. In this case the pollution of layers above the convective core does not destabilize the surrounding stable regions and local overshoot does not appear (Bressan et al. 1986). If one allows for large overshoot then also the semi-convective instability and even the breathing pulse phenomenon disappear. For the choice made in PARSEC, a sizable semi-convective region appears after the central He mass fraction falls below about 60 % (right panel of Fig. 1).

Overshoot (non local and/or local), semi-convection and breathing pulses may increase considerably the amount of fuel that the star can use during the central He-burning phase, increasing its lifetime. But the impact they have on the following phase, the Early Asymptotic Giant branch phase, is even larger. The star enters this phase with a larger he-exhausted core and the path toward the double shell phase may be shortened by a significant fraction. It has been soon recognized that the ratio between the observed number of stars in the E-AGB and in the HB branches of globular clusters, being proportional to the lifetime ratio of the corresponding evolutionary phases, may constitute a strong diagnostic for the efficiency of mixing during the helium burning phase (Buonanno et al. 1985). On the other hand, this simple diagnostic may be challenged by the presence of multiple populations because those with high helium content populate the HB but could escape the E-AGB phase. Nevertheless in some metal rich clusters there is no evidence of the latter evolutionary path and this diagnostic may still be used. For example, in the case of 47 Tuc we obtain from the ACS HST data (Sarajedini et al. 2007) $R2 = (n_{EAGB}/n_{HB}) = 0.14$–$0.15$. This value is in good agreement with the corresponding one predicted by PARSEC isochrones with $[\alpha/\mathrm{Fe}] = 0.4$ and global metallicity $Z = 0.006$ and for a HB mass between $0.65\,M_\odot$ and $0.7\,M_\odot$.

5 Overshoot at the Bottom of the Convective Envelope

It has been argued that a moderate overshoot region (0.25–$1.0\,H_P$) below the base of the convective envelope may help to better reproduce the observed location of the RGB Bump in the red giant branch of low mass stars in globular clusters and old open clusters (Alongi et al. 1991). The observed RGB bump in globular clusters is about 0.2 to 0.4 mag fainter than that predicted by models without envelope overshooting (Di Cecco et al. 2010) though, at the higher metallicities, this result depends on the adopted metallicity scale. Adopting an overshoot size of $\Lambda_e = 0.5\, H_P$, the RGB bump becomes typically $\sim$0.3 mag fainter than in models with negligible envelope overshoot (Alongi et al. 1991), and in good agreement with observations. This value is in very good agreement with the overshoot size (not fully adiabatic however) at the base of the convective envelope in the Sun, that has been estimated to be $\Lambda_e \sim 0.4 - 0.6\, H_P$ using solar oscillations data (Christensen-Dalsgaard and et al. 2011).

Another interesting effect of the overshoot at the base of the convective envelope concerns the extension of the blue loops of intermediate mass and massive stars. During their central helium burning phases these stars may perform a characteristic excursion from the red to the blue side of the HR diagram, commonly referred to as the “blue loop". In nearby star-bursting dwarf galaxies this excursion give rise to two well resolved sequences of red helium burning (RHeB) and blue (BHeB) and stars (e.g., McQuinn et al. 2010), the latter being almost attached or even superimposed to the main sequence in the more metal poor galaxies. Indeed the blue loops become more pronounced at lower metallicities, but they may depend on several other factors. In particular it has been found that their extension decrease or they are even suppressed using either a lower $^{12}C(\alpha,\gamma)^{16}O$ reaction or a larger amount of core overshoot (Alongi et al. 1991; Godart et al. 2013). In spite of the strong evidence in favor of a significant amount of core overshoot (or an extended mixing beyond the formal convective core), models with convective core overshoot fail to reproduce the observed blue loops. To cure this problem Alongi et al. (1991) suggested to use a certain amount of overshoot from the convective envelope. They showed that by using an extra mixed region of at least 0.7 H_P below the formal Schwarzschild border of the envelope convection, they were able to obtain extended blue loops even with models computed with convective core overshoot.

