Stellar Evolutionary Models: challenges from observations of stellar systems

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Abstract. We briefly review some constraints† for stellar models in various mass regimes and evolutionary stages as provided by observational data from spectroscopy to multi-wavelenghts photometry. The accuracy of present generation of stellar models can be significantly improved only through an extensive comparison between theory and observations.

Keywords. stars: evolution, stars: interiors, stars: Population II

1. Introduction

Stellar evolution models are pivotal ingredients in order to understand the evolutionary properties of the various Stellar Populations present in both resolved and un-resolved stellar systems, so that they play a fundamental role in assessing the 'nature' and the contribution of the different blocks that contribute to build the galaxies.

In view of this relevance, it is quite important to establish the level of accuracy and reliability of present generation of stellar models. This can be achieved only by comparing theoretical predictions with empirical constraints.

During the second half of the last century, stellar evolution theory has allowed to properly understand the 'meaning' of the various branches observed in the Color Magnitude Diagram (CMD) of both galactic globular clusters (GGCs) and open clusters. This notwithstanding for a long time these theoretical predictions were accounted for with an uncritical approach. They were used at face value without accounting for theoretical uncertainties and their effect in deriving estimates about cluster age and distances. More recently, this approach to the theoretical framework drastically changed and more critical assessments were adopted. The motivations at the base of this change have to be searched both in the will of providing reliable estimates of the systematic uncertainties affecting this kind of comparison and in the relevant advances made in the observational techniques and in the 'Physics' applied to stellar models.

On the observational side, in recent years, the impressive improvements achieved for both photometric and spectroscopic observations, has allowed to collect data of an unprecedent accuracy, which provide at the same time a stringent test and a challenge for the accuracy of the models.

On the theoretical side, even if significant improvements have been achieved in the determination of the Equation of State (EOS), opacities, nuclear cross sections, neutrino emission rates that are all fundamental physical inputs for solving the stellar structure equations, residual uncertainties do exist still as it is clearly testified by the not negligible differences still existing among evolutionary results provided by different theoretical

† Owing to the limited number of pages of present review, only a sub-sample of the topics discussed during the talk are briefly summarized. For the interested readers we are pleased to send them upon request the complete presentation file.
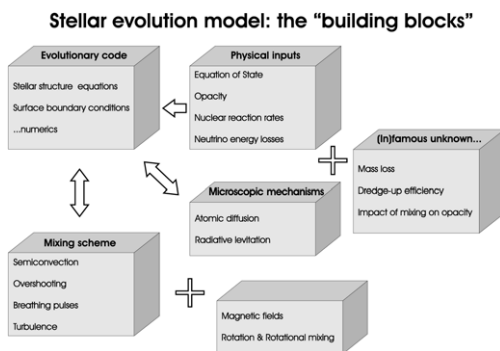
Stellar evolution model: the "building blocks"

Figure 1. A qualitative view of the main 'blocks' needed for 'building' a stellar model.

groups. At the same time, models computed with this updated physics have been extensively tested against the latest observations, and this has also contributed to increase the awareness that it is no more possible to neglect physical processes as radiative levitation, rotation, magnetic fields, considered secondary physical mechanisms until few years ago.

A careful discussion of the uncertainties affecting stellar models for low-mass stars was early addressed by Chaboyer (1995), who investigated the reliability of theoretical predictions concerning H-burning structures presently evolving in GGCs and, in particular on the accuracy of age predictions. Such an investigation has been extended to later evolutionary phases by Cassisi *et al.* (1998, 1999), Castellani & Degl'Innocenti (1999), and Gallart *et al.* (2005). A discussion of the drawbacks of stellar models for low-mass stars and their impact on the most used age, distance and chemical composition indicators has been also provided by Cassisi (2005 and references therein); while the issue of the main uncertainties affecting the evolutionary properties of intermediate-mass stars has been reviewed by Cassisi (2004).

2. Stellar models: the 'building blocks'

From the point of view of people using stellar models, they provide: i) evolutionary lifetimes that can be compared with suitable star counts; ii) bolometric luminosity and effective temperature that once converted in useful magnitudes and colors in various photometric systems by using color-T_{eff} relations and Bolometric Correction scales, can be compared with empirical data, and iii) predictions about the surface chemical abundances that can be tested against spectroscopical measurements.

