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Stellar evolution for old stellar populations: good news and ... open problems

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Abstract. In these last decades stellar evolution theory has made significant progress, thanks to the improvement in the stellar physics. However, the impressive development of observational tools – as the Hubble Space Telescope and large ground-based telescopes – has produced very accurate observations which created new challenges to theoreticians. In order to explain the latest generation of stellar observations, we need to further improve the reliability of stellar models and include non standard physical processes (like, e.g., atomic diffusion, rotational induced mixing, radiative levitation) in the model computation. I present some recent results concerning the comparison between theory and observations for old stellar populations, and discuss the still outstanding uncertainties facing the theory of stellar evolution for low mass stars.

Key words. CM diagram – H burning – He burning stars

1. Introduction

During the second half of last century, stellar evolution theory has enabled us to understand the Color Magnitude Diagram (CMD) of galactic globular clusters (GGCs), so that now we can explain the distribution of stars in the observed CMDs in terms of the nuclear evolution of stellar structures and, thus, in terms of cluster age and chemical composition. In recent years, however, the significant development of both photometric and spectroscopic observations, has allowed us to collect data of an unprecedent accuracy, which constitute at the same time a stringent test and a challenge for the accuracy of the models.

On the theoretical side, significant improvements have been achieved in the determination of the Equation of State (EOS) of the stellar matter, opacities, nuclear cross sections, neutrino emission rates, that are, the physical inputs needed in order to solve the equations of stellar structure; at the same time, and models computed with this updated physics have been extensively tested against the latest observations. In the following I will select few topics in order to provide an idea of present situation concerning the level of agreement between theory and observations. In particular, I will present some results concerning Very Low Mass (VLM) stars, Red Giant Branch (RGB) structures and He-burning low mass stars. A

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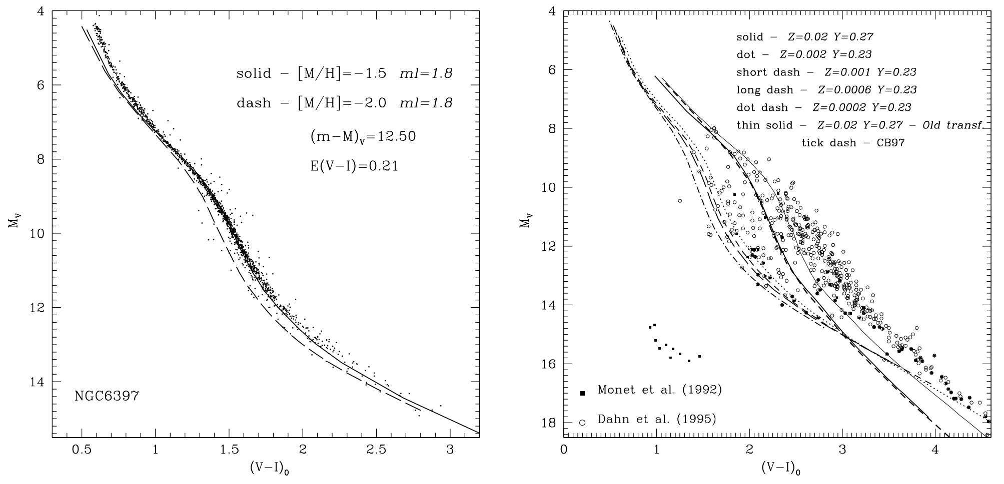

Fig. 1. Left panel: the best fitting theoretical models ([M/H]=-1.5) to the MS of NGC6397 observed with HST by King et al. (1998). For the sake of comparison, the dashed line shows the location of models with [M/H]=-2.0. Right panel: comparison between theoretical models (Cassisi et al. 2000) for selected assumptions about the stellar metallicity and the observed distribution of field dwarfs with known parallaxes (see references). Solar composition models by Chabrier & Baraffe (1997, CB97) are also shown. Thin solid line refers to solar metallicity VLM models by Cassisi et al. (2000), but transferred in the observational plane by using an old set of colour - effective temperature transformations (see Cassisi et al. 2000, for details).

final section briefly presenting some still unsolved problems follows.

2. VLM stars: the state of art

During the past few years, a significant progress has been achieved in modeling cool and dense objects like the ones populating the bottom of Main Sequence (MS) in GGCs. The successful confrontation of the theory with the several detections of low-mass stellar and sub-stellar objects allows a better understanding of their thermal and structural properties, and more reliable predictions about their evolutionary properties. For a detailed analysis of the properties of VLM stars we refer the interested reader to Chabrier & Baraffe (2000), Cassisi et al. (2000) and references therein.