It is possible to check the goodness of this assumptions by comparing the models with the colour magnitude diagrams of star-forming regions in nearby low metallicity galaxies. These regions, that contain a large number of intermediate mass and massive stars, are generally dominated by the latest star formation episodes for which one may assume a narrow range in metallicity or, often, even a single metallicity. We are analyzing this issue by comparing new evolutionary tracks with observed C-M diagram of selected nearby dwarf galaxies from the sample of Bianchi et al. (2012) as well as Dalcanton et al. (2009). We show in Fig. 2 how the HR diagram of intermediate/massive stars changes by increasing the amount of envelope overshoot. The simulations shown in Fig. 2 refers to a metal poor environment ($Z = 0.001$) and the amount of envelope overshoot is 0.7 H_P (left panel) the standard choice in PARSEC, 2 H_P (middle panel) and 4 H_P (right panel). A similar result is obtained for $Z = 0.002$. The comparisons with the observed CM diagrams of WLM, NGC 6822 and Sextans A, three dwarf galaxies with spectroscopic metallicities confined within the above range, indicate the need of an extra mixing of at least 2 H_P below the bottom of the convective envelope (Tang

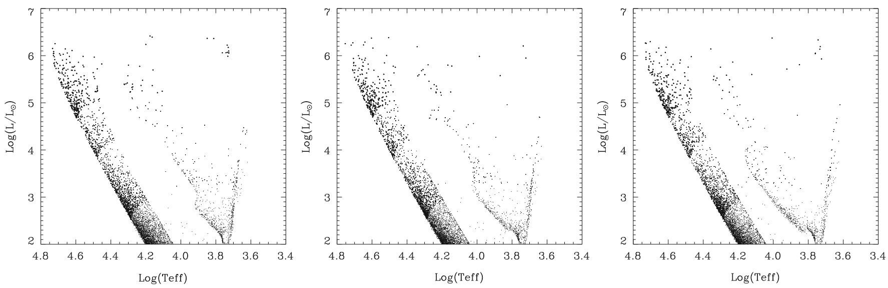

Fig. 2 Envelope overshoot and extension of blue loops in intermediate and massive stars at $Z = 0.001$. From *left* to *right* the simulations are made with $EO = 0.7\ H_P$, $2\ H_P$ and $4\ H_P$, respectively. For sake of clarity, different symbol sizes and total number of stars have been considered in the mass ranges $M < 4M_{\odot}$, $4M_{\odot} \leq M < 10M_{\odot}$, $10M_{\odot} \leq M < 20M_{\odot}$ and $M \geq 20M_{\odot}$

et al. 2014). With the standard PARSEC choice ($0.7\ H_P$), the C-M diagram of these galaxies could be reproduced only adopting a significantly lower metallicity, $Z = 0.0005$. Though large, the above value is not uncommon and similar values are used to enhance the efficiency of the carbon dredge-up during the thermally pulsing Asymptotic Giant Branch phase (Kamath et al. 2012).

Conclusions

Convective mixing plays a major role in stellar evolution, since it can modify the structure of the star in an irreversible way. Whether convection is accompanied by significant overshoot remains an unsolved problem. The existence of extra mixing is one of the most uncertain factors in stellar astrophysics affecting H-burning lifetimes and the lifetimes of advanced evolutionary phases (HB, E-AGB), luminosities and effective temperatures (Main Sequence termination, Clump stars, Blue He burning stars) and in particular cases also the surface chemistry. Classical tests with colour magnitude diagrams indicate the presence of this extra mixing outside the central convective region. Recent asteroseismic observations put even more robust constraints on this phenomenon, even if the nature of this mixing remains still unclear since it could also be due to the effects of rotational mixing. In some cases observations are even more challenging. In fact if one allows for a larger mixing above the convective core during the H-burning phase, the theoretical blue loops of intermediate and massive stars become less extended, at variance with observations, unless an even higher extra mixing is applied to the bottom of the convective envelopes. The size required to reproduce the observed blue loops in the CM diagrams of well studied star forming regions in nearby dwarf galaxies ($\geq 2\ H_P$), is significantly larger than that required to reproduce the RGB bump in globular clusters ($\sim 0.5\ H_P$).

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