

CEPHEID PERIOD-LUMINOSITY RELATIONS: GALACTIC VS. LMC AND THE RESULTS FROM T -TEST

C. Ngeow, S. Kanbur

University of Massachusetts, Amherst, USA

ABSTRACT

The period-luminosity (PL) relation for Galactic Cepheids is derived with recent independent distance measurements taken from the literature. Our PL relation confirms the work of Tammann et al. (2003), which showed that the Galactic Cepheids follow a different PL relation to their LMC counterparts. Our results also show that the slope of the Galactic PL relation is inconsistent with the LMC slope with more than 95% confidence. The details of this work can be found in Ngeow & Kanbur (2004).

Key words: Cepheid; Distance Scale.

1. INTRODUCTION

The Cepheid period-luminosity (PL) relation is important in deriving the distance to nearby (<30 Mpc) galaxies. This relation takes a very simple form: $M_\lambda = a_\lambda \log(P) + b_\lambda$, where M , a and b are the absolute magnitudes, slope and zero-point (ZP) in bandpass λ , respectively, and P is the pulsational period in days. Both of the slopes and ZP can be obtained either from the theoretical predictions or calibrated from the observations.

In most cases, the Cepheid PL relation is assumed to be *universal*, i.e., the slope of the PL relation remains fixed, and the distance modulus to a target galaxy is found by obtaining the *difference* of the ZPs from the calibrated and the fitted PL relation to the Cepheids in the target galaxy. The most-widely used PL relations are calibrated with the large number of well observed Cepheids in the Large Magellanic Cloud (LMC), by adopting a distance modulus of 18.5 ± 0.1 mag to the LMC (see, e.g., Freedman et al. 2001).

There are numerous studies on the metallicity dependency of the PL relation (see, for example, Stothers 1988; Freedman & Madore 1990; Kochanek 1997; Sasselov et al. 1997; Kennicutt et al. 1998; Caputo et al. 2000; Freedman et al. 2001; Kanbur et al. 2003; Groenewegen et al. 2004; Romaniello et al. 2004; Sakai et al. 2004; Storm et al. 2004). Most of these studies suggest that the metallicity dependency enters the PL relation through the ZP, while the slope is still universal and

fixed by the LMC Cepheids. Therefore, a metallicity correction term is commonly applied to derive the Cepheid distances to nearby galaxies that have a different metallicity environment to that of the LMC (for example, as in Freedman et al. 2001; Kanbur et al. 2003; Leonard et al. 2003). However, a recent study by Tammann et al. (2003) shows that the Galactic PL relation is *steeper* than the LMC PL relation, which suggests that the *slope* of the PL relation may also depend on the metallicity. Recall that the values of the metallicity for the Galaxy (with $Z = 0.020$) and LMC (with $Z = 0.008$) are:

- $12 + \log[O/H]_{LMC} = 8.50 \pm 0.08$ dex, (Ferrearese et al. 2000).
- $12 + \log[O/H]_{GAL} = 8.87 \pm 0.07$ dex, (Grevesse et al. 1996).

Therefore, the metallicity dependency on the slope of the PL relation can be tested by comparing the calibrated Galactic and the LMC PL relations. The difference between this study and the work of Tammann et al. (2003) are:

1. We include some additional Galactic Cepheids that have independent distance measurements from recent literature.
2. We took the weighted average from different distance measurements for a given Cepheid as the final adopted distance.
3. We use a statistical test to examine the consistency of the slopes for the Galactic and LMC PL relations.

The details of this work are presented in Ngeow & Kanbur (2004).

2. CALIBRATING THE GALACTIC PERIOD-LUMINOSITY RELATION

In order to calibrate the Galactic PL relation, the distances to the Galactic Cepheids need to be known via independent measurements (i.e., not dependent on the *assumed* PL relation). There are a few ways to measure the independent distances to the Galactic Cepheids:

I. **Open Cluster Distance:** If the membership of a Cepheid in the open cluster can be verified (Turner 1988), then the distance of this Cepheid is equal to the distance of the open cluster. The distance of the open cluster can be found via the main-sequence fitting method (see, e.g., Turner et al. 1998; Feast 1999; Turner & Burke 2002; Hoyle et al. 2003).