In order to give an idea of the level of agreement existing between predicted and observed CMD location of VLM stars, Fig. 1 (left panel) shows a comparison between VLM stars in the metal-poor GC NGC6397 observed with the HST (King et al. 1998), and the stellar models by Cassisi et al. (2000). One can notice that the shape of the cluster faint MS is nicely reproduced; the same is however not true in case of field VLM stars (right panel of Fig. 1). In this case the models do not properly match the distribution of metal-rich field stars for magnitudes larger than $M_V \approx 14$ mag. This discrepancy seems to be related to an inadequacy of the adopted color-temperature relations, due to the still existing drawbacks in the set of model atmospheres used for deriving these relations (see the discussion in Cassisi et al. 2000 and Baraffe et al. 1998).

Recent development in interferometric analysis have allowed also to obtain accurate determinations of the radii for VLM stars (Segransan et al. 2003); this allows a direct comparison with theoretical models without the need to use bolometric corrections or color-T_{eff} relations which are, as noticed above, still affected by not negligible uncertainties. Fig. 2 displays the comparison between theory and

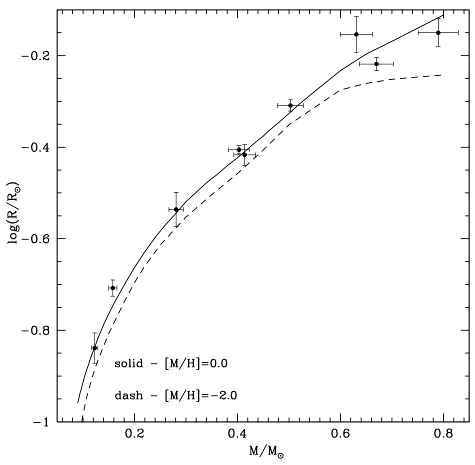

Fig. 2. Comparison between empirical radii and masses measurements with theoretical mass-radius relations. The observations are from Segransan et al. (2003). Theoretical models for an age of 10Gyrs and two metallicities are from Cassisi et al. (2000).

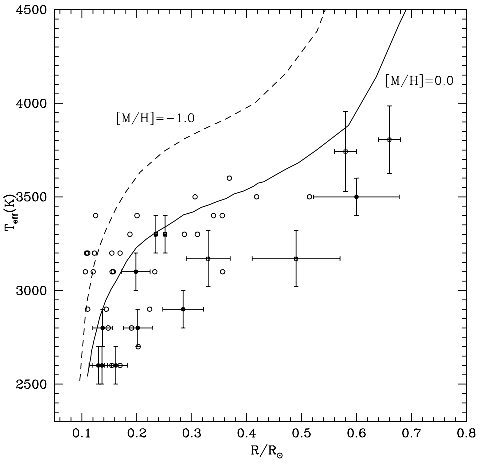

Fig. 3. Comparison between observational data and theoretical models for M dwarfs in the effective temperature - radius diagram. The observations are from Leggett et al. (2000). Filled circles refer to flare stars and variable stars. Open squares correspond to data for eclipsing binaries. Theoretical models for two metallicities are from Cassisi et al. (2000).

observations in the stellar radius - mass plane. The agreement is encouraging for both eclipsing binary and resolved single stars data, a fact that provides a further support to the reliability of current theoretical models. It is also clear that a larger number of accurate measurements is necessary in order to conclusively test the theory.

Empirical evidences suggest that present models for VLM stars are not able to describe certain properties of these stars, in particular for those objects showing a significant magnetic activity (dMe stars). More in detail, it appears that active M dwarfs show radii that are larger than expected for their effective temperature values. This is shown in fig. 3 but see also the interesting analysis performed by Mullan & Macdonald (2001). On the basis of these analysis, it appears evident that the presence of a significant magnetic activity, so far not properly accounted for in computing stellar models, can affect not only the properties of the stellar outer layers, but also the interior of a star, and in particular the extension of the convective zone. More accurate models for VLM stars, taking into account the presence of a magnetic field are needed in order to assess to what extent this non-canonical mechanism affect the stellar structure.

In spite of the impressive progress made in the last decade regarding the modeling of VLM stars, outstanding problems remain to be fully solved, like the computation of a more accurate equation of state, an improved treatment of convection in the atmospheres, more accurate and reliable estimates of the low-temperature opacity - with particular attention to the role played by grains - and a proper knowledge of generation and dissipation of magnetic fields in active VLM stars.