However, any user before accounting for these theoretical predictions should ask himself this fundamental question: How much accurate and reliable are the predictions coming out from stellar models?

It is clear that the reliability of a stellar model depends mostly on the accuracy of the adopted physical inputs as well as on the physical processes accounted for as: atomic diffusion, levitation, rotation.

In figure 1, we show a qualitative picture showing the most important 'building blocks' that are required in order to construct a stellar model.

The equations that describe the physical behavior of any stellar structure are well known since long time and a detailed discussion on their physical meaning can be found in many books such as Cox & Giuli (1968), Kippenhan & Weigart (1990) and Salaris & Cassisi (2005). The solution of these equations is no more a problems – thanks also to

the advances in computing program and computer science -, as it has been shown by Weiss (2007, this conference) in the framework of the 'Stellar Model Challenge': updated stellar evolution codes, once the physical scenario has been homogeneously fixed, provide results quite similar.

However, in order to solve the stellar structure differential equations outer boundary conditions have to be provided: one can rely on some empirical relation for the thermal stratification as that provided by Krishna-Swamy (1996) or a fully theoretical law as the so-called gray (or Eddington) approximation, or alternatively one can adopt the predictions given by suitable model atmospheres. This issue for H-burning stellar models has been recently reviewed by Vandenberg *et al.* (2007, and references therein) during this conference.

The meaning and role played by the various 'ingredients' listed in fig. 1 has been extensively discussed in the literature (see for instance Castellani 1999; Cassisi 2005). Some of them will be reviewed in the following in connection with the challenges provides by recent observations such as for diffusive processes or with recent advances in stellar physics as for the case of conductive opacity.

Before closing this section, we wish to comment a bit on fig. 1. As already stated, this picture has only a qualitative purpose. In the 'block' *"(in)famous unknown..."* we put: mass loss efficiency, dredge-up efficiency and the impact of mixing on opacity. When referring to the dredge-up efficiency we are considering the process occurring during the Asymptotic Giant Branch (AGB). In any case, for all the 'ingredients' listed in this block we are not yet able to predict their efficiency from fundamental principles and indeed we still rely on – quite approximate – parametrization of the various processes.

In the block *"Additional physical processes"*, we include the presence of magnetic fields and the occurrence of rotation and rotational-induced mixing. It is clear that in the implementation of both processes in an evolutionary code, due to our poor knowledge of the physics at work would require a sizeable number of assumptions and free parameter. The reason for which we do not include them in the *"(in)famous unknown..."* block is due to the evidence that we are always forced to account for mass loss and the 3rd dredge-up in order to explain the Horizontal Branch morphology (HB) and the evolution of AGB stars; whereas we really need to account for magnetic field and rotation only to interpret some specific observational features related, for instance, to the evolutionary properties of VLM stars and HB stars.

3. Comparison theory – observations: the challenges

It is well known that depending of the stellar mass range, different physical processes affect the thermal and opacitive properties of stellar structure. The accuracy of the adopted physical framework in different regimes can be tested by comparing model predictions with various empirical data.

3.1. *Very-Low-Mass Stars*

For many years, the computation of reliable models for Very-Low-Mass (VLM) stars has been severely challenged by the lack of robust predictions about the thermal and opacitive properties as well as of suitable outer boundary conditions (Chabrier & Baraffe 2000). As a consequence one was facing the tantalizing evidence that theoretical models were 'too blue' to reproduce the observed sequences of VLM both in clusters and in the field (Vandenberg *et al.* 1983).

