

Part 9

Evolutionary and pulsation properties of variable stars

Evolutionary properties of intermediate-mass stars

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Abstract. We briefly review the main problems related to the computation of the evolution of intermediate-mass stars: the treatment of turbulent convection and the occurrence of blue loops during the core He-burning phase. It is shown that, in order to obtain more accurate and reliable stellar models for this class of stars, one has to consider all possible theoretical and observational constraints. These include observations of low-mass stars to constrain the treatment of envelope convection, and the analysis of the pulsational behaviour of Cepheid stars.

1. Introduction

In the last decade, thanks to the large advances in the computation of opacity, equation of state (EOS) and nuclear reaction rates in stellar conditions, numerical stellar modeling has been able to greatly improve our understanding of stellar evolution throughout the H-R diagram. Strong confirmation of the reliability of evolution theory has come from the wonderful agreement between the predicted positions of stars in the Color-Magnitude Diagram (CMD) and observations. The pulsational behaviour of Cepheids and other radially oscillating stars has further confirmed the accuracy of stellar modeling for specific classes of stars. A detailed confirmation of some of the physics of stellar models has also been provided by the excellent agreement between the oscillation spectrum predicted by the standard solar model and helioseismic measurements.

This notwithstanding, many aspects of stellar evolution theory have not been observationally confirmed, and thus deserve further investigations. In this respect, the evolutionary and structural properties of intermediate-mass stars play a central role; as an example, it is commonly believed that existing uncertainties in the theory of turbulent convection still greatly affect our understanding of the internal structure of these stars.

The plan of this paper is as follows: in the next section we briefly discuss the reasons why stellar models for intermediate-mass stars appear, in principle, to be more reliable than models for low-mass stars, and we outline the still-existing questions concerning their evolution. To this aim, we will consider observations of the pulsational properties of Cepheid stars. Specific attention will be devoted to highlight the 'sensitivity' of the stellar model properties to the underlying physical assumptions. Conclusions follow.

2. The physics of intermediate-mass stars

The recent literature for intermediate-mass stars is quite rich (see Bono et al. 2000 and references therein), and a detailed discussion of the main evolutionary and structural properties of these stars can be easily found elsewhere. Here we wish to shed light on the questions one has to face when trying to model this class of stars.

As stated in the previous section, the theoretical investigation of low-mass stars appears well supported by the results of helioseismology, but this is not the case for intermediate-mass stars. The reason is not due to the difficulty in describing the microscopic physics at work in this kind of stars. In fact, contrary to less massive objects, the evaluation of their thermodynamic properties is relatively simple, due to the fact that intermediate-mass stars are not affected, all along their major evolutionary phases, by electron degeneracy and other non-ideal effects such as Coulomb interaction. The same applies to the computation of the radiative opacity; that is not affected by the significant uncertainties existing in the higher density and lower temperature regime.

The evolutionary properties of intermediate-mass stars are strongly influenced by two open problems: 1) the extension of the convective core during the H-burning phase; 2) the – almost – unpredictable nature of the loop(s) in the CMD during the He central burning phase. These two problems are closely connected and have large implications for the pulsational properties of intermediate-mass stars when they cross the Cepheid instability strip.

3. The treatment of convection during the H-burning phase

Owing to the lack of a conclusive test for the adequacy of the current theory of convection, one can find a variety of different approaches to the inclusion of convection in stellar models. Instability against turbulent convection is classically handled by means of the Schwarzschild criterion for a chemically homogeneous fluid. This well-known criterion is based on the comparison between the expected temperature gradient produced by the radiative transport of energy, and the adiabatic one. It is worth noting that the proper estimate of the size of the convective region is then primarily dependent on the accuracy of the input physics. Any improvement of the adopted physics may produce a change in the estimated temperature gradient and, in turn, modify the location of the boundaries of the convective regions.

A second important point concerns the possibility that the motion of the convective fluid elements is not drastically stopped at the stable region located just outside the formal convective core. Although outside the Schwarzschild boundary a moving fluid element is subject to a strong deceleration, it might be possible that a nonzero velocity is maintained along a certain length. This mechanical overshoot may induce a significant amount of mixing in the region stable against convection. Another important aspect which has to be taken into account is that a sizeable increase in the internal mixing, and hence a larger core, could be also achieved as a consequence of rotationally induced mixing (Meynet & Maeder 2000).

