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An updated theoretical scenario for Anomalous Cepheid pulsating stars

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Abstract. We have computed new pulsation models to supply an updated theoretical scenario for Anomalous Cepheids (ACs) variable stars These models span a large range of intrinsic parameters, such as luminosity, mass and effective temperature, and two values of metallicity, namely Z=0.0001, 0.0004. The results of these computations show that the properties of ACs are almost unchanged when Z increases from 0.0001 to 0.0004. Fundamental relations connecting pulsational (period, amplitude) to stellar parameters are derived. The application to observational samples represents a promising tool for evaluating the intrinsic properties and the distance of ACs. As a first preliminary test of the models, in this work we compare the results with the observations of ACs in the Dwarf Spheroidal Galaxy Carina, and suggest a method to determine simultaneously their mass and pulsation mode.

Key words. Variables stars – He burning stars – Anomalous Cepheids

1. Introduction

ACs are among the least explored classes of pulsating variables stars. However, they are believed to play a crucial role as distance indicators, being intrinsically brighter than RR Lyrae stars, for each fixed period. These stars are rare in globular clusters, but they have been observed in all the dwarf galaxies in which they have been searched for. They are currently interpreted as metal poor helium burning stars, with masses in the range $\sim 1.3 - 2$ $M_\odot$ (Bono et al 1997, hereinafter B97).

As reviewed by Caputo (1998), for low metal abundances ($Z \leq 0.0004$) and relatively young ages ($t \leq 4$ Gyr) the effective temperature of Horizontal branch (HB) stars reaches a minimum ($\log T_e \sim 3.76$) for a mass of about 1.0-1.2 $M_\odot$, while if the mass increases above this value, the luminosity and the effective temperature start increasing, forming the so called "HB turnover". ACs variables belong to the post-turnover portion of the ZAHB (Caputo 1998) which crosses the instability strip.

Their origin is still debated and the most widely accepted interpretations are: (1) they are young (≤ 5 Gyr) single stars due to recent star formation; (2) they formed from mass transfer in binary systems as old as the other stars in the same stellar system.

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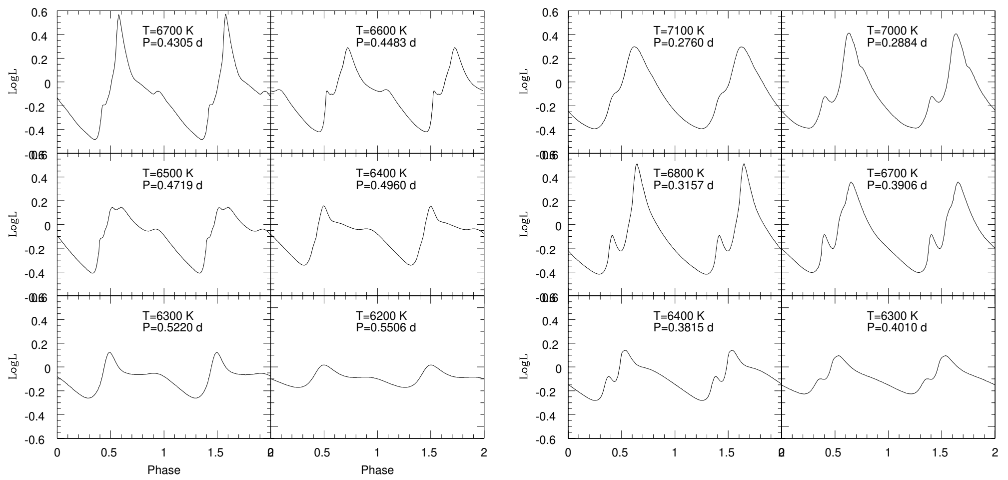

Fig. 1. Lightcurves of fundamental (left panel) and first overtone (right panel) models with M=1.6 $M_{\odot}$, logL/L$_{\odot}$ = 1.88 and Z=0.0001. In each panel the model effective temperature and period are reported.

From the observational point of view, the pulsational properties of ACs have been analysed by Nemec, Nemec & Lutz (1994, hereinafter NNL), who provided empirical PL relations, in the B and V bands, for fundamental (F) and first overtone (FO) pulsational modes. According to NNL, the discrimination of the pulsation mode is not simple, because in the Period-Amplitude and in the Color-Amplitude planes ACs do not show, at variance with RR Lyrae stars, a real distinction between F and FO modes.

On the other hand, using theoretical pulsation models and evolutionary tracks, B97 constrained the blue absolute magnitude and the period of such high-mass metal-poor pulsators, predicting a minimum mass of these stars around $\sim$ 1.3 M$_{\odot}$ for Z = 0.0001 and $\sim$ 1.8 M$_{\odot}$ for Z = 0.0004. According to the position in the PL and PA planes, B97 confirmed that observed ACs are a mix of F and FO pulsators and derived two distinct non parallel PL relations in the B band for the two pulsation modes. These relations were significantly different from the empirical parallel ones derived by NNL, whereas they better conformed with the analysis by Nemec et al. (1988).

To supply a new theoretical scenario, here we present nonlinear pulsational models that include updated input physics and cover a large range of stellar parameters.

