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Stellar pulsation and evolution: a stepping-stone to match reality

G. Bono[1], F. Caputo[1], V. Castellani[1]

INAF - Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monte Porzio Catone, Roma, Italy e-mail: `bono,caputo,vittorio@mporzio.astro.it`;

Abstract. We discuss current status of evolutionary and pulsation predictions for intermediate-mass stars. In particular, we focus our attention on the different physical mechanisms that might affect the current discrepancy between evolutionary and pulsation estimates of Galactic and Magellanic Cepheid masses. Theoretical findings and recent empirical evidence indicate that the mass-loss may play a significan role in this long-standing problem.

Key words. Stars:Cepheids – Stars: distance scale – Stars: evolution

1. Introduction

Since to the seminal investigations by Baker & Kippenhahn (1961,1965), Iben (1971), van Albada & Baker (1973), Becker, Iben & Tuggle (1977), and by Tuchman et al. (1979) and Wood (1979) the coupling between evolutionary and pulsation predictions for low and intermediate-mass stars has been firmly rooted. These investigations provided the opportunity to address on a quantitative basis several long-standing stellar astrophysical problems by accounting for both evolutionary (luminosities, effective temperatures, luminosity functionis, evolutionary times) and pulsation (periods, pulsation amplitudes, hot edges of the instability strip) observables. These substantial efforts provided a robust theoretical framework to compare with empirical data (Caputo et al. 1989). These investigations provided important constraints on the physical parameters of radial variables and on the intrinsic accuracy of different standard candles to estimate stellar distances (Feast 2004; Sandage 2006).

In spite of the many interesting findings reached by the new approach, several problems remained unsettled. No firm conclusion was reached on the Oosterhoff dichotomy for RR Lyrae stars observed in Galactic Globular Clusters (GGCs). Theoretical predictions were indeed hampered by the lack of robust predictions concerning the location of the cool edge of the instability strip. This limit affected the topology of the entire Cepheid instability strip. The occurrence of first overtone pulsators among classical Cepheids was still vigorously debated during the eighties (Bohm-Vitense 1988) and a definitive conclusion was only reached with the huge photometric databases collected by the microlensing experiments (Alcock et al. 1995; Beaulieu et al. 1995).

A new spin to properly address these problems was provided by the pioneering theoretical framework developed by Stellingwerf

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Send offprint requests to: G. Bono

(1982, 1984, 1985) to simultaneously account for radial displacements and convective motions. Nonlinear, time-dependent, convective models present, when compared with linear convective (mixing-length) models, two main advantages: *i)* no *ad hoc* assumption is required to mimick the efficiency of convective transport when moving from the blue (hot) to the red (cool) edge of the instability strip; *ii)* the topology of the instability strip and the pulsation amplitudes appear to be in fair agreement with actual properties of radial variables. At the same time, evolutionary models have also experienced a substantial improvement not only for the micro-physics (radiative and molecular opacities, equation of state, nuclear cross-sections), but also for macro-physics (gravitational settling). The reader is referred to Castellani & Degl'Innocenti (1999), Cassisi et al. (1999), and Weiss (2006, these proceedings).

In the following we discuss evolutionary and pulsation properties of classical Cepheids and in particular of the Cepheid mass discrepancy. In section 2 we briefly outline predicted evolutionary and pulsation evidence, and in section 3 current empirical evidence. In section 4, we briefly discuss future theoretical and observational developments and their impact on the distance scale and on pulsation properties of variable stars.

