Modern Stellar Evolution Models for Low Mass Stars

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Abstract. The status of the art for evolutionary models of low mass, population II stars is revisited, stressing the need for the models to be preliminarily tested with suitable observational data. The uncertainties still affecting the theory are discussed in the aim of guiding the users in a reasoned choice of the models. The powerful coupling of evolutionary with pulsational theories is shortly recalled. A short conclusion and a mention of the problem of tilted HB close the paper.

1. Introduction

When I was invited to give a talk about ”Modern Stellar Evolution Models” I began wondering about the meaning of the word ”modern”. Obviously, with such a word the promoters of the meeting intended refer to an increased reliability reached by recent stellar evolutionary models: thus ”modern” would mean ”what we are able to do at the present time”. However, stellar models appearing in the current literature not necessarily and not always represent the best ones can we now do, i.e., not necessarily ”recent” means ”modern”. Bearing in mind such a warning, in this talk I will discuss the ”status of the art” of stellar evolutionary theories, highlighting which -at least in my opinion - should be the more suitable ground for modern stellar models.

In order to approach this issue, one has to remind that stellar evolution theories were born to account for the evolutionary evidences as given by the CM diagram of stellar clusters. In particular, evolutionary theories for low mass stars find their experimental (observational) counterpart in the CM diagrams of Galactic Globular Clusters (GGC). It may be interesting, especially for the younger people in this audience, to recall how tremendous was the increase of observational evidences concerning GGCs along the past century. Before the II World War only Red Giant Branches (RGB) and Horizontal Branches (HB) were barely known, whereas the first evidence for the bright end of the cluster Main Sequence was only attained during the 50’s (Arp, Baum & Sandage 1953).

Since that time, and for several decades, a huge amount of investigations dealt with such a ”canonical portion” of the cluster CM diagram, lacking any observational evidence for the fainter stars we knew should populate the cluster. Only in rather recent time the improved capability of both ground and space based observations allowed us to gain evidence on the large majority of cluster stars, adding information on the ”newcomers” as represented by the Very Low
Mass (VLM) MS stars, as well as reaching the bright end of the cooling White Dwarf sequence, fainter WDs waiting for deeper observations.

In the same century, following the pioneering work of the "Fathers of Evolution" (Hayashi, Schwarzschild, followed by Kippenhan, Iben, Demarque ....) stellar models were continuously improved in order to follow the evolution of low mass stars all along their nuclear burning phases and down to their final cooling as WD. As a result, about twenty years ago stellar models were already able to "reasonably" account for the main CM diagram features, where "reasonably" means within observational uncertainties concerning not only the photometry but also the cluster reddening and distance modulus. In this way, the main goal of evolutionary theories was achieved, i.e., to account for the observed CM diagram morphologies.

2. Stellar models and theoretical uncertainties

In normal life, theories are expected to fit experimental data. However, the quoted agreement between evolutionary theories and observations has early prompted several people to use theoretical results in a rather unconventional way, attempting a theoretical calibration of observational data. As an example, by comparing the observed with the predicted luminosity of the HB in a given globular, one could derive the distance modulus of the cluster and - coming back to theory - its age. Similar procedures have however raised several debates for the very simple reason that at that time different authors gave (not surprisingly, as we will see) different predictions for the HB luminosity as well as for other relevant observational parameters.

To have light on such an occurrence, one has to make clear a relevant point, not generally acknowledged by people not concerned with stellar models. "Model" is indeed an ambiguous word, suggesting perhaps some degree of freedom. On the contrary, a stellar model is a strong and solid computational architecture, without any degree of freedom, and a stellar model is as good as the input physics used to feed the model. Different models with the same input physics must give, as they give, the same results. If not, it is matter of (rare) computational mistakes.

What I am saying is that different results were, and are, the expected consequence of different input physics. The amount of physics required by a model is indeed tremendous, with difficult quantitative evaluations of the behavior of stellar plasma, which normally requires some sort of approximation and that along the time has been subject to continuous improvements. To avoid an unnecessary and damaging confusion, people computing stellar models should update their code to the most trustworthy and documented physical evaluations, submitting the result to all possible observational tests. This, in my feeling, appears the only reasonable route to modern stellar models. At the same time, when fitting observations, models should be chosen on the basis of a proved adequacy of the adopted physics, and not according to criteria of convenience, institution, friendship .. if not nationality.
3. The Solar Connection

To test the solidity of the various alternative model results, and of the related physical assumptions, one needs more stringent observational constraints than given by globular cluster stars. A first opportunity is offered by the SUN, since helioseismology already provided relevant constraints on its internal structure. The Sun is indeed a low mass stars, which - like GGC stars - will undergo electron degeneracy during the H shell burning evolution, evolving as a RG till attaining its central He burning, HB phase. Thus, the Sun represents a reasonable test for low mass, central H burning structures, even if with a different metallicity.