2. The pulsational models

The physical and numerical assumptions adopted in the pulsational models are the same ones already discussed in a series of previous papers (see Bono, Castellani, Marconi 2000 and references therein), but differently from B97 we have used updated opacity tables (Iglesias & Rogers 1996; Alexander & Ferguson 1994) and a wide range of stellar parameters ($1.3 \leq M/M_{\odot} \leq 2.2$, $1.82 \leq logL/L_{\odot} \leq 2.28$ and $Z = 0.0001, 0.0004$). For each mass, the luminosity levels have been selected, taking into account the evolutionary predictions by Castellani & Degl'Innocenti (1995).

For each selected mass and luminosity we have explored an extensive range of effective temperatures ($5900 \leq T_e \leq 7200$) to derive the topology of the instability strip for both Z = 0.0001 and 0.0004. The results show that the metallicity effect is very small. But nonlinear

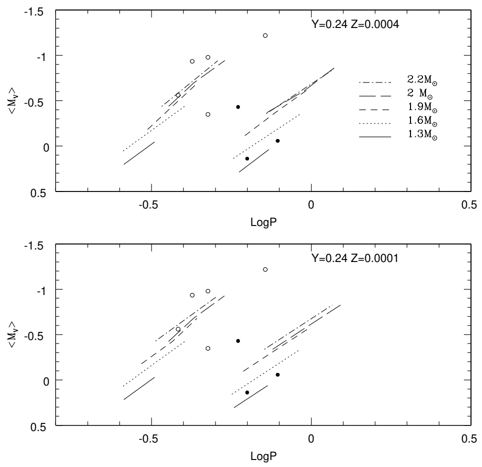

Fig. 2. Comparison bewteen model predictions and Carina AC pulsators in theM_V-logP plane. Solid line are the predicted boundaries of the instability strip, whereas symbols represent F (filled) and FO (empty) pulsators. We have assumed for Carina a distance modulus μ_0 = 20.10 ± 0.12 and a reddening E(B-V) = 0.03.

pulsation models also provide us with the variations of relevant stellar properties (luminosity, radius, radial velocity, etc.) along the pulsation cycle. In particular the derived lightcurves for fundamental and first overtone models (see Fig. 1 and 2) show a variety of morphologies, preventing a clear discrimination of the pulsation mode.

Finally, in analogy with the RR Lyrae pulsation relation (van Albada & Baker 1971), linear regression through the AC models allows us to derive relations connecting the pulsation period of both F and FO modes to the intrinsic parameters luminosity, mass and effective temperature (Marconi et al. 2003 in preparation).

3. From theoretical to observational quantities

Using the atmosphere models provided by Castelli, Gratton & Kurucz (1997), we have transformed the instability strip boundaries and bolometric lightcurves into the UBVRIJK observational bands to compare the theoretical results with observations. The natural outcome of the pulsation equations in the observational plane is a mass-dependent Period-Magnitude-Color (PLC) relation in which the period is correlated with the pulsator absolute magnitude and color, for any given mass. PLC relations have been derived both for static and mean magnitudes and colors. Moreover, neglecting the color dependence, we can also derive the UBVRIJK Period-Magnitude (PL) relations. However, the intrinsic dispersion of these PL relations is very high and in the optical bands the slope is very small for both pulsation modes. Such an occurrence clearly points out that these PL relations are not useful to derive accurate distances. Mass dependent Period-Magnitude-Amplitude (PLA) relations for the fundamental mode have also been derived (Marconi et al. 2003, in preparation).

3.1. Comparison with observation

For a preliminary test of model predictions, we show in Fig. 3 the comparison between ACs belonging to the Dwarf Spheroidal galaxy Carina (Dall'Ora et al. 2003) and the theoretical instability strip in the M_V-logP plane. We have assumed a reddening $E(B-V) = 0.03$ and a distance modulus $\mu_0 = 20.10 \pm 0.12$ (the latter derived from RR Lyrae stars, see Dall'Ora et al. 2003). The general agreement is satisfactory, since almost all pulsators fall within the theoretical boundaries, but there are three super-luminous ACs that could have mass > 2.2 M/$M_{\odot}$.

The available dataset for Carina include periods, magnitudes and amplitudes in the B and V bands. Therefore, we can use the mass dependent BV PLC relations, of both F and FO pulsators, to determine the mass for each variable, once μ_0 and E(B-V) have been assumed. At the same time we can use the mass dependent PLA relations to derive the mass, by assuming that all stars are F pulsators. In this way, we decide that a star is a F pulsator if the mass values derived by means of the PLC and PLA are consistent. Applying this method we find that only three ACs in Carina, represented with filled symbols in Fig. 3, are F pulsators.

4. Conclusions

We have presented new nonlinear pulsation models of Anomalous Cepheids, covering a wide range of mass and luminosity and two metal abundances. The theoretical instability strip and light curves have been derived, as well as relations connecting the pulsational properties (period, amplitude) to the intrinsic stellar parameters.

The application of mass dependent PLC and PLA relations is a promising method to evaluate:

- the mass spread of ACs belonging to the same system;
- absolute mass values if we know reddening and distance modulus;
- mass and distance modulus if a multiwavelenght dataset is available;
- the pulsation mode from the comparison between mass obtained from PLC and PLA relations.

As a preliminary test of the predictive capabilities of pulsation models, we have compared model results with the observations for ACs in Carina. A satisfactory agreement has been found as far as the instability strip topology is concerned. By comparing the masses obtained from PLC and PLA relations we derive that only three ACs in Carina are F pulsators.

In the future we plan to extend this kind of analysis to other samples of ACs in the recent literature and to concentrate on the distance scale problem.

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