Bump Cepheids and the Stellar Mass-Luminosity Relation

Stefan C. Keller

*Institute of Geophysics and Planetary Physics, LLNL, Livermore, CA 94550, U.S.A.*

Peter R. Wood

*Research School of Astronomy and Astrophysics, Australian National University, A.C.T. 2600, Australia*

**Abstract.** We present the results of non-linear pulsation modeling of bump Cepheids in the LMC and SMC. By obtaining an optimal fit to the observed MACHO $V$ and $R$ lightcurves we can determine the fundamental parameters of each Cepheid, namely mass, luminosity, effective temperature, distance modulus and reddening. We are able to describe the mass-luminosity relation for core-He burning intermediate mass stars. The mass-luminosity relation depends critically upon the level of internal mixing during the course of the star’s main-sequence evolution. Under the paradigm of convective core overshoot, our results enable us to place tight quantitative limits of the level of overshoot. We derive an overshooting parameter of $\Lambda_c$ of $0.65 \pm 0.03$ and $0.67 \pm 0.04 \, l/H_p$ for the LMC and SMC respectively.

1. Introduction

Cepheids form the first step to extra-galactic distances and are fundamental to modern observational cosmology. It remains a goal to have theoretical models capable of predicting the period-luminosity relation and its metallicity dependence. The regularity of Cepheid pulsation provides a set of well defined observational parameters with which to confront the predictions of theoretical models of stellar pulsation. In this way, Cepheids provide close scrutiny of the accuracy of input physics within pulsation models.

One of the weakest points in our description of the internal structure of intermediate to massive stars is the description of convection in the vicinity of the convective core. Ongoing debate centers of the degree of extension of the convective core above its classical Schwarzschild boundary. Convection is of course a fundamentally 3d problem awaiting hydrodynamical simulation such as is planned with Djehuty (see Bazan in these proceedings).

For the time being it suffices to treat the extension of the classical convective core by means of mixing-length theory. The convective core overshoot parameter $\Lambda_c$ sets the height (as a fraction of the pressure scale height) to which convective motion extends the core into the formally convectively stable region.
The size of the convective core determines the helium core mass laid down by the end of core H burning. A larger He core mass increases the luminosity of the post-main-sequence evolution and hastens its pace. Consequently the mass-luminosity relation for Cepheids is determined by the level of convective core overshoot whilst the star was on the main-sequence.

2. The Modeling Procedure

The lightcurve morphology of a Cepheid is determined by the stellar mass, luminosity and effective temperature. A feature of the lightcurves of a subset of the Cepheid population is the presence of a bump either preceding or following maximum light. This is the bump in bump Cepheids (see Figure 1). The bump arises from the 2:1 resonance between the fundamental mode and the second overtone. It becomes particularly prominent when the period ratio of these two modes ($P_{02}$) is close to two.

We have selected a sample of bump Cepheids from the MACHO photometric database in both the LMC (20 stars) and the SMC (10 stars). The details of the non-linear pulsation code are provided in Keller & Wood (2002). In contrast to the work of Bono, Castellani & Marconi (2002) we use only stellar pulsation and atmosphere theory - we do not make recourse to the assumption of existing mass-luminosity relations.

Throughout standard abundances for LMC and SMC populations are assumed ($Z=0.008$ and 0.004 respectively). This uses three fundamental parameters to describe the pulsation envelope: M, L and $T_{\text{eff}}$. Hence we require three constraints to determine these. The first constraint is that the fundamental period of the model matches that observed and this is achieved from linear theory. The second and third are obtained from the lightcurve fit from the nonlinear code. This procedure is illustrated in Figure 1.

In Figure 1 effective temperature is varied vertically and $P_{02}$ horizontally. As $P_{02}$ is varied the phase of the bump is modified; $T_{\text{eff}}$ varies the amplitude. The best fit to the observed lightcurve is located in the central panel. In this way we have determined the fundamental parameters of the Cepheid: M, L, $T_{\text{eff}}$, distance and reddening.