3. The Tip of the Red Giant Branch as a standard candle

While the use of the luminosity of the tip of the Red Giant Branch (TRGB) as standard candle dates back to 1930, the development of the method as an accurate technique is relatively recent (see Salaris, Cassisi & Weiss 2002 and references therein). The TRGB method is as precise and accurate as the Cepheid period-

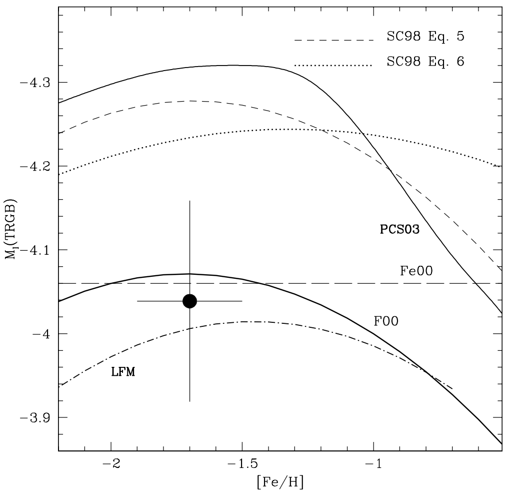

Fig. 4. Comparison between different calibrations of the TRGB absolute I magnitude as a function of the metallicity. The point with error bars corresponds to the estimate obtained by B01 for ω Cen. Long dashed line reports the calibration of $M_I(TRGB)$ as a secondary distance indicator obtained by Ferrarese et al. (2000, Fe00). The calibrations of Ferraro et al. (2000, F00) and Lee et al. (1993, LFM) are also shown. The theoretical calibrations provided by Salaris & Cassisi (1998, SC98) for two different I band BC scales (see their equations 5 and 6), and the one recently obtained by Pietrinferni et al. (2003, PCS03) are also plotted.

luminosity relation (albeit limited to shorter distances than Cepheid-based techniques) , being both capable of determining distances to better than 10%. Moreover, the TRGB method is applicable to any galaxy containing a detectable population of old, metal-poor, low-mass stars. In practice, this means that nearly all nearby galaxies, regardless of Hubble type and/or inclination, can be placed onto a common distance scale out to the crowding and the flux limits of current CCD detectors and telescopes.

The underlying physical processes are clearly understood and well-rooted in the theory of stellar evolution (Salaris & Cassisi 1998), while the key observable quantity is the magnitude of the bright end of the RGB measured in the Cousins I passband. In fact in this passband, and for metallicities up to [Fe/H]~ -0.7, the TRGB absolute magnitude is almost independent on metallicity (Da Costa & Armandroff 1990).

Even if in these last ten years the TRGB method has been extensively used for deriving the distance to several galaxies, there is not yet a general consensus about its calibration. Presently available calibrations can be separated in two groups: semi-empirical and theoretical ones. As far as it concerns the semi-empirical calibrations which are based on the detection of the TRGB in a sample of GGCs coupled to an assumed cluster distance scale, (Lee, Freedman & Madore 1993, Ferraro et al. 2000 and references therein) they (can) suffer from two major sources of uncertainty:

– the brightest RGB star detection can be biased due to the effects of low stellar number statistics;
– the uncertainty affecting the RR Lyrae distance scale commonly adopted for fixing the absolute distance of the GGCs used for the calibration.

On the other hand, theoretical calibration (Salaris et al. 2002 and references therein), being based on predictions of stellar models, can be affected by the still existing uncertainties on the electron conduction opacity and plasma neutrino emission rates, which govern the size of the He core at the He-burning ignition and, in turn, the bolometric luminosity of the RGB tip. Another significant source of uncertainty comes from the adopted I Cousins bolometric scale (see the detailed discussion in Salaris & Cassisi 1998).

