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Metallicity effects on distances based on double-mode Cepheids

G. Kovács

Konkoly Observatory, Budapest, Hungary e-mail: kovacs@konkoly.hu

Abstract. We test the effect of systematic metallicity difference between the two types of double-mode Cepheids in the Magellanic Clouds. We show that lowering the metallicity for the short-periodic Cepheids leaves the distances at their canonical values and, at the same time, improves the agreement between the observed and model periods.

Key words. Stars: evolution, fundamental parameters, abundances, distances, variables: Cepheids – Galaxies: Magellanic Clouds

1. Introduction

Double-mode variables are important in our understanding of the simplest form of steady multimode pulsations and they are also the prime targets in the simplest application of asteroseismology. In this latter aspect we investigated the use of the observed periods and color in deriving distances to various classes of variables (RR Lyrae stars in globular clusters: Kovács & Walker 1999; RR Lyrae stars in the Large Magellanic Cloud [LMC]: Kovács 2000b; beat [i.e., double-mode] Cepheids in the Small Magellanic Cloud [SMC]: Kovács 2000a [hereafter K00a]; preliminary study of the LMC beat Cepheids: Kovács 2002). In these works we routinely assumed that the double-mode variables share the same common metallicity [Fe/H] as the rest of the given population of the cluster or galaxy. This is a crucial assumption, because the derived mass and luminosity (and therefore the distance) depend sensitively on [Fe/H].

The discovery of large number of first overtone Cepheids in the Magellanic Clouds (MCs) by the microlensing projects drew the attention to the evolutionary status of these objects. The problem with these stars is that they do not blue-loop into the instability strip as required by canonical Cepheid evolution scenarii, based mostly on longevity arguments at these looping periods of evolution. Recently, Cordier et al. (2003) concluded that, at least in the SMC, the only way to produce extended blue-loops at the expected luminosity level is to lower [Fe/H] by some 0.4 dex.

Beaulieu et al. (2001, hereafter B01) discussed the systematic discrepancy between the theoretical and observed periods in the SMC beat Cepheids. They concluded that lowering the metallicity may ease this discrepancy but never eliminate it completely. They also mention that the distance modulus derived from beat Cepheids by K00a may not be correct, because of the use of the ‘optimum period fit’ (as defined in that paper) instead of ‘exact period fit’.

Send offprint requests to: G. Kovács

In this paper we address the problem of the accurate period fit for the beat Cepheids in the MCs. We check the effect of a possible metallicity difference between the fundamental/first overtone (FU/FO) and first/second overtone (FO/SO) variables on the period fit and on the derived distance moduli.

2. Method and database

Our approach is basically identical with that of K00a. Briefly, we use the following set of relations to derive the mass M and luminosity L, e.g., for FU/FO variables:

$$P_0 = G_0(M, L, T_{\rm eff}, Z) \quad (1)$$

$$P_1 = G_1(M, L, T_{\rm eff}, Z) \quad (2)$$

$$\log T_{\rm eff} = H(V-I, \log g, Z) \quad (3)$$

Here the functions G_0 and G_1 are given in a tabulated form as the outputs of our linear non-adiabatic (LNA), fully radiative pulsation code (Buchler 1990). Function H is a simple linear relation when the appropriate parameter regime is fitted from the Castelli et al. (1997) stellar atmosphere models. The zero point is adjusted to the one derived from the infrared flux method by Blackwell & Lynas-Gray (1994).

Our LNA models contain 400 shells down to inner boundary, where $q_{\rm in} \equiv (R_{\rm in}/R_{\rm surf})(M_{\rm in}/M_{\rm surf}) = 0.05$. With this condition the innermost temperature was always greater that 2×10^6 K but less than $\sim 10^7$ K. All models have $X = 0.76$. With solar-type heavy element distribution, we computed 7 model sequences with $Z = 0.0003$, 0.001, 0.002, 0.003, 0.004, 0.008, 0.01. At each Z we have the following equidistand model grid:

$$(T^{\rm min}_{\rm eff}, \Delta T_{\rm eff}, N_{T_{\rm eff}}) = (5000.0, 100.0, 21)$$

$$(M^{\rm min}, \Delta M, N_{\rm M}) = (2.0, 0.25, 17)$$

$$(\log L^{\rm min}, \Delta \log L, N_{\rm L}) = (2.0, 0.1, 16)$$

Altogether we computed nearly 40000 models for the 7 metallicity values. For accurate period fits we employed quadratic interpolation among the above models. Tests have shown that the interpolated periods often approximated the model periods with an accuracy of $\sim 10^{-4}$ d.