Constraints from the solar structure have already required several improvements in the previous input physics as given, e.g., by the OPAL results concerning the Equation of State (EOS) for stellar matter and the evaluation of radiative opacities, bringing also the additional evidence for the efficiency of element diffusion in the external solar layers. Adopting such a modern evolutionary scenario, one eventually attains quite a good agreement of theoretical Solar Standard Models (SSM) with solar constraints, as shown in fig. 1, where theoretical predictions on the behavior of the ratio between pressure and density along the solar structure are compared with helioseismic constraints.

As a relevant points, one finds that the input physics passing the solar test provides stellar models which appear also in agreement, even in varying the star metallicity, with the absolute CM diagram of stars in nearby open clusters with distance moduli from the Hipparcos parallaxes (Castellani et al 2001). Waiting for further observational constraints, as expected from the next generation of astrometric satellites, in my opinion one should regard as MODERN stellar models only those models passing both the solar and the Hipparcos tests.

However, these tests are largely neglected, making difficult an a priori choice among different results. Bearing this in mind, in the following we will discuss the "status of the art" from the recent literature, to make clear the existence

Figure 1. The predicted run of $P/\rho$ along the solar structure (full line) as compared with the corresponding helioseismic experimental data (dashed line).
of additional uncertainties and to help people in properly handling theoretical data.

4. Stellar Models for Low Mass Stars: the canonical portion

The best way to make clear the need for an observational calibration of theoretical results is given in fig. 2, which discloses recent theoretical predictions for the MS location of low mass stars with solar metallicity. It appears that for a given effective temperature the predicted luminosity can vary over a range of about \( \Delta \log L \sim 0.12 \). This means an intrinsic uncertainty of 0.3 mag, if no additional errors in transferring luminosity to magnitude are made.

However, even when dealing with models calibrated on the Sun, there are additional uncertainties. Models in a rather large portion of the MS are indeed sensitive to the assumptions to be made about the mixing length parameter which governs the efficiency of superadiabatic convection in the external stellar layers (see, e.g., fig. 2 in Castellani, Degl’Innocenti & Prada Moroni 2001). In principle, the MS location should also depend on the efficiency of element diffusion: fortunately Salaris, Groenewegen & Weiss (2000) have already found that such a dependence is largely negligible.

As for the mixing length, one can adopt the value calibrated on SSM, but there is no reason for the mixing length remaining constant in varying the star mass, evolutionary phase and chemical composition! Moreover, the often used calibration of the mixing length on solar models without element diffusion is not completely meaningful, since one is using a "wrong Sun" to find out a mixing length value which pastes the efficiency of convection (actually larger in SSM) with the effect of sedimentation. Thus at the present time, this uncertainty cannot be fully removed.

As for the TO luminosity and its dependence on the cluster age, this is little affected by the mixing length, but the main problem is whether or not in Pop.II stars element diffusion is at work. It has indeed already proved that a solar-like diffusion sensitively affects the predicted evolutionary track of low
mass stars. The lack of evidence for depletion of Fe or Li in the atmosphere of globular cluster subgiants (Gratton et al 2001, Bonifacio et al 2002) led some people to suspect that, for unknown reasons, Pop.II star are not affected by this mechanism. Without entering in such a discussion, one can only notice that we have no observational evidence concerning the diffusion of He, which - in turn - has the major influence on the off-MS evolution (Castellani et al 1997).

Passing to the Red Giant phase, one has to notice that these structures are now sensitive to the efficiency of additional physical mechanisms, like electron conduction or neutrino production(for a recent discussion see Salaris, Cassisi & Weiss 2002) . Whereas color predictions are again depending on the assumption on the mixing length, the luminosity distribution appears as a rather firm theoretical result, which has been already proved in beautiful agreement with observational constraints. Till recent time, the main uncertainty was related to electron conduction, whose efficiency governs the mass of the He core at the flash and, in turn, the predicted luminosity of the following Horizontal Branch phase.

Old evaluations of electron conduction as given by Hubbard & Lampe (1969) have been largely used in stellar models. However Itoh and coworkers (Itoh et al 1983, 1993, Mitake et al 1984) presented new and more accurate evaluations but within a range of validity not properly adequate for RG structures. Owing to this situation, the choice between the two alternatives has been largely a matter of opinion of the various authors. Note that authors adopting Hubbard & Lampe derives smaller cores and, thus, lower HB luminosities. More recently, according to updated evaluations covering the RG internal structures (Pothekin 1999, Pothekin et al 1999)) one finds that Itoh’s choice should have been preferred, as shown in Table 1 where the He core mass and the star luminosity at the He flash are reported under the various labelled assumptions about electron conduction (Piersanti, Prada Moroni & Straniero 2002). A detailed discussion on the influence of other physical ingredients on the HB luminosity can be found in Cassisi et al (1998), Castellani (1999).