3. Caveat Pulsator

The above models treat convective energy transport via the mixing-length approximation. This approximation is expected to break down at cooler temperatures as the convective zone becomes a substantial fraction of the envelope. A consequence is that our models do not reproduce the red edge of the instability strip. In the vicinity of the red edge the pulsation amplitude is too high. The additional dissipative effect of turbulent convection is present in a real Cepheid atmosphere.

To avoid this shortcoming we have selected our sample of bump Cepheids close to the blue edge of the instability strip. This region has the added advantage that driving and hence amplitude, is very sensitive to effective temperature.
Figure 1. Constraining the mass and luminosity of the bump Cepheid: $M_V$ and $V-R$ against time for five models of the MACHO Cepheid 79.5139.13. Lines show model output except that the observed $V$ and $V-R$ have been shifted vertically to give the best match to the model in each case. This provide the distance modulus and reddening. The parameters shown in each of the five boxes are, top line: $P_{02}$, $T_{eff}$ and the initial perturbation velocity applied to the envelope, bottom line: mass, luminosity and distance modulus.
Figure 2. The mass-luminosity relation for the sample of 10 SMC (top) and 20 LMC (bottom) bump Cepheids. Overlaid are mass-luminosity relations from evolutionary models with three values of the convective core overshoot parameter ($\Lambda_c=0.0$, 0.5 and 1.0 $l/H_p$).
4. The Mass-Luminosity Relation

Our results for our sample of LMC and SMC bump Cepheids are presented in Figure 2. Overlaid are M-L relations from stellar evolutionary models for three values of $\Lambda_c$. It is evident that both samples are significantly more luminous than classical models. This difference amounts to a reduction of 20% in mass from classical models, with an optimal $\Lambda_c$ of 0.65±0.03 pressure scale heights for the LMC sample and 0.67±0.04 for the SMC. We also note that we do not see evidence for a metallicity dependence in the level of convective core overshoot.

This runs counter to other circumstantial evidence that would suggest that core overshoot should increase as we decrease metallicity. The findings of Venn (1999 and 1995) indicate a higher level of chemical enrichment amongst A supergiants, more massive cousins of the Cepheids examined here. Rotationally induced mixing has been proposed as the mechanism for this more efficient mixing in the stellar envelope. This suggests a generally more rapid rotation amongst lower metallicity stars (Keller et al. 2001b). If rotation were responsible we would expect the SMC stars to be of generally higher luminosity relative to classical models.

5. Summary

The problem of reconciling pulsation masses with evolutionary masses for Cepheids has a long history much of which has been resolved with the introduction of the OPAL opacities. The discrepancy between pulsation and classical evolution mass that we have demonstrated here is the remainder of the debate which has not been removed with improved input physics.

Rather, the discrepancy shown here has a basis in a higher level of internal mixing within intermediate mass main-sequence stars. Our findings are supported by a number of studies using linear pulsation analysis (Sebo & Wood 1995) and studies of stellar populations (Keller et al. 2001a) which show the need for a level of convective core overshoot of order 0.5 $l/H_p$. Our study of bump Cepheids has enabled us to place stringent limits on $\Lambda_c$ and we now wait to see if the results of 3d hydrodynamical simulations such as those available from Djehuty match that observed.

Acknowledgments. Work performed by SCK was performed under the auspices of the U.S. Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-47.

References

Bono, G., Castellani, V., & Marconi, M. 2002, ApJL, 565, L83
Keller, S. C., Da Costa, G. S., & Bessell, M. S. 2001a, AJ, 121, 905
Keller, S. C., Grebel, E. K., Miller, G. J., & Yoss, K. M. 2001b, AJ, 122, 248
Keller, S. C., & Wood, P. R. 2002, ApJ, accepted, astro-ph/0205555
Sebo, K. M., & Wood, P. R. 1995, ApJ, 449, 164