2. Cepheid Mass Discrepancy: Theory

Classical Cepheids are fundamental laboratories for stellar evolution, stellar pulsation, and galactic chemical evolution theories. However, current predictions are still hampered by several problems. Circumstantial evidence suggests that pulsation masses of Classical Cepheids are systematically smaller than their evolutionary masses. Evidence for this was brought forward more than 30 years ago by Fricke et al. (1972) who found that pulsation masses were roughly a factor of two smaller than the evolutionary masses. This conundrum was partially solved (Moskalik, Buchler, & Marom 1992) by the new sets of radiative opacities released by OPAL (Rogers & Iglesias 1992) and by the Opacity Project (Seaton et al. 1994). However, several recent investigations focussed on Galactic (Bono et al. 2001a; Caputo et al. 2005) and Magellanic (Beaulieu et al. 2001; Bono et al. 2002; Keller & Wood 2002,2005) Cepheids suggest that such a discrepancy still amounts to 10-20%. A similar discrepancy was also found by Evans et al. (2005a) using dynamical mass estimates of Galactic binary Cepheids and by Brocato et al. (2004) using a sizable sample of cluster Cepheids located in NGC 1866 — an intermediate-age, Large Magellanic Cloud (LMC) cluster. We can follow two different paths to account for such a discrepancy: *i)* current evolutionary predictions underestimate the He-core size for intermediate-mass structures, and in turn their Mass-Luminosity (M/L) ratio. This possible drawback has a substantial impact on pulsation predictions (shorter periods), since envelope models assume an M/L relation. *ii)* Current Cepheid masses are smaller than their MS progenitors, because they have lost a fraction of their initial mass. The latter working hypothesis implies that the Cepheid mass discrepancy is intrinsic, i.e., it is not caused by limits in the physical assumptions adopted in constructing evolutionary and pulsation models.

In order to provide a more detailed theoretical framework, in the following we mention the physical mechanisms affecting the size of the He-core among intermediate-mass structures (Chiosi & Maeder 1986; Brocato & Castellani 1993; Stothers & Chin 1993,1996; Cassisi 2004). The most popular are: *i)* Extra-mixing — efficiency of convective core overshooting during central Hydrogen burning phases; *ii)* Rotation — the sheer layer located at the interface between convective and radiative regions causes a larger internal mixing, and in turn, a larger He-core size; *iii)* Radiative opacity — an increase in stellar opacity causes an increase in the central temperature, and in turn in the efficiency of central Hydrogen burning; *iv)* Mass Loss — efficiency of mass loss along the Main Sequence, the Hayashi track, and the blue loop, if any.

i) **Extra-mixing** — Several detailed studies based on the comparison between predicted