Table 1. Mass of the He core and luminosity at the He flash for a star of 0.8 $M_{\odot}$, Z=10$^{-4}$ adopting electron conduction from the labelled authors

| Authors | Mc  | Ltip |
|---------|-----|------|
| H&L     | 0.5077 | 3.271 |
| Itoh    | 0.5116 | 3.292 |
| Pothekin| 0.5108 | 3.289 |

Let me finally quote the still large uncertainties in the HB lifetimes, often used to calibrate the number ratio $N_{HB}/N_{RG}$ in terms of the original He content of cluster stars. To follow the time evolution of the central convective cores, one has to make a choice between classical semiconvection or core overshooting. In the former case, semiconvection, the uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction produces an uncertainty of about 10% in the lifetime of central He burning structures, which increases when the reaction cross section increases (Cassisi
et al 1998, Zoccali et al 2000). HB models with overshooting taken from the literature can have lifetime even larger by about 40%.

5. Theoretical RR Lyrae

When dealing with the canonical portion of the CM diagram, let me spend only few words also on theoretical models for pulsating RR Lyrae stars, which appears to me a branch of the evolutionary tree laden with fruit. As well known, evolutionary models give for these stars a prediction about the mass M and the luminosity L, fully constraining the curve of light (period, amplitude, shape) predicted by the pulsational theory for each given value of effective temperature Te. Thus, the coupling of evolutionary with pulsational theory is a quite efficient device to submit theoretical predictions to stringent observational tests.

In this context, it has been already shown that pulsational constraints can play a relevant role in our knowledge of globular clusters. As an example, let me only quote some recent results: i) the periods of RR Lyrae stars at the Blue Edge for instability can gives reliable GC distances (Caputo et al. 2000); ii) the period-K magnitudes relation can be used to give the parallax of RR Lyr itself better than HST astrometric measurements (Bono et al. 2002); iii) the shape of the light curve can constrain the absolute magnitude of the pulsators (Bono et al 2000). Here one can add that pulsational constraints for RR Lyrae stars in M3 provide pulsator masses in beautiful agreement with evolutionary predictions (Di Crescenzo, Marconi & Caputo 2002).

Finally, let me close this brief section with a warning: the mean V magnitude of a RR Lyrae is not necessarily the magnitude of the static structure, since it can be fainter up to 0.12 mag for the fundamental pulsators with large amplitudes (Bono, Caputo % Stellingwerf 1995, Di Crescenzo, Marconi & Caputo 2002). As a corollary, it follows that the mean magnitude of a sample of RR Lyrae stars IS NOT the mean magnitude of the HB.

6. The Newcomers

The evidence brought to the light by HST has recently stimulated a large amount of theoretical investigations on VLM MS stars. The theoretical approach to these cool and dense structures has required a remarkable amount of work to produce adequate evaluations of both the EOS and the radiative opacity, as well as new and adequate model atmospheres. As expected, stellar models from different authors but with the same (updated) input physics give same results, being in beautiful agreement with observation for the lower metallicity (Cassisi et al 2000 and references therein). However, for unknown reasons this agreement decreases increasing the metallicity, becoming worse at solar metallicity (possibly for problems with the bolometric correction BC ?).

As a warning, it has been recently found that models at the faint end of the sequence dramatically depends on the treatment of EOS. Available EOS tables give the various physical quantities for selected values of the plasma temperature (T) and pressure (P), with steps ∆logT=0.08, ∆logP=0.2. However, decreasing the step (Cassisi, private communication) the models undergo relevant variations.
Figure 3. Cooling laws (luminosity versus time) for CO WD from the current literature.

Finally, as for WD, evaluation of the cooling history obviously requires a lot of physics, including a detailed treatment of liquefaction and crystallization (see, e.g., Prada Moroni & Straniero 2002). Looking at the relevant differences among recent models, one concludes that before using WD as a clock a decision has to be taken concerning the better physics.

7. Conclusion

As a first conclusion, it appears to me that differences among the recent models of low mass stars are sometime much larger than the unavoidable uncertainties still connected with the input physics. A co-operative effort among evolutionary people could greatly improve this situation, offering to the "common users" of theoretical predictions a clearer insight on the theoretical scenarios. In this context, I very much appreciated the collaboration with the Padua group (L.Girardi) giving light on the different results concerning the luminosity of He burning giants.

In my feeling, users of stellar models should not take theoretical results without seeing it first. In the same time, theoretical people should realize a "code of conduct", including - e.g.- the prescriptions for observational tests not only with the sun but also with stellar clusters relevant for the computations. A procedure often but not always adopted. In this context, stellar models should be regarded as a bottle of wine: without a label exhaustively reporting the kind of wine, the vintage an so on, no one is tempted to taste the contents.

8. The open question of Tilted HB

Before closing, I have however to quote a still open question concerning the basic goal of stellar evolution, as represented by the lack of explanation for the "tilted" red HB in metal rich GCs. A possible connection with the dynamic of stars in that dense clusters has been often suspected, but no clear answer has been till now reached.
On the contrary, the occurrence of an extended HB in these as in other GCs is not, strictly speaking, an evolutionary problem, as it can be easily understood in terms of a sample of RG loosing a substantial fraction of their mass.

If this is the result of close encounters during the core collapse, as I suspect, this would imply that post core collapse clusters develop an EHB lasting 1 - 2 $10^8$ years before coming back to a normal cluster with a normal HB. However, for the moment this is only matter of speculation.

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