Theoretical models for Bump Cepheids

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ABSTRACT

We present the results of a theoretical investigation aimed at testing whether full amplitude, nonlinear, convective models account for the I-band light curves of Bump Cepheids in the Large Magellanic Cloud (LMC). We selected two objects from the OGLE sample that show a well-defined bump along the decreasing (short-period) and the rising (long-period) branch respectively. We find that current models do reproduce the luminosity variation over the entire pulsation cycle if the adopted stellar mass is roughly 15% smaller than predicted by evolutionary models that neglect both mass loss and convective core overshooting. Moreover, we find that the fit to the light curve of the long-period Cepheid located close to the cool edge of the instability strip requires an increase in the mixing length from 1.5 to 1.8 Hp. This suggests an increase in the efficiency of the convective transport when moving toward cooler effective temperatures. Current pulsation calculations supply a LMC distance modulus ranging from 18.48 to 18.58 mag.

Subject headings: Cepheids – Magellanic Clouds – stars: distances – stars: evolution – stars: oscillations
1. Introduction

Classical Cepheids are key objects for estimating stellar distances and for calibrating secondary distance indicators necessary to evaluate the Hubble constant (Ferrarese et al. 2000; Saha et al. 1999). From a theoretical point of view Cepheids can also be regarded as fundamental physical laboratories to assess both the accuracy of the input physics (Simon 1989) and the reliability of the physical assumptions adopted in modeling radial pulsations (Bono, Marconi, & Stellingwerf 1999, hereinafter BMS). Thus, any new test concerning the accuracy of theoretical predictions appears of paramount relevance. Moreover, this effort is mandatory to improve our confidence on Cepheids as a robust rung of the cosmic distance ladder and to disentangle relevant open questions such as the dependence of the Cepheid distance scale either on metal content (Bono et al. 1999; Bono, Castellani & Marconi 2000a; Caputo et al. 2000; Laney 2000; Storm et al. 2000) or on blending (Mochejska et al. 2000).

In this context, one has to remind that the current theoretical framework based on nonlinear, convective pulsation models, is facing with a fundamental problem, i.e. the calibration of the turbulent convection (TC) model adopted to account for the coupling between pulsation and convection (Castor 1968; Stellingwerf 1982). The approach originally suggested by Bono & Stellingwerf (1993, 1994, hereinafter BS) relies on the combination of leading physical arguments and empirical constraints on the topology of the RR Lyrae instability strip in Galactic globulars. Such a theoretical scenario accounts for some relevant properties of radial variables in the Cepheid instability strip (Bono et al. 1997a,b; BMS; Bono, Caputo, & Marconi 2001). However, the predicted RR Lyrae light curves close to the low-temperature instability edge are somehow at variance with empirical data (Kovacs & Kanbur 1998). This appears as a disturbing evidence, since empirical light curves supply tighter constraints on the accuracy of theoretical predictions than mean magnitudes and/or pulsational periods.

In a recent paper (Bono, Castellani, & Marconi 2000b, hereinafter BCM) we have approached such a problem and successfully reproduced the luminosity variation over a full pulsation cycle of the field, first overtone RR Lyrae U Com. At the same time, we also constrained the adopted TC model, and indeed in that paper we found that the Bump located just before the luminosity maximum can be reproduced by nonlinear models only by assuming a vanishing overshooting efficiency at the boundaries of the convective unstable regions. To explore the general reliability of this finding, we undertook a further investigation aimed at checking whether this TC model can also account for Cepheid light curves. To this purpose we selected two Bump Cepheids from the OGLE database (Udalski et al. 1999) of the LMC, with the Bump either along the decreasing (OGLE194103, short-period) or along the rising (OGLE56087, long-period) branch of the light curve. Table
lists the empirical data of the selected objects.

The reason for this choice follows from the evidence that both the amplitude and the phase of the Bump are crucial features to nail down the predicting power of theoretical models. Moreover, both stars present quite similar apparent magnitudes, and therefore the period difference suggests that the short-period Cepheid is located close to the blue (hot) edge, while the long-period one close to the red (cool) edge of the instability strip. When moving from hotter to cooler effective temperatures the thickness of the convective unstable region, and in turn the efficiency of the convective transport increases. This means that the envelopes of the two Bump Cepheids present substantially different physical structures. Finally, the intimate nature of the Hertzsprung progression is still controversial (Bono, Marconi, & Stellingwerf 2000c), and a reliable fit to empirical light curves can supply new insights into the physical mechanisms that govern the occurrence of this phenomenon.