In order to overcome all quoted sources of uncertainty, Bellazzini, Ferraro & Pancino (2001, hereinafter B01) have recently provided an independent empirical calibration of the absolute I band magnitude of the TRGB, based on the GC ω Cen. They adopted the distance obtained by Thompson et al. (2001) from the analysis of an eclipsing binary system in the cluster and measured the apparent I brightness of the TRGB, relying on the fact that the CMD of this cluster is quite well populated and this opportunity should allow an unbiased estimate of the TRGB level. Fig. 4 shows the comparison between all semiempirical TRGB calibration, the one provided by B01, and the theoretical calibrations given by Salaris & Cassisi (1998). It is worth noticing that the theoretical calibrations (the same outcome applies to almost all theoretical calibration currently available in literature) are ≈ 0.15 mag brighter than empirical calibrations, and within $\approx 1.5\sigma$ of the B01 value. The disagreement appears even larger when considering the new TRGB calibrations, based on very recent updated stellar models, provided by Pietrinferni, Cassisi & Salaris (2003). It is evident that the reasons for this not negligible discrepancy between theoretical predictions and semi-empirical calibrations has to be fully understood. For this aim, a more accurate estimate of the eclipsing binary distance to ω Cen (possibly analyzing additional binary systems) has to be derived. In addition, extensive observations of the most massive GGCs are urged in order to properly calibrate the empirical relations. From the theoretical side more accurate checks of the accuracy and reliability of stellar models have to be performed and a more reliable bolometric correction scale has to be provided.

4. The R parameter: an update

Being the GGCs the oldest stellar systems in the Galaxy, their initial He abundance is supposed to be similar to the primordial He abundance (Y_P) produced by the Big Bang nucleosynthesis (BBN). The values of Y_P derived from spectroscopy of low-metallicity, extragalactic H II regions, even if appear to be still subject to systematic uncertainties (see the discussion in Bono et al. 2002 and reference therein) seem to cluster around a value of the order of $Y_P \approx 0.24$. In addition, recent analysis of the cosmological baryonic matter density from the cosmic microwave background (CMB) power spectrum obtained by the BOOMERANG, DASI, MAXIMA and WMAP experiments (Pryke et al. 2002, Ödman et al. 2002, Sievers et al. 2003, Spergel et al. 2003) coupled with standard BBN calculations (Burles, Nollett & Turner 2001) provide $Y_P = 0.248 \pm 0.001$.

For GGC stars the best He indicator is the so-called R parameter (Iben 1968), defined as the number ratio of HB stars to RGB stars brighter than the HB level. Recent analysis performed by Sandquist (2000, S00) and Zoccali et al. (2000, Z00) on a large sample of GGCs and based on predictions provided by stellar evolution models, have provided a value for the initial He abundance in GGCs of the order of 0.20, in severe disagreement with the CMB results and spectroscopical measurements in extra-galactic regions.

The huge discrepancy between CMB and R parameter results casted doubts on the ability of stellar models to properly predict the evolutionary times for both shell H- and He-burning phases. The main source of uncertainty has been ascribed to the not-well known cross section for the $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction, but there could be also a non negligible contribution due to an improper treatment of the mixing inside the convective core of HB stars.

Very recently, Cassisi, Salaris & Irwin (2003, hereinafter CSI) have reanalized the problems by using the same observational database adopted by S00 and Z00, but relying on a new calibration of the R parameter as a function of the He content based on an updated set of stellar models computed using new and more accurate estimates of the equation of state for the stellar matter and of the uncertain $^{12}C(\alpha,\gamma)^{16}O$ reaction rate.

Fig. 5 shows the comparison between empirical and theoretical (CSI) R parameter values, for both the Z00 and S00 samples. In view of the large uncertainty still affecting the GC metallicity scale, both the metallicity scale of Carretta & Gratton (1997) and Zinn & West 1984) have been adopted.

By performing an accurate statistical analysis on the data plotted in fig. 5, and properly accounting for current uncertainties on the GC metallicity scale, the observational errors on the R parameter as well as uncertainties in the treatment of convection and the $^{12}C(\alpha,\gamma)^{16}O$ rate, CSI have estimated an initial He abundance equal to $Y = 0.243 \pm 0.006$ when adopting the Z00 database and $Y = 0.244 \pm 0.006$ in the case of the S00 sample. These estimates are in good reciprocal agreement and consistent