II. **Baade-Wesslink Method:** The Baade-Wesslink (BS) method involves the comparison of the angular size of the Cepheid and its radius to obtain the distance. The radius of the Cepheid is obtained via the integration of the velocity curve:

$$R(t) \propto \int V_r(t) dt$$

There are two ways of obtaining the angular size of the Cepheids, as follows:

(a) Barnes-Evans (BE) surface brightness techniques – The BE surface brightness techniques are first introduced by Barnes & Evans (1976) and frequently applied with the BW method to obtain the Cepheid distances. The idea behind the BE surface brightness techniques is simple: starting from the Stefan-Boltzmann law, $L = 4\pi R^2 \sigma T^4$, dividing by $4\pi D^2$ (where D is the distance) on both sides, we obtain the expression for the angular size (θ) after the $\log(L) - V_o$ and $\log(T) - (V - K)_o$ conversions:

$$\log(\theta) = \alpha V_o + \beta(V - K)_o + \gamma$$

The coefficients in this expression can be obtained with the independent calibration, such as using supergiant stars (Fouqué & Gieren 1997). Detailed applications of this method can be found, e.g., in Gieren et al. (1993, 1997, 1998).

(b) Optical interferometry – By using optical interferometry, the angular sizes for some large and/or nearby Cepheids can be obtained from the measured visibility (Lane et al. 2002; Nordgren et al. 2002; Kervella et al. 2004).

III. **Parallax/Astrometry:** The distances to Galactic Cepheids can also be obtained from the trigonometrical parallax with Hipparcos or the astrometry measurement from the HST. However, after converting the parallax to distance modulus, the error bars for the Hipparcos measurements are large, as can be seen in Figure 2 of Madore & Freedman (1998). Therefore, the Hipparcos measurements are not used in this study. For the HST astrometry measurements, currently there is only one Cepheid, δ CEP, with the distance measurement from HST astrometry (Benedict et al. 2002).

We collect the available distance measurements with these different techniques from the literature, and took the weighted average for those Cepheids with different

independent distance measurements. The final list contains 50 Galactic Cepheids, and the Galactic PL relations are constructed with the data of these Cepheids, as shown in Figure 1. The list of these Cepheids can be found in Ngeow & Kanbur (2004).

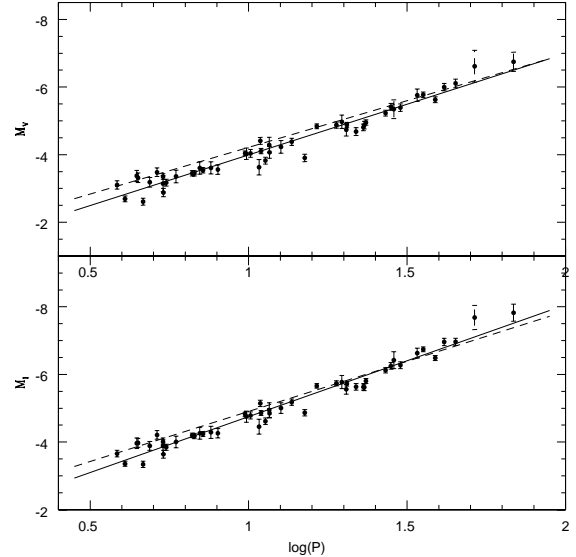


Figure 1. The Galactic PL relations in V - and I -band. The solid lines are the linear least squares fit to the data. The dashed lines are the LMC PL relations, for comparison.

3. COMPARISON OF THE GALACTIC AND THE LMC PL RELATIONS

The slopes of the resulting Galactic V - and I -band PL relations from Figure 1 are given in Table 1. These slopes are consistent with the Galactic slopes found in Tammann et al. (2003). In this table, we also include the slopes of the LMC PL relations used in the H_0 Key Project (H_0 KP, Freedman et al. 2001). These LMC PL relations are obtained with ~ 650 Cepheids from the Optical Gravitational Lensing Experiment (Udalski et al. 1999). As can be seen from the table, the slopes of the Galactic PL relations are more than 2σ away from their LMC counterparts. Are the slopes from Galactic Cepheids consistent with the slopes of the LMC PL relation? We can use the t -statistical test to answer this question (see, for example, Zwilling & Kokoska 2000). Assume that the Galactic data are (randomly) drawn from the same parent population, which is consistent with the LMC data, then the distribution of the Galactic slopes should follow the t -distribution under the null hypothesis that $a_{\text{GAL}} = a_{\text{LMC}}$ (see Figure 2 for illustration). By calculating the corresponding t values, we can obtain the p -values (or the probability) for the null hypothesis. The results are:

For V -band slope, $p(V) = 0.017$

For I -band slope, $p(I) = 0.001$

The small p -values indicate that the null hypothesis can be rejected with more than 95% confidence level. Therefore the slopes of the V - and I -band Galactic PL relation are not consistent with their LMC counterparts. These statistical results strongly suggest that the PL relation is *not universal*, at least in galaxies with metallicity that is comparable to the Galactic or LMC values.