In these last decade, on the theoretical side, the situation largely improved thanks to the recent availability of appropriate EOS, radiative opacity, and outer boundary
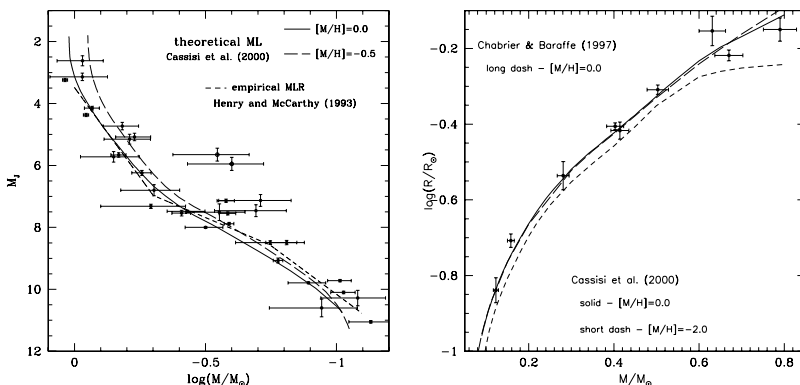
Figure 2. Left panel: comparison between VLM models and empirical data concerning the mass – luminosity relation. Right panel: as left panel but for the mass-radius diagram (data from Segransan *et al.* 2003).

conditions (Allard *et al.* 1997). From the observational point of view, thanks to the superb photometric capabilities of the Hubble Space Telescope, a 'pletora' of empirical data for such objects were collected (see King *et al.* 1998). A plain evidence of the remarkable improvements achieved on this issue is represented by the nice fit to the faint MS of the GGC NGC 6397 performed by VLM models by both Baraffe *et al.* (1998) and Cassisi *et al.* (2000). Firm constraints for the theoretical framework are also provided by different types of empirical data as those given by the Mass-Luminosity and Mass-Radius diagrams (see fig. 2). The data showed in this plot reveal the existence of a very good agreement between theory and observations.

Therefore it seems that we can now be fully confident about the accuracy and reliability of VLM models; however unfortunately this is not yet the case. The existence of shortcomings in these models appears when taking into account empirical constraints represented by CMDs of intermediate- and metal-rich VLM stars. Left panel of fig. 3 shows the comparison between VLM models and empirical optical data for the largest sample of field subdwarfs with known parallaxes: while models for metal-poor composition finely reproduce the corresponding empirical sequence, the solar composition one clearly does not match the data for $M_V > 11$ mag. This evidence could be considered as a proof for a problem in the evolutionary models, however, right panel of fig. 3 shows the comparison at longer wavelenghts between the same solar metallicity VLM models and empirical data for field stars in the Bulge (Zoccali *et al.* 2000). It is worth noting that the same models that in the optical CMD do not fit the data, in the Near-Infrared bands nicely reproduce the peculiar shape of the MS.

This result points out that the source of the shortcoming showed in fig. 3 (left panel) has not to be searched in the evolutionary models but really in the adopted color – T_{eff} relation: a drawback seems to exist in the evaluation of the opacity contribution at wavelenght $\lambda \leqslant 1\mu m$ in the computation of the model atmospheres.

This kind of results strongly suggest that evolutionary models for VLM stars have already attained a significant level of accuracy in reproducing empirical constraints, and that a big improvement has to be expected in the adopted color - T_{eff} relations as a consequence of a more accurate treatment of the opacitive properties in model atmospheres of cool and dense stellar objects.
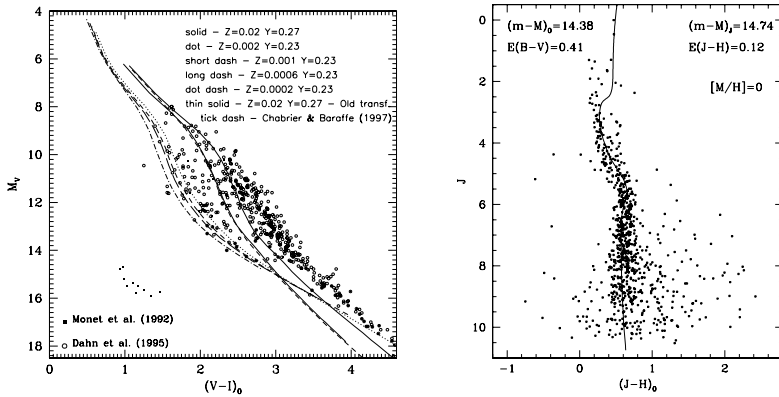
Figure 3. Left panel: comparison between VLM models (Cassisi *et al.* 2000) and the observed distribution of field dwarfs with known parallaxes. Solar composition models by Chabrier & Baraffe (1997) are also shown. Thin solid line refers to solar metallicity VLM models transferred in the observational plane by using an old set of colour – T_{eff} transformations (see Cassisi *et al.* 2000). Right panel: the fit of the MS stars population in a window of the bulge (Zoccali *et al.* 2000). The VLM models are the solar metallicity ones adopted also in the left panel.