There are therefore at least three different reasons why the temperature gradient and, in turn, the size of the convective cores can be really different than the ones predicted by a ‘canonical’ model¹. The question is: is the size of the convective core, as determined by the (classical) Schwarzschild criterion, able to properly match the observations, or does it have to be ‘artificially’ increased?

This long-standing problem has always been interpreted in terms of *overshooting*, i.e. a proof of the existence or non-existence of the specific phenomenon where the convective cells cross the classical border of the convective core². However, when accounting for the various processes which, in principle, can produce the same effect, this interpretation appears meaningless. It is our belief that it is better to denote by “overshooting” an unspecified mechanism(s) able to increase the convective core size beyond the classical Schwarzschild boundary.

The case for a significant amount of overshooting has been presented many times both theoretically and observationally, but the results so far have been contradictory, even those based on the analysis of stellar counts in young populous clusters (Testa et al. 1999; Barmina, Girardi & Chiosi 2002; Brocato et al. 2003). The facts that are unarguably known concern only the basic theory: during the core H-burning phase the star has a brighter luminosity, a longer lifetime and, at the central H exhaustion, a larger He core than in case of no overshooting. During the core He-burning phase, the luminosity is brighter, the lifetime is shorter and the blue loops are less extended than in the absence of overshooting. Theory therefore predicts that the mass-luminosity (M-L) relationship for stars crossing the Cepheid instability strip is greatly affected by the amount of overshooting accounted for in the stellar evolution computations. The comparison of the theoretical M-L relationship with empirical data could, in principle, put tight constraints on the efficiency of this process. In the following, we will show that this is a feasible approach, but the results have to be cautiously treated.

3.1. The mass-luminosity relationship for Bump Cepheid stars

Keller & Wood (2002, hereinafter KW) have used “bump” Cepheids in order to probe the stellar M-L relationship for intermediate-mass stars. By fitting empirical light curves for 20 bump Cepheids in the Large Magellanic Cloud with their own pulsational models, they estimated the intrinsic luminosity and mass of these variables. This allowed them to obtain a semi-empirical M-L relation. The comparison between their data and theoretical results from the Padua group and from our own models is shown in Fig. 1. It is evident that semi-empirical data are systematically brighter than canonical models, or alternatively, KW results support a mass $\approx 15 - 20\%$ lower than predicted by classical models, at a fixed luminosity. The location of the data with respect to theoretical M-L

¹When referring to a canonical model we mean a stellar structure computed by neglecting rotation and mechanical overshoot, and accounting for the best physics *currently* available.

²The extension of this non-canonical mixed region is usually defined in terms of a parameter λ which sets the length – expressed as a fraction of the local pressure scale height – which is crossed by the convective cells in the convectively stable region surrounding the convective core.

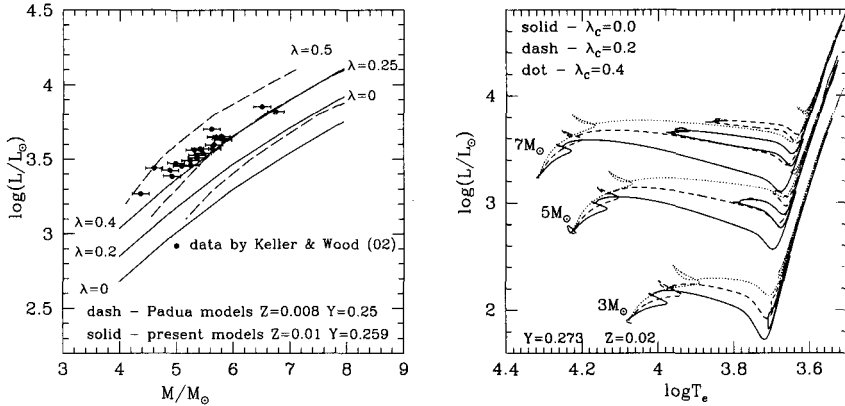


Figure 1. *Left panel:* M-L relationship for the sample of bump Cepheids analyzed by KW. Overplotted are the theoretical M-L relationships provided by Padua models (see KW for details) and our own models for different (see labels) assumptions on the chemical composition and the core overshoot efficiency. *Right panel:* H-R diagram for selected intermediate-mass stars for different assumptions on the core convective overshoot efficiency.

relationships based on models accounting for overshooting seems to suggest the need for a degree of convective core overshooting with $\lambda_C \approx 0.5$.