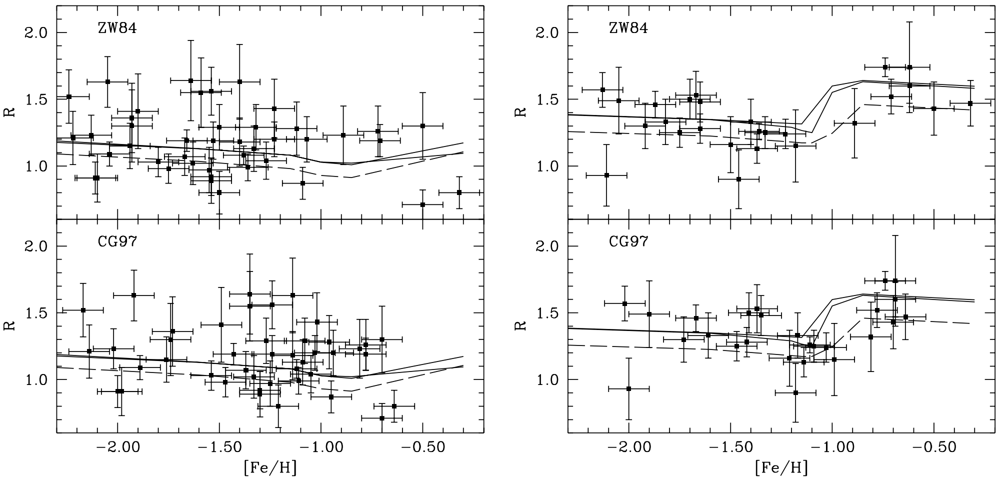

Fig. 5. Left panel: the behavior of the R parameter as a function of the metallicity for the two adopted metallicity scales (see labels). The observational points are from S00. Theoretical calibrations for Y=0.245 and ages of 11 and 13 Gyrs are shown (solid lines). The dashed line corresponds to theoretical predictions for Y=0.23 and an age equal to 13Gyr. Right panel: as left panel but for the observational database provided by Z00. Notice that the definitions of R employed by Z00 and S00 are slightly different; they have been accounted for when evaluating the theoretical counterpart.

with the value recently obtained from CMB analysis and primordial nucleosynthesis computations. It is worth noticing that this result provides strong support to the adequacy of the theoretical framework adopted by CSI.

5. Open problems

In the previous sections I provided a few selected results concerning the capability of current low-mass stars models to match the observations. This picture is not and cannot be (!) exhaustive; many more are the 'hot' topics concerning the comparison between stellar models and recent observational evidences. From the results briefly discussed in the previous sections, it appears evident how pivotal is the comparison with as many as possible observational constraints, in order to firmly assess the adequacy of the theoretical models. In the meantime, the observational people should not take theoretical predictions at their face values, accounting always for the fact that the 'theory' is not the 'truth'.

I already mentioned the existing uncertainties regarding colour transformations, bolometric correction scales and electron conduction opacities. Another very uncertain issue in the low mass star model computation is the efficiency of element transport mechanisms, that is:

– microscopical mechanisms: such as atomic diffusion and radiative levitation;
– macroscopical processes: outer convection, convective overshooting, breathing pulses.

Solar standard models computed including fully efficient atomic diffusion are able to properly fulfill the constraints provided by helioseismological measurements; however, the same models applied to metal-poor stars such those in GGCs are not able to reproduce the surface chemical abundances measurements obtained from recent spectroscopical analyses (Gratton et al. 2001). This means that some other mechanism (e.g., rotation induced mixing) is at work in the envelope of these stars, reducing the effect of diffusion.

As far as radiative levitation is concerned, great improvements have been recently achieved thanks to the work of Richard, Michaud & Richer (2002). However, we still need self-consistent evolutionary predictions of the efficiency of radiative levitation in the envelope of hot Horizontal Branch stars, which is fundamental in order to explain the observations obtained in these recent times (Momany et al. 2002 and references therein).

The treatment of macroscopical mechanisms in stellar models is, after 50 years of evolutionary computations, still an hot topic as certified also by the very recent literature (e.g., Barmina, Girardi & Chiosi 2002). Whereas the amount of convective overshoot in intermediate mass stars is still subject to debate, the situation for low mass stars appears more clear. Concerning, for instance, the occurrence of breathing pulses (i.e. the occurrence of a 'pulsating' instability of the convection at the end of the He central-burning phase): recent improvements in the evolutionary computations (CSI) provide strong support to the early finding of Caputo et al. (1989) that such mechanism should have, if any, a negligible efficiency.

People like myself, computing stellar models since long time, does try always to compute the 'best' models they can. However, the goodness of their models is always strongly dependent on the reliability of the adopted physical scenario which - we hope! - is continuously improving. This evidence should be properly accounted for when comparing theory and observational data. In order to obtain a meaningful comparison, as well as to estimate the intrinsic uncertainty affecting the adopted theoretical framework, it would be worthwhile to use as many as possible independent sets of stellar evolution models.

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