3.2. *Diffusive processes*

Since many years, the constraints provided by Helioseismology have shown that atomic diffusion has to be at work in the Sun. When relying on this circumstantial evidence, it is obvious to assume that this process has to be (more) efficient also in metal-poor, low-mass stars (as a consequence of their thinner convective envelope). However, this certainty is currently severely challenged by spectroscopical measurements (Gratton *et al.* 2001, and references therein) showing that the iron abundance observed in stars belonging to metal-poor GCs are in disagreement with the predictions provided by stellar models accounting for atomic diffusion: more in detail they found no significant differences between the iron abundance observed in Turn-Off stars and RGB ones as one has to be expect in the case of efficient atomic diffusion. However, recently Korn *et al.* (2006) have claimed the detection of a diffusion signature in the GC NGC 6397. According to their analysis the TO stars disclose a lower [Fe/H] than the more evolved stars.

From the theoretical point of view, the problem of the efficiency of the various diffusive processes: atomic diffusion and radiative levitation; has received a lot of attention thanks to the work by Richard *et al.* (2002), Vandenberg *et al.* (2002), and Richard *et al.* (2005). Their sets of models, accounting simultaneously for atomic diffusion and levitation, predict that, at odds, with models accounting only for atomic diffusion, the surface abundance of iron – and of the other heavy elements – is less depleted and it can be also become overabundant – at the TO – due to radiative levitation (Richard *et al.* 2002).

However, one has to note that in order to achieve a fine agreement with both helioseismological constraints and spectroscopical data for both field and clusters stars as for instance for the Li trend with the T_{eff} (the so-called Spite plateau; Richard *et al.* 2005), some additional amount of mixing at the bottom of the canonical convective envelope has to be included. It is common to refer to this extra-mixing as 'turbulence', but so far there is no firm physically grounded explanation for this process.

Although the recent results provided by Korn *et al.* (2006) can be nicely interpreted in the framework of the diffusive (+ turbulence) models of Richard *et al.* (2005), there are at least two issues that should be considered: i) What is the physics behind the turbulence?, ii) Why for the same GC, do independent groups find so different results?

Is this occurrence due to a problem in the adopted T_{eff} scale for metal-poor MS stars (see also Thévenin *et al.* 2001)?

A lot of theoretical work has to be done in order to understand all the physical mechanisms that can contribute to enhance or to decrease the effects of diffusive processes. However it is also of pivotal importance to collect as many as possible independent spectroscopical measurements in order to set on a more firm ground the observational scenario that has to be used in order to constraint the theoretical framework.

3.3. *The Red Giant Branch evolutionary stage*

The RGB is one of the most prominent and well populated feature in the CMD of stellar populations with ages larger than about $1.5 - 2$ Gyr. The theoretical modeling of RGB stars plays therefore a wide ranging role, involving various fields of galactic and extragalactic astrophysics (see Salaris *et al.* 2002). So, it is very important to verify the consistency between theoretical predictions and observational data for RGB stars.