Table 1. Average observed minus computed period ratio as a function of the envelope depth. FO/SO stars in the LMC are tested at $Z = 0.003$.

$q_{\rm in}$	0.20	0.10	0.05
$\Delta(P_2/P_1)$	+0.00333	+0.00053	+0.00001

The best matching (M, L) parameters are searched by minimizing the following expression:

$$D = [\Delta \log P_0]^2 + [\Delta \log P_1]^2 \ , \quad (4)$$

where the symbol Δ denotes the differences between the model and observed values. In cases when D had two minima, for the FO/SO variables, the solution with $M < 4.5$ was selected on evolutionary basis (by assuming that these stars are in the phase of second or third crossings).

We used the OGLE Cepheid database for the periods and intensity-averaged colors as published by Udalski et al. (1999) and Soszyński et al. (2000). We have 19 FU/FO and 57 FO/SO variables in the LMC. The corresponding figures for SMC are 23 and 70, respectively.

3. Results

First we test the probable cause of the discrepancy between the theoretical and observed periods found by B01. With the method described in Sect. 2, we compute average period ratio differences for the LMC FO/SO stars for model envelopes of various depth. As it is seen in Table 1, for shallow envelopes the period fit shows the same type of discrepancy as mentioned by B01. This discrepancy disappears for models with deep envelopes. From this test we conclude that the discrepancy found by B01 was caused most probably by the *shallowness* of their model envelopes. Next we check the dependence of the accuracy of the period fit on metallicity. Figs. 1 and 2 show this dependence for the LMC beat Cepheids. It is seen that if Z is near to its canonical value, the FO/SO stars show systematic differences

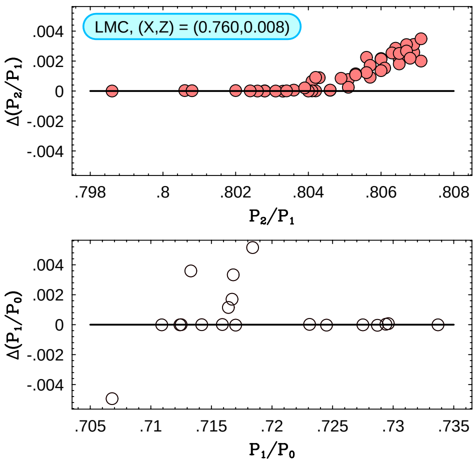

Fig. 1. Observed minus computed period ratios vs. observed period ratios for the LMC beat Cepheids. The chemical composition used in the models is shown in the upper panel. FO/SO and FU/FO variables are plotted in the upper and lower panels, respectively.

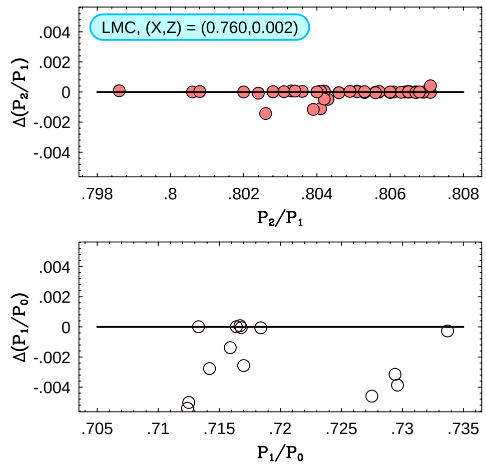

Fig. 2. As in Fig. 1 but for lower Z.

at higher period ratios, whereas the FU/FO stars, except for a few discrepant stars, show a good/exact fit. By lowering Z brings nearly all FO/SO stars in exact fit but destroys the previous good fit for most of the FU/FO stars. This result implies that the two groups of beat Cepheids might have different metallicities and that chemical inhomogeneties might exist even within the same group. This latter statement is in agreement with the evolutionary results, because stars of higher luminosity (i.e., FU/FO variables) are able to blue-loop both at high and low metallicities.