2. Theoretical best fit models

To fit the empirical light curve of U Com, BCM computed several iso-period sequences of nonlinear models at fixed chemical composition. For each given assumption on the stellar mass, the iso-period sequence was constructed by changing a single input parameter, namely the effective temperature, since the luminosity was constrained by the observed period. However, the fit to Bump Cepheid light curves will be performed by adopting a different and stronger constraint. At first we undertake the fit of one of the two variables according to suitable Mass-Luminosity (ML) relations based either on canonical or on mild overshooting evolutionary models (BMS; Girardi et al. 2000), both neglecting mass-loss. This approach obviously decreases the degrees of freedom of the problem. In fact, for each selected luminosity we adopt the stellar mass as given by the ML relation, thus only one effective temperature accounts for the constraint on the observed period. If and when the best fit of the light curve of the former Cepheid is accomplished, we derive the stellar parameters (L, M, Te), and in turn an estimate of the LMC distance modulus. According to this result, the fit to the light curve of the latter object will be accomplished under the even stronger constraint to adopt the same ML relation and the same LMC distance modulus already derived for the former object.

For both stars we adopted a chemical composition typical of LMC Cepheids (Y=0.25, Z=0.008). We considered at first the short-period Cepheid OGLE194103 and constructed various iso-period (P = 8.7d) sequences at different luminosity levels by adopting the canonical ML relation used in previous papers (BMS; Bono et al. 1999; Bono et al. 2000d). A glance at these iso-period sequences disclosed that the shape of the light curve is
mainly governed by the stellar parameters $L$, $M$, and $T_e$, whereas the luminosity amplitude sensitively depends on the adopted mixing length parameter. However, we found that under the quoted assumptions theoretical models appear unable to reasonably fit observational constraints. Several numerical experiments were performed to test the dependence of both pulsation amplitude and shape of the light curve on the free parameters adopted in the TC model (BS), but the shape of the predicted light curve was still at variance with the observed one.

Therefore we decided to test models with a noncanonical ML relation. To mimic the luminosity predicted by evolutionary models that account for mild convective core overshooting (Girardi et al. 2000), we increased the luminosity of canonical models, for each stellar mass, by 0.25 dex (Chiosi et al. 1993). We repeated once again the quoted experiments and now we found that our basic TC model gives a reasonable fit to the OGLE194103 light curve for the couple of parameters $\log \frac{L}{L_\odot} = 3.55$ ($\frac{M}{M_\odot} = 5.57$), and $T_e = 5660$ K, and our canonical mixing length value i.e. $l = 1.5$ Hp (BS94). Note that the value of the effective temperature refers to the static linear model. The temperature variation along the pulsation cycle of the best fit nonlinear model is equal to 850 K. The agreement between theory and observations appears quite satisfactory over the entire pulsation cycle (see Fig. 1) and accounts for the phase and the amplitude of the Bump.

The same approach has been applied to fit the light curve of the long-period Bump Cepheid (OGLE56087, $P=13.6$ d). In particular, we adopted the same ML relation and the same distance modulus (DM=18.48) we found for the short-period Cepheid. The bottom panel of Fig. 1 does show that a remarkable agreement between theory and observations is obtained by adopting $\log \frac{L}{L_\odot} = 3.61$ ($\frac{M}{M_\odot} = 5.70$), and $T_e = 5160$ K, but now we were forced to assume $l = 1.8$ Hp. In fact, the model constructed by adopting $l = 1.5$ Hp (dotted line) presents the same secondary features but the luminosity amplitude is systematically larger, i.e. $\Delta I = 0.88$ against the observed 0.51 mag. A glance at the data plotted in the bottom panel clearly shows the accuracy with which the best fit model does reproduce the well-defined dip of the observed light curve at $\phi \approx 0.4$, soon after the Bump secondary maximum. Present computations thus suggest that the mixing length parameter $l$ becomes larger when a star becomes cooler, and the convective unstable region becomes thicker, i.e. the efficiency of the convection increases more than predicted by the assumption of a constant mixing length.

The use of a slightly higher metal abundance $Z=0.01$, according to recent empirical evidence (Luck et al. 2000) that LMC Cepheids seem to cover a wide metallicity range ($0.006 \leq Z \leq 0.013$), does not improve the fit. The same outcome applies to plausible changes in the He content, and indeed a change from 0.25 to 0.26 does affect neither the
shape of the light curve nor the luminosity amplitude.

To investigate the robustness of current best fit solutions we also explored whether plausible changes in the input parameters still supply a reasonable fit to the observed light curves. The top panel of Fig. 2 displays that a nonlinear model constructed by adopting $\log L/L_\odot = 3.586$ ($M/M_\odot = 5.7$), $T_e = 5780$ K, and a mixing length $l = 1.5$ Hp properly fits the luminosity variation of the short-period Cepheid (OGLE194103). This finding implies a LMC distance modulus of 18.58 mag and the fit to the long-period Cepheid (OGLE56087) now requires: $\log L/L_\odot = 3.65$ ($M/M_\odot = 5.95$), $T_e = 5225$ K, and a mixing length $l = 1.85$ Hp (see Fig. 2). No agreement was found outside this range of stellar luminosities.

As a whole, previous numerical experiments support the evidence that the pulsational LMC distance modulus can be safely bracketed between 18.48 and 18.58 mag. Moreover, a decrease in the evolutionary mass between canonical and best fit models of the order of 15% is, in any case, required. Finally, the variation of a single free parameter, the mixing length, allows us to account for the shape of empirical Bump Cepheid light curves across the instability strip.