One of the major deficiencies in the stellar evolution theory is the lack of a a rigorous theory of convection. As a consequence in the outer, super-adiabatic layers of stellar models, the mixing length theory is almost universally used. It contains a number of free parameters, whose numerical values affect the model $T_{\rm eff}$; one of them is $\alpha_{\rm MLT}$, the ratio of the mixing length to the pressure scale height, which provides the scale length of the convective motions: for a given stellar luminosity it fixes the radius of the stellar model, and hence its T_{eff}. The $\alpha_{\rm MLT}$ parameter is commonly calibrated by forcing stellar models of the Sun to reproduce the solar radius. However, the thermal conditions inside the envelope of RGB stars are quite different in comparison with those existing in the solar envelope. So it is extremely important to check if RGB models whose $\alpha_{\rm MLT}$ has been calibrated on the Sun, reproduce properly the empirical T_{eff} of RGB stars. In this context the availability of multi-bands photometry (from the optical to the Near-Infrared ones), allowing an accurate determination of the effective temperature of cool stars as the RGB ones, is a fundamental benchmark for stellar models.

Left Panel of fig. 4 shows the comparison between the most updated empirical database of T_{eff} values for GC RGB stars from Ferraro *et al.* (2006) and theoretical predictions as provided by some of the most recent stellar models libraries†. One can notice that almost all model predictions reproduce quite well the empirical estimates in the whole metallicity range. However, at the same metallicity significant differences are present between the various stellar models. This evidence has to be taken into account when comparing theory with observations in order to retrieve information about the properties of a given stellar populations such as its metallicity.

An other relevant issue for RGB stellar models is the uncertainty associated to the conductive opacity adopted in model computations. When the degree of electron degeneracy is significant, electron conduction is the dominant energy transport mechanism, and the value of the electron-conduction opacity enters the equation of the temperature gradient. This physical condition is verified in particular in the He-core of low-mass stars during their RGB evolution (see Salaris *et al.* 2002). The precise computation of the conductive opacities is fundamental for deriving the correct value of the He-core mass (M_{cHe}) at the He-flash, and hence the brightness of both the RGB Tip and of the HB, i.e. two of the most important standard candles for Pop. II stellar systems.

Regardless of the pivotal importance played by this 'ingredient', so far all available sources of conductive opacity were affected by several limitations and shortcomings (see Catelan 2005). Recently Cassisi *et al.* (2007) provided new predictions about the

† We note that all these theoretical models are based on a solar calibration of the $\alpha_{\rm MLT}$.
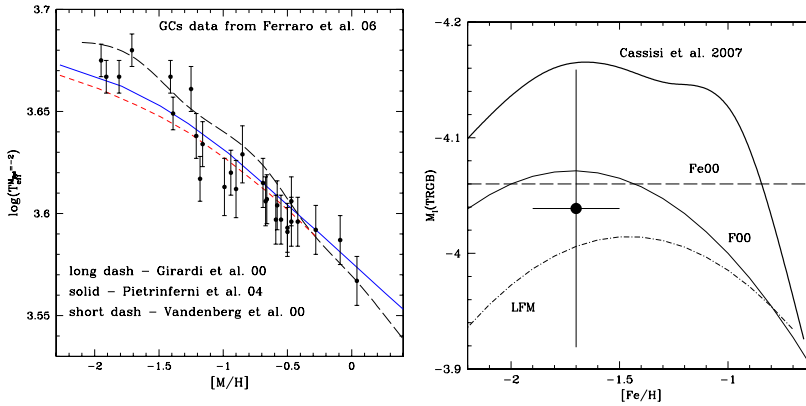
Figure 4. Left panel: RGB Effective temperature at $M_{Bol} = -2$ as a function of the metallicity for a sample of GGCs, with superimposed selected theoretical predictions from Girardi *et al.* (2000), Vandenberg *et al.* (2000) and Pietrinferni *et al.* (2004). Right panel: comparison between various calibrations of the TRGB absolute I magnitude as a function of the metallicity. The point with error bars corresponds to the estimate by Bellazzini *et al.* (2001) for ω Cen. The other calibrations are those by Ferrarese *et al.* (2000), Ferraro *et al.* (2000) and Lee *et al.* (1993). The theoretical calibration based on updated conductive opacity is shown as heavy solid line.

conductive opacity that largely improve in many aspects the old results: the use of the new opacities cause a decrease of the value of M_{cHe} of $\sim 0.006 M_\odot$.