Although, in our belief, the uncertainties in the M and L values as estimated by KW appear too small, their result seems to provide plain support for the occurrence of a significant amount of core convective overshoot in intermediate stars. However, this result should not be uncritically accepted. In fact, one has to take into account that by increasing the overshoot efficiency to the value required by KW results, the blue loop excursion (see Fig. 1, right panel) is strongly reduced. One has therefore to check if models accounting for this overshoot efficiency are still able to cross the Cepheid instability strip.

In Fig. 2 (left panel), we plot the minimum and maximum effective temperature reached during the blue loop by an intermediate-mass stellar model, as a function of the core overshoot efficiency parameter λ_C ; we also display the T_{eff} value at which the star spends more time during the blue loop, as a function of λ_C . The red and blue edges of the Cepheid instability strip are also shown. It is worth noting that for a core overshoot efficiency larger than ≈ 0.3 the model does not cross the strip any longer. This suggests that it is not possible to claim, on the basis of the M-L relation alone, the need for a sizeable amount of core overshoot, without checking if that amount of core overshoot still allows the model to cross the instability strip. We will come back to this point in the next section; here we conclude by stating that if, as suggested by the KW analysis, a significant amount of core overshoot is really needed, one has to invoke some additional mechanism(s) in order to force the structure to cross the instability strip.

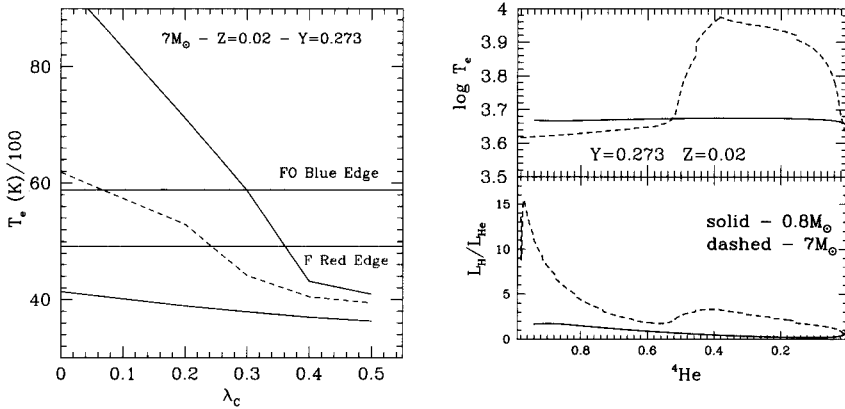


Figure 2. *Left panel:* The run of the minimum, maximum and mean effective temperature during the blue loop of a $7M_\odot$ model with solar composition as a function of the core overshooting efficiency. The location of the fundamental red edge and first overtone blue edge of the Cepheid instability strip is also shown. *Right panel:* The behaviour of the effective temperature and of the ratio between the H-burning energy and He-burning one as a function of the central abundance of He in $0.8M_\odot$ and $7M_\odot$ models.

Before closing this section, it is worthwhile to note that a suggested possible resolution of the discrepancy between evolutionary and pulsation mass for canonical models is to consider the occurrence of quite efficient mass loss (Bono, Castellani & Marconi 2002). However, this does not appear the right route for solving the problem at least for two reasons: 1) the required amount of mass loss for solving the discrepancy is at odds with empirical estimates (Deasy 1988); 2) if the mass loss efficiency in these stars is really larger than currently expected, the effect on the blue loops of a high-efficiency mass loss is to decrease both the T_{eff} excursion and the mean luminosity.

4. “To loop or not to loop”

For a long time the physical reasons for the existence of blue loops challenged our understanding of stellar evolution. In this last decade, a big effort has been devoted to this subject. Thanks mainly to the pivotal work made by Renzini et al. (1992, hereinafter R92) and Renzini & Ritossa (1994), we know better the physical reasons for the occurrence of blue loop(s) during the He burning phase. This notwithstanding, it is not yet possible to easily predict the behavior of an intermediate-mass star model during this phase when changing some physical inputs and/or the physical assumptions adopted in the evolutionary computations. This is in contrast with what occurs for low-mass stars, for which the changes in their H-R diagram location induced by any variation of the input physics can be easily predicted. The reason is that in intermediate-mass stars the contribution to the stellar energy budget provided by the H-burning shell is