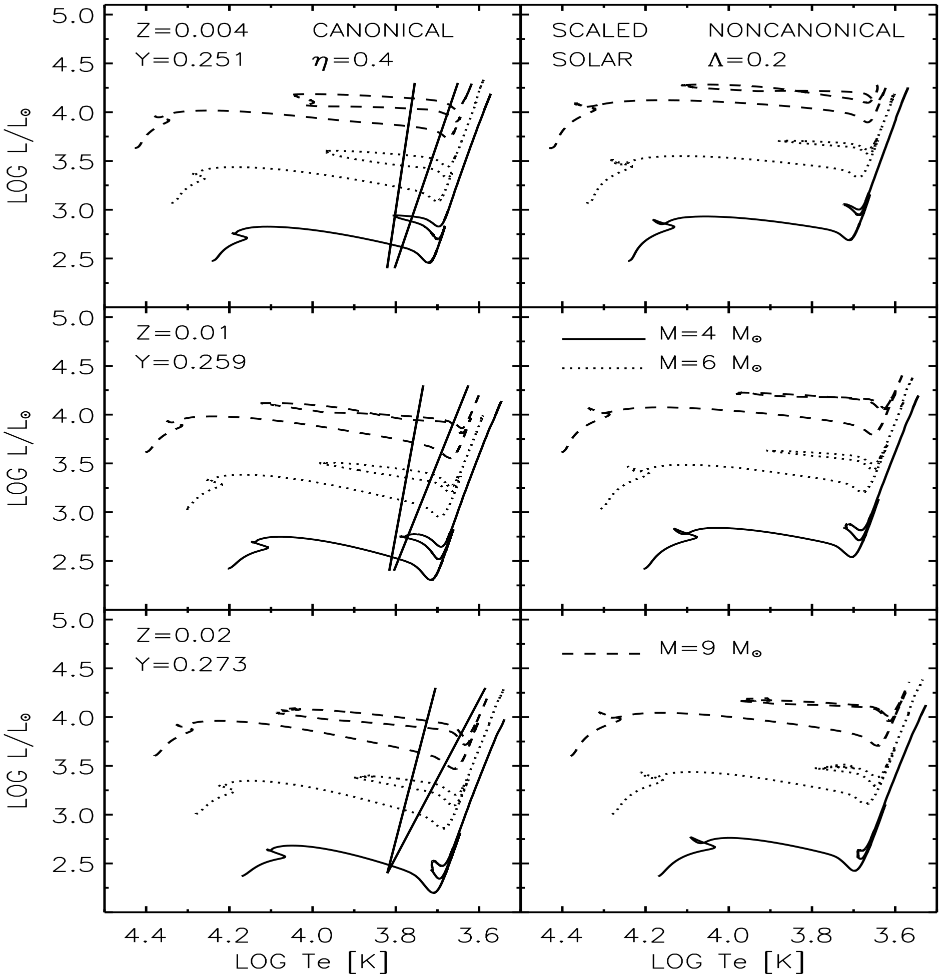

Fig. 1. H-R Diagram for intermediate-mass structures with different initial mass values constructed by accounting for a mass loss rate *a la* Reimers with a free parameter η = 0.4. The evolutionary models plotted in the left panels neglect the convective core overshooting (Canonical), while those ones in the right panel account for this mechanism (Noncanonical, Λ_c = 0.2). Current models have been constructed (Pietrinferni et al. 2004,2006; see also `http://www.te.astro.it/BASTI/index.php`) by adopting scaled solar chemical abundances and heavy element abundances typical of the SMC (Z=0.004, top), the LMC (Z=0.01, middle), and the Galaxy (Z=0.02, bottom) intermediate-age stellar populations (Luck et al. 1998). Vertical solid lines plotted in the left panel display the predicted instability strips for fundamental Cepheids provided by Bono et al. (2000a) by adopting chemical compositions similar to evolutionary models.

Color-Magnitude Diagrams and Luminosity Functions of NGC1866, a LMC intermediate-age cluster, reached opposite conclusions in favor (Barmina et al. 2002) and against (Testa et al. 1999; Brocato et al. 2003) the occurrence of mild convective core overshooting. The need for a mild overshooting was also suggested by Keller et al. (2001) who investigated several young clusters in the LMC and in the Small Magellanic Cloud (SMC). More recently, it has also been suggested by Cordier et al. (2002) that the degree of overshooting might also depend on the metal abundance, namely it increases when metal abundance decreases. Left and right panels of Fig. 1 show the comparison between two different theoretical frameworks for intermediate-mass stars (Pietrinferni et al. 2004,2006)[1]. Evolutionary models have been constructed by adopting different chemical compositions, but the same initial stellar masses, and a mass loss rate *a la* Reimers (1975), i.e., $dM/dt = -4 \times 10^{-13}\eta L/gR$, where the symbols have their usual meaning and $\eta = 0.4$ is a free parameter empirically calibrated on cluster low-mass stars. Evolutionary tracks have been constructed either neglecting (Canonical, left) or including the convective core overshooting (Noncanonical, right) according to the formalism suggested by Chiosi et al. (1992 and references therein), with $\Lambda = 0.2H_p$, where H_p is the pressure scale height (see e.g., Cassisi 2004). Data plotted in this figure clearly display the substantial dependence of the blue loop on the adopted physical assumptions (see Bono et al. 2000b, and references therein). In particular, the extension in temperature of the blue loop depends on the input physics (opacity, equation of state), chemical composition, efficiency of mixing, rotation.

ii) **Rotation** — Evolutionary models constructed by accounting for the effects of rotation predict an enhancement in the surface abundance of both Helium and Nitrogen (Meynet & Maeder 2000). It has also been suggested that rotation might account for the significant changes in surface chemical compositions observed in Galactic and Magellanic supergiants (Korn et al. 2005). Moreover, recent theoretical (Maeder & Meynet 2002) and empirical (Venn 1999) investigations indicate that the efficiency of such a mechanism might depend on the initial metal abundance, i.e., it increases when metal abundance decreases.