Assuming that variables within the same group have the same metallicity, we can study the effect of changing metallicity on the derived distance moduli. We see in Figs. 3 and 4 that the distance moduli derived from the FU/FO stars are much more sensitive to metallicity than those obtained from the FO/SO stars. These plots strongly suggest the existence of a systematic metallicity difference of $\sim$ 0.4 dex in both clouds between the two groups of beat Cepheids. Remarkably, at the metallicity regimes where the period fit is nearly exact, we obtain the same 'canoni-

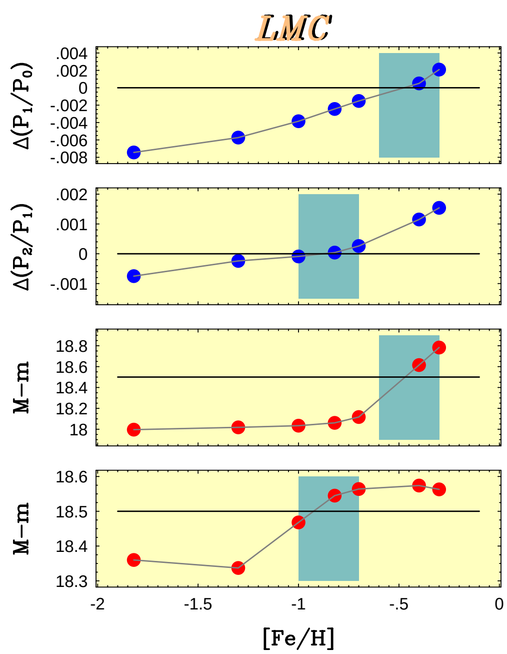

Fig. 3. Metallicity dependence of the average period ratio difference (observed minus computed) and the distance modulus. Results for FU/FO and FO/SO variables are shown, from the bottom, in the second and fourth and in the first and third panels, respectively. Horizontal lines in the lower two panels indicate the canonical value of 18.5 mag for the distance modulus. Shaded boxes mark the ±0.15 dex neighborhood of the exact overall period fit.

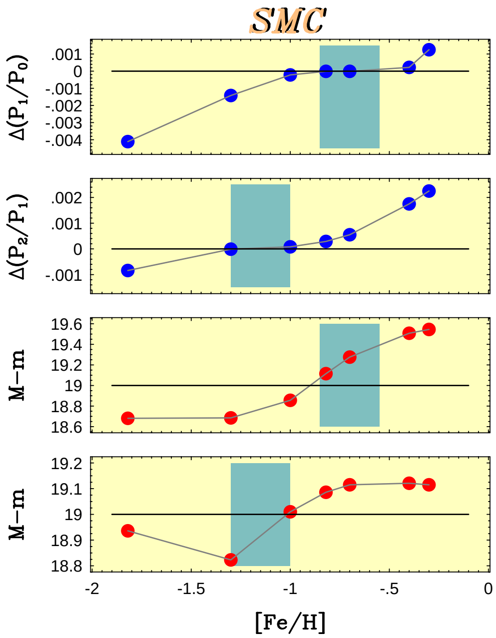

Fig. 4. As in Fig. 3 but for the SMC. The horizontal lines in the lower two panels indicate the canonical value of 19.0 mag for the distance modulus.

cal' distance moduli from both types of beat Cepheids.

4. Conclusions

We have shown that exact match can be achieved between the linear pulsational model periods and the observed ones if the 'canonical' metallicities of -0.4 and -0.7 are used for the FU/FO Cepheids in the LMC and SMC, respectively. On the other hand, FO/SO Cepheids can be fitted accurately only if their metallicities are lowered by some 0.4 dex relative to the above values. The derived distance moduli from the FO/SO Cepheids are rather insensitive to these changes and they yield the same 'canonical' values as the FU/FO Cepheids. These results are in agreement with those of Cordier et al. (2003) on the systematically lower metallicities of short-periodic Cepheids in the SMC.

We also note that Moskalik & Dziembowski (2005) analyzed two triple-mode Cepheids in the LMC. By searching for exact fit between the observed and model periods, they found that Z could not be lower than ~ 0.004, because otherwise not all the relevant modes would be excited. Here we only mention that for SC3 − 360128, Z cannot be greater than ~ 0.004 because then $T_{\rm eff}$ would be more than 400K lower than estimated from the observed color index. It is also important to remark that when matching the observed periods with the ones derived from the LNA models, one needs to observe a 'reasonable' error margin by which the periods can be fitted, because of the unknown difference between the LNA and nonlinear periods due to the lack of successful hydrodynamical modelling of FO/SO stars and, in particular, triple-mode ones.

Direct metallicity measurements (Mottini 2005) will be very important in confirming the above results and in yielding more accurate observational constraints on future theoretical works.

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