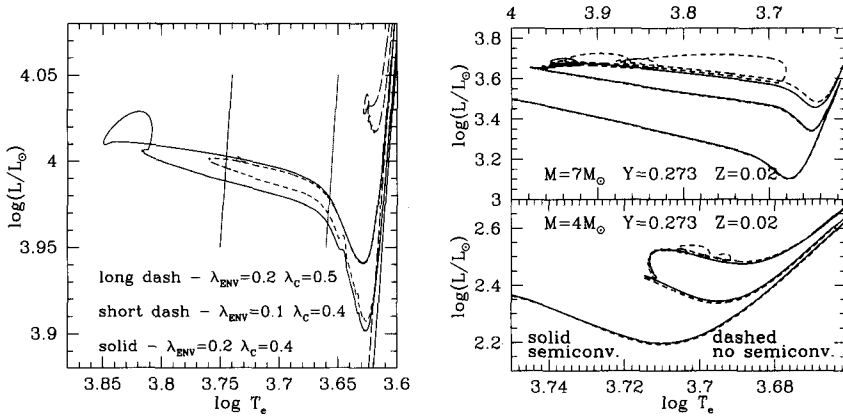


Figure 3. *Left panel:* The location of the blue loop for a $7M_{\odot}$ model accounting for different efficiency of both core and envelope convective overshooting, compared to the edges of the Cepheid instability strip. *Right panel:* The H-R diagram location of the blue loops for two intermediate-mass models computed alternatively by accounting for or neglecting the semiconvective region during the core He-burning phase.

significantly larger than in low-mass stars, and in addition the relative energy contribution of the He- and H-burning (see Fig. 2, right panel) changes significantly during the core He-burning phase. As a consequence, any variation of physical inputs able to modify the H-burning efficiency may either trigger or inhibit the loop.

An accurate analysis of the role of several factors known to affect the blue loops has been performed by R92 and we refer the interested reader to the quoted reference. In the following we address only the problem of the dependence of blue loops on convective envelope overshooting and semiconvection.

4.1. The consequence of convective envelope overshooting

The role played by convective envelope overshooting has been investigated by several authors (e.g., Alongi et al. 1991; Stothers & Chin 1991; R92). Nevertheless, its effect still appears somewhat intricate. Evolutionary computations seem to suggest that a blue loop is apparently favoured by a sharper H profile in the envelope chemical stratification, as a consequence of the drastic change in the H-shell burning efficiency (Cassisi & Salaris 1997); this means that envelope overshooting, being able to produce this kind of sharper discontinuity during the first dredge up, may be able to trigger a loop that otherwise would not occur. However, as shown by R92, the general picture is more complicated, depending also on when the H-shell burning encounters this discontinuity – if this occurs after the central He ignition, envelope overshooting has no effect at all on the development of the blue loop.

We have previously shown that the comparison between the semi-empirical M-L relationship for bump Cepheids and theoretical stellar evolution models does seem to indicate the need of accounting for a core overshooting of the or-

der of $\lambda_C \approx 0.5$; however, models accounting for this large overshoot efficiency are not able to cross the instability strip. If core overshooting really occurs, it is reasonable to consider also the occurrence of envelope overshooting, whose efficiency promotes the occurrence of blue loops. In Fig. 3 (left panel) we show the shape of the blue loops for a selected intermediate-mass model computed under several assumptions about both core and envelope overshooting, and their location with respect to the boundaries of the instability strip. For a core overshooting efficiency of the order of $\lambda_C = 0.4$, an envelope overshooting efficiency of the order of $\lambda_{ENV} = 0.1$ is enough to push the model inside the instability strip. Nevertheless, for $\lambda_C = 0.5$ (see previous section) theoretical evidence shows that an envelope overshooting efficiency $\lambda_{ENV} > 0.2$ is required.

We can now ask if observational data can help constrain the efficiency of envelope overshooting. The answer is positive, and this can be done accounting for the brightness of the Red Giant luminosity function bump (see Salaris, Cassisi & Weiss 2002) in galactic globular clusters: the comparison between observational data and evolutionary models clearly suggests that *if* envelope overshooting is really useful for improving the match between theory and observations, then its efficiency has to be lower than $\lambda_{ENV} = 0.2$. It is therefore evident that the amount of envelope overshooting needed by intermediate-mass stars is in marginal agreement – if not ruled out – by evolutionary evidence for low-mass Red Giant stars. Of course, one has to bear in mind that the efficiency of envelope overshooting – if any – can depend on the stellar mass, and in principle the amount of overshooting in intermediate-mass stars could be different than that in low-mass stars. However, in our belief, the constraint provided by low-mass stars has to be properly accounted for. If this is the case, one has to invoke some different physical mechanism(s) able to favour the occurrence of extended blue loops in intermediate-mass models accounting for huge amounts of core overshooting.