iii) **Radiative opacity** — A new set of radiative opacities has been recently computed by the Opacity Project (Badnell et al. 2005). The difference between old and new opacities is at most of the order of 5-10% across the Z-bump ($T \approx 250,000$ K). To account for the mass discrepancy the increase in the opacity should be almost a factor of two. This indicates that the adopted radiative opacities have a marginal impact on the mass discrepancy problem.

iv) **Mass Loss** — Evolutionary models accounting for the mass loss, during Hydrogen and Helium burning phases, by means of several semi-empirical relations (Reimers 1975; Nieuwenhuijzen & de Jager 1990) do not solve the Cepheid mass discrepancy problem: plausible values for the free parameter η give mass loss rates that are too small. This is not surprising, since current semi-empirical relations are only based on scaling arguments and they are not rooted on a robust physical basis (Schroeder & Cuntz, 2005). In order to provide a more quantitative estimate the evolutionary tracks plotted in Fig. 1 present at the blue tip, i.e., the hottest point along the blue loop, a decrease in the total mass at most of the order of 1%. The difference between more metal-poor and solar metallicity structures is marginal. Plausible increases in the free parameter η decrease the actual mass of Cepheids by at most a few percent.

In passing we note that different physical assumptions concerning the quoted mechanisms affect the Mass-Luminosity (ML) relation predicted by evolutionary models, and in turn pulsation predictions. Pulsation models assume a ML relation to properly anchor the envelope structure, since they typically neglect the innermost regions.

3. Cepheid Mass Discrepancy: Observations

In spite of an ongoing paramount observational and theoretical effort we still lack robust quantitative estimates of the different physical mechanisms affecting the ML relation of intermediate-mass stars. A new compelling support to the Cepheid mass discrepancy problem was recently provided by Evans et al. (2005b) for Polaris. This object pulsates in the first overtone mode and belongs to a triple system. Using the high-resolution channel of the Advanced Camera for Surveys on board of the Hubble Space Telescope they detected for the first time the close companion of Polaris. The combination of Hipparcos measurements

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[1] A few selected evolutionary tracks have been specifically computed by S. Cassisi for this project.

of the instantaneous proper motion with long-term measurements and its radial-velocity orbit (Kamper 1996; Wielen et al. 2000) provided the first purely dynamical mass ever obtained for a Cepheid, i.e., $M = 4.3 \pm 1.1 M_{\odot}$. Evolutionary mass estimates assuming $d = 132 \pm 9$ pc; metal and Helium abundance by mass Z=0.02, Y=0.273 (Usenko et al. 2005); and $m_v = 1.98$ mag range from $M = 5.5 \pm 0.9\, M_{\odot}$ to $M = 6.0 \pm 0.9\, M_{\odot}$ using evolutionary models including/neglecting a mild convective core overshooting.
On the other hand, the pulsation mass of Polaris based on the predicted mass-dependent Period-Luminosity-Color (PLC) relation (see Table 2 in Caputo et al. 2005) gives a mass $M = 5.0 \pm 0.8\, M_{\odot}$. The use of the Period-Radius-Mass relation for First Overtone Cepheids provided by Bono et al. (2001b) and the Polaris radius ($R = 46 \pm 3 R_{\odot}$) estimated by Nordgren et al. (2000) give $M = 4.9 \pm 0.7\, M_{\odot}$. Taken at face value, the difference between the different mass estimates for the closest Cepheid is larger than 25%.