3. Discussion

According to the results given in the previous section, our pulsational computations require a larger mixing length value when the star becomes cooler. We note that this is not a very surprising result, since a mixing length roughly equal to 1.9 Hp is also required by the evolutionary models that best fit the red giant branch of Galactic globular clusters (Castellani 1999). This notwithstanding, as already discussed in BCM, a substantial variation in the mixing length parameter causes a sizable change in the efficiency of the convective transport across the driving regions, and in turn in the temperature width of the instability strip. To estimate the dependence of the instability edges on $l$ we constructed new models with the stellar mass of the long-period best fit model. We find that when moving from $l = 1.5$ to 1.8 Hp the temperature width decreases from 1100 K to 800 K. This change is mainly due to a shift toward hotter effective temperatures of the red boundary and could be marginally at odds with empirical estimates. In fact, estimates by Pel & Lub (1978, see their Fig. 3) do suggest that in this period range the strip is slightly larger than 800 K. Unfortunately, we are not aware of any recent empirical estimates that can allow us to supply firm constraints on this observable.

The pulsational scenario we are dealing with accounts for the empirical light curves of the selected Bump Cepheids provided that their stellar masses are 15% smaller than
predicted by canonical evolutionary models. This theoretical evidence, if taken at face value, could be due either to the occurrence of mass-loss among intermediate-mass stars, as originally suggested by Cox (1980), or to convective core overshooting, or both of them. Unfortunately, the pulsational approach adopted in this investigation does not allow us to discriminate between the two different hypothesis. Current results supply some support to the evidence recently brought out by Beaulieu et al. (2001) concerning the \textit{discrepancy} between evolutionary and pulsational masses among Magellanic Cepheids. On the basis of a new approach they found that evolutionary masses are up to $\Delta \log M/M_\odot = 0.1$ larger than pulsational ones. On the other hand, we found that for the two selected Bump Cepheids the discrepancy is of the order of 0.07 and 0.08 dex for the short and the long-period respectively.

Note that Bono et al. (2001) performed a detailed analysis of both pulsation and evolutionary masses of Galactic Cepheids for which are available both accurate empirical estimates of mean radii, distances, and individual reddenings. Interestingly enough, they found that pulsational masses are approximately 10% smaller than evolutionary ones. A similar result was found by Wood, Arnold, & Sebo (1997) by fitting the light curve of a LMC Bump Cepheid (HV905). However, they found that the luminosity of this object was substantially higher than predicted by ML relations based either on canonical or on mild overshooting evolutionary models.

To assess whether our best fit models support either the occurrence of a resonance between fundamental and second overtone or the Christy’s echo mechanism (Bono et al. 2000c, and references therein) we finally constructed two new models by adopting the same input parameters of the models plotted in Fig. 1, but by perturbing the linear second overtone radial eigenfunctions. We find that both of them, after a transient phase lasting $\approx 200$ (long-period) and $\approx 700$ (short-period) cycles, undergo a mode switch from the second to the fundamental mode. The period ratios between second overtone and fundamental period are $P_2/P_0(OGLE194103)=0.523-0.528$ and $P_2/P_0(OGLE56087)=0.495-0.503$ respectively. For each object the former value was derived by adopting linear $P_2$ and $P_0$ periods, while the latter one with linear $P_2$ and nonlinear $P_0$ periods. The values of these ratios still fall in the so-called \textit{resonance region} (Simon & Schmidt 1976). However, we note that the physical structure of the best fit models does not show any nodal line (Bono et al. 1997c) along the pulsation cycle. This finding together with the good agreement between theoretical predictions and empirical data further strengthens the plausibility that the Bumps are triggered by the Christy’s echo mechanism.

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3 Discussion

### Table 1. Empirical data\(^a\)

<table>
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<th>OGLE194103</th>
<th>OGLE56087</th>
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<td>$05^h00^m48.3^s$</td>
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<td>$-69^\circ31^\prime54.8^\prime$</td>
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<td>Period (d)</td>
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<tr>
<td>$m_I$ (mag)</td>
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<td>13.68 ± 0.01</td>
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<td>$\Delta_V$ (mag)</td>
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<tr>
<td>$\Delta_I$ (mag)</td>
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<td>0.51</td>
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\(^a\) Empirical data for the two selected Bump Cepheids according to Udalski et al. (1999).
Fig. 1.— Comparison between predicted (solid line) and observed (open circles) I-band light curves for the short-period (OGLE194103, top panel) and the long-period (OGLE56087, bottom panel) Bump Cepheid. The input parameters of the best fit model are labeled. By assuming a color excess equal to $E(B-V)=0.1$ mag, the inferred true distance modulus for the two objects is 18.48 mag. The dotted line plotted in the bottom panel shows the light curve of a model constructed by adopting the same input parameters of the best fit model but with a mixing length $l=1.5$ Hp. See text for more details.

Fig. 2.— Same as Fig. 1, but the pulsation models were constructed by adopting the labeled input parameters. By assuming a color excess equal to $E(B-V)=0.1$ mag, the inferred true distance modulus for the two objects is 18.58 mag.