4.2. The role of semiconvection

On the basis of preliminary numerical experiments R92 suggested that the presence of a semiconvective region at the edge of the He-burning convective core, by changing the rate at which He is mixed into the core, could have significant effects on the occurrence of the blue loops. More specifically, the larger the semiconvective region, the lower the chance is for the occurrence of blue loops. In order to explore this scenario we computed selected models for intermediate-mass stars by alternatively accounting for or neglecting semiconvection. In Fig. 3 (right panel) we show the comparison between these models. One can easily see that, at variance with previous indications, the effect of semiconvection on the morphology of the blue loops is quite negligible due to the fact that the semiconvective region in these stars is only a small fraction of the whole convective core ($\approx 10\%$ for a $4-M_{\odot}$ model and $\approx 1\%$ for a $7-M_{\odot}$ one).

5. Conclusions

Even if the analysis of the evolutionary and structural properties of intermediate-mass stars has been the subject of many investigations in recent years, there remain many aspects of their evolution which still have to be fully understood. In

this respect, the study of the efficiency of turbulent convection at the 'canonical' boundaries of both convective core and envelope has to be reanalyzed by properly accounting also for the constraints coming from low-mass stars in globular clusters, as well as asteroseismic measurements (Guenther 2002), whose impact will increase in the near future thanks to various planned space missions. As far as this last point is concerned, it is worthwhile remembering that the accurate analysis of pulsational spectra of field white dwarfs (Metcalf, Salaris & Winget 2002) is starting to provide a powerful tool for investigating the efficiency of mixing in the He core of their intermediate-mass progenitors. One can also predict an improved understanding of the evolution of intermediate-mass stars when both observations of pulsational properties and theory will be analyzed together.

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References

- Alongi, M., Bertelli, G., Bressan, A., Chiosi, C. 1991, *A&A*, 244, 95
Barmina, R., Girardi, L., Chiosi, C. 2002, *A&A*, 385, 847
Bono, G., Caputo, F., Cassisi, S., Marconi, M., Piersanti, L., Tornambé, A. 2000, *ApJ*, 543, 955
Bono, G., Castellani, V., Marconi, M. 2002, *ApJ*, 565, L83
Brocato, E., Castellani, V., Di Carlo, E., Raimondo, G., Walker, A.R. 2003, *AJ*, 125, 3111
Cassisi, S., Salaris, M. 1997, *MNRAS*, 285, 593
Deasy, H.P. 1988, *MNRAS*, 231, 673
Guenther, D.B. 2002, *ApJ*, 569, 911
Keller, S.C., Wood, P.R. 2002, *ApJ*, 578, 144
Meynet, G., Maeder, A. 2000, *A&A*, 361, 101
Metcalf, T.S., Salaris, M., Winget, D.E. 2002, *ApJ*, 573, 803
Renzini, A., Greggio, L., Ritossa, C., Ferrario, L. 1992, *ApJ*, 400, 280 (R92)
Renzini, A., Ritossa, C. 1994, *ApJ*, 433, 293
Salaris, M., Cassisi, S., Weiss, A. 2002, *PASP*, 114, 375
Stothers, R.B., Chin, C.-w, *ApJ*, 374, 288
Testa, V., Ferraro, F.R., Chieffi, A., Straniero, O., Limongi, M., Fusi Pecci, F. 1999, *AJ*, 118, 2839

Discussion

Evans: I am delighted to see the studies working on matching the blue loops to observations. When I try to match isochrones to Cepheid binary systems, that is one problem. The other is that a number (but not most) of the companions are to the right of Terminal Age Main Sequence in the HR diagram.

Cassisi: I thank you for your comments. I agree with you that sometimes there are problems matching isochrones and observational points. I think that people involved in evolutionary computations should try to compute as much as possible updated models, taking care of the adopted physics and mixing length calibration.

Morgan: Is there any change in luminosity of the blue loop in the models with envelope overshooting?

Cassisi: In the model with envelope overshooting the blue loop is slightly brighter, but the difference with respect to canonical model is very little.

Dambis: How much do the ages of Cepheids increase if we reconcile pulsational and evolutionary masses via overshooting?

Cassisi: The increase of the Cepheid age when increasing the core overshoot efficiency does depend on the Cepheid mass, if we account for a $7-M_{\odot}$ model the increase in the stellar age during the blue loop phase is of the order of 30% when comparing a canonical model with one accounting for a core overshoot efficiency equal to $\lambda_C = 0.5$.



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