It is important to check if this improvement in the physics adopted for RGB model computations is supported by empirical constraints. For this aim, figure 4 (right panel) shows a comparison between theoretical predictions about the I-Cousin band brightness of the RGB Tip as a function of the metallicity and various empirical and semi-empirical calibrations. The new theoretical calibration of this standard candle appears to be in agreement at the level of 1σ with the relevant empirical measurement in the GC ω Cen performed by Bellazzini *et al.* (2000).

3.4. *The Asymptotic Giant Branch*

The AGB stage is one of the most important evolutionary phases for several reasons: i) the nucleosynthesis, ii) AGB stars are reliable population tracers, ii) its contribution to the integrated colors – mainly in the NIR bands – of unresolved stellar populations. From the theoretical point of view, the stellar models for AGB stars are really a challenging task. This is due to the evidence that the evolutionary and structural properties of such objects are strongly affected by the strong link existing between the nuclear burning sources (the H- and the He-burning shells), the mixing efficiency both in the envelope and in the inter-shell region, the opacitive properties of the envelopes as well as the mass loss efficiency.

Concerning the mixing efficiency, the most important issue is related to the occurrence of the 3rd Dredge-up occurring in all stars with initial mass larger than $1.2 - 1.4 M_\odot$: we are not able to predict from first principles the efficiency of this mechanism and as a consequence we are forced to use *ad hoc* parametrizations (Straniero *et al.* 2006). The main consequence of the 3rd Dredge-up is that a huge amount of Carbon is dredged up the stellar surface and, indeed, C/O values quite larger than unity – as really observed in C-stars – are achieved. When this occurs the opacity properties of the star can not be longer described relying on opacity computed for scaled-solar heavy elements mixtures.

In this context, although many improvements have been obtained thanks to the work by Marigo (2002) and Marigo *et al.* (in preparation), we still lack of robust predictions about the trend of radiative opacity for C/O values of the order of unity or larger. This occurrence partially hampers our capability to properly predict the effective temperature of AGB models and, hence, their color, as well as the mass-loss efficiency.

Acknowledgements

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Discussion

MEIXNER: For the convection mixing length included in the models, do you scale it or change it with the metallicity of the star?.

CASSISI: No, in stellar model computations we use a unique value for this mixing length: the one obtained via the Solar STandard Model calibration.

GUSTAFSSON: You referred to the possibility of understanding the discrepancy between the Gratton *et al.* results and those of Korn *et al.* as reagards the presence of diffusion/levitation in NGC6397. In the Korn *et al.* study, however, they adopted a differential procedure, by determining the temperature difference between TO, SGB and GB, using several different temperature criteria obtaining consistent results.

CASSISI: I agree with you. However, the adopted temperature scale in the quoted paper is really a very important issue. A change of only 50K in the T_{eff} value does change remarkably the conclusions. In addition, also in the case of differential comparison can we, for sure, exclude the possibility of dependence of the T_{eff} error on the mean T_{eff} as it occurs when using MS stars and RGB ones.

RENZINI: There used to be an old "rule of thumb" according to which including or not diffusion made a difference in age of $\sim$1 Gyr. You reported instead that a factor of 2 difference in the diffusion coefficient makes a difference of $\sim$2.5 Gyr. What is the origin of this change?.

CASSISI: To a change of a factor of 2 atomic diffusion coefficient affects the GC age determination of the level of 2-3 Gyr. The effect is lower than expected on the basis of the "rule of thumb" you quoted, since it was based on stellar models where only Helium diffusion was accounted for. To properly account for the diffusion of heavy elements also counterbalances partially the effect of He diffusion. This occurrence does explain the difference you noticed.

BECKMAN: You mentioned magnetic fields but did not quantify them. Can you tell us if, and where, magnetic fields can make a real difference to observed stellar parameters?.

CASSISI: Yes. The occurrence of magnetic field is important for explaining some empirical evidence such as the Radius – T_{eff} diagram for magnetic M dwarfs. We are currently working for including "magnetic field" in stellar models for very low and low mass stars.

Santi Cassisi (l) together with Antonio Aparicio. On the left Carme Gallart. Right: Sebastian Hidalgo.

One of the parallel sessions. The panel consisted of Eva Grebel, Marc Balcells and James Rose.