Moreover and even more importantly, a large circumstellar envelope (CSE) around l Car has been recently detected by Kervella et al. (2006), using mid-infrared N-band data collected with MIDI available at VLTI. This is a long-period Galactic Cepheid and according to the quoted authors the CSE might be the aftermath of a significant mass loss rate during previous evolutionary phases. It is worth mentioning that the size of the CSE peaks around $8 - 11 \mu$m and in this region exceeds the emission from the star, but no mid-IR excess was detected in their N-band spectrum. Robust detections of mid-IR excesses, based on IRAS data, are only available for three Cepheids (RS Pup [Deasy 1988], X Pup, SU Cas [Welch & Duric 1986]). Unfortunately, it is not clear whether this paucity is caused by an observational bias due either to a limited sensitivity in current IR surveys or to the composition and temperature of the CSE. A plausible working hypothesis suggested by Kervella et al. (2005) to account for the lack of mid-IR excess in l Car is that the CSE has a cold temperature. This would imply that the excess might show up at longer wavelengths. It is worth mentioning that Merand et al. (2006)[2] using the same technique adopted by Kervella et al. detected a CSE envelope also around Polaris and δ Cephei. The different pulsation properties of these stars indicates, according to the quoted authors, that the occurrence of envelopes around Cepheids is a typical phenomenon.

Current empirical estimates of mass-loss rates based on infrared (IRAS) and ultraviolet (IUE spectra) emissions for Galactic Cepheids suggest mass-loss rates ranging from 10^{-10} to 10^{-7} Myr^{-1} (Deasy 1988), but the upper limit only applies to a few objects. Estimates based on VLA observations (Welch & Duric 1988) and on resonance absorption line profiles (Rodrigues & Bohm-Vitense 1992) provide similar upper limits. In this context it is worth mentioning, that He burning lifetimes for a 5 $M_{\odot}$ Cepheid at solar chemical composition is of the order of 20 Myr, while for a 11 $M_{\odot}$ Cepheid it is 2.5 Myr. Thus supporting a possible dependence of the mass loss efficiency on the pulsation period.

4. Final remarks

The mass loss might be the key culprit among the physical mechanisms suggested to explain the mass discrepancy problem. This working hypothesis is further supported by the following circumstantial evidence. The semi-empirical mass loss relation derived by Reimers (1975) underestimates the mass loss along the red giant branch of low-mass stars (Alard et al. 2001; Origlia et al. 2002; Serenelli & Weiss 2005). Plausible increases in the values of the free parameter (η) do not account for the entire range in stellar mass of Horizontal Branch (HB, central Helium burning) stars in globular clusters (Yong et al. 2000; Castellani et al. 2005). At present, it is not clear whether such a discrepancy in the actual mass of HB stars is caused either by an intrinsic phenomenon (chromospheric activity, rotation) or by binarity. This evidence together with the Cepheid mass discrepancy suggests that current semi-empirical mass-loss rates appear to

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[2] For more details see the ESO press release http://www.eso.org/outreach/press-rel/pr-2006/pr-09-06.html

underestimate the efficiency of such a mechanism.

We would also like to mention the long-standing problem concerning the heavy metal abundances of Galactic and Magellanic Cepheids. Accurate iron abundances based on high-resolution, high signal to noise spectra indicate that individual abundances among Galactic and Magellanic Cepheids present an intrinsic spread. This suggests that the use of mean iron abundances for different Cepheid samples might introduce systematic errors in the estimate of individual Cepheid masses and absolute distances (Romaniello et al. this volume). Moreover, we still lack accurate estimates of α-element abundances in Cepheids. These data are crucial to estimate their global metallicity (Salaris, Chieffi & Straniero 1993), i.e., the heavy element abundances adopted in theoretical predictions. These elements are significant opacity sources, thus affecting evolutionary and pulsation predictions (see section 3).

Current empirical estimates for Galactic stars suggest a steady decrease in α-element abundances when moving from metal-poor to metal-rich structures (Gratton, Sneden, & Carretta 2004). However, empirical estimates for Magellanic Clouds suggest that Oxygen, Calcium, and Titanium among intermediate-age and young supergiant stars appear to be underabundant and present a flat distribution when compared with Galactic stars (see Figures 15.2 and 15.3 in Hill 2004). On the other hand, α-element abundances based on high-resolution spectra of Magellanic Cepheids (Luck et al. 1998) are, within the uncertainties, quite similar to the Galactic ones (Fry & Carney 1997). It goes without saying that current abundance estimates are still hampered by small number statistics (Mottini et al. these proceedings).

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