Table 1. Comparison of the Galactic and the LMC PL relations

PL relation	a_V	a_I
GAL (Here)	-2.999 ± 0.097	-3.303 ± 0.094
LMC (H_0 KP)	-2.760 ± 0.030	-2.962 ± 0.020

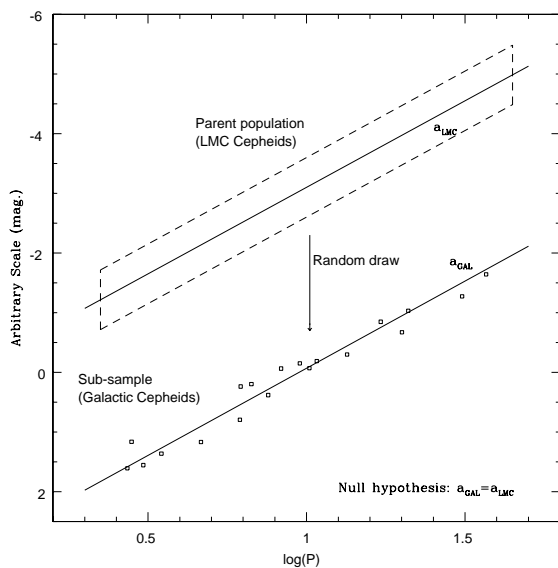


Figure 2. Illustration of the idea behind the t -test for the slopes of the Galactic PL relation.

4. CONCLUSION & DISCUSSION

In this study, we compare the slopes of the Galactic and the LMC PL relations with a t -test, and the results strongly suggest that the PL relation is not universal. However the current calibrated Galactic PL relations are based on 50 Cepheids, and there are about 500 Cepheids in our Galaxy (see the Galactic data base maintained by Fernie et al. 1995¹). Therefore the astrometric and photometric measurements from the Gaia mission (see, e.g., Eyer 2005; Mignard 2005; Perryman 2005) to the Galactic Cepheids can greatly improve the calibration of the Galactic PL relation and provide a larger statistical sample for the t -test. The importance of having the accurately calibrated Galactic PL relation are two-fold:

1. Distance scale study: The distances to the high metallicity galaxies, either in the H_0 KP or in the

future observations, should be obtained with the Galactic PL relations. Attempts at using the Galactic PL relations to calibrate the Cepheid distance to the H_0 KP target galaxies can be found in Kanbur et al. (2003).

2. Constraints on the pulsational/evolutionary models: The slopes from the theoretical Galactic PL relations are much *shallower* (Fiorentino et al. 2002) than the observed slopes as presented here, therefore the improvements for the theoretical Galactic PL relation is desired.

Finally, it is worth while to point out that the study by Heacock (2004), who applied Bayesian analysis to the Hipparcos data, has found that the Galactic slope is much shallower than the slopes found in this study or even in the LMC. Therefore, the results from the Gaia mission is clearly desirable to solve this discrepancy.

ACKNOWLEDGMENTS

CN would like to acknowledge the support from the Organizing Committee of the Gaia Symposium, who provided the grants for the registration fee and the accommodation; and the American Astronomical Society and the National Science Foundation for providing the international travel grants to cover the airfare.

REFERENCES

- Barnes, T., Evans, D., 1976, MNRAS., 174, 489
 Benedict, G. F., McArthur, B. E., Fredrick, L. W., et al., 2002, AJ, 124, 1695
 Caputo, F., Marconi, M., Musella, I., Santolamazza, P., 2000, A&A, 359, 1059
 Eyer, L., 2005, ESA SP-576, this volume
 Feast, M., 1999, PASP, 111, 775
 Fernie, J.D., Beattie, B., Evans, N.R., Seager, S., 1995, IBVS, No. 4148
 Ferrarese, L., Ford, H. C., Huchra, J., et al., 2000, ApJS, 128, 431
 Fiorentino, G., Caputo, F., Marconi, M., Musella, I., 2002, ApJ, 576, 402
 Freedman, W., Madore, B., 1990, ApJ, 365, 186
 Freedman, W., Madore, B., Gibson, B. K., et al., 2001, ApJ, 553, 47
 Fouqué, P. & Gieren, W., 1997, A&A, 320, 799
 Gieren, W., Barnes, T., Moffett, T., 1993, ApJ, 418, 135
 Gieren, W., Fouqué, P., Gómez, M., 1997, ApJ, 488, 74
 Gieren, W., Fouqué, P., Gómez, M., 1998, ApJ, 496, 17
 Grevesse, N., Noels, A., Sauval, A. J., 1996, in *Cosmic Abundances*, ed. Holt & Sonneborn, ASP Conf. Series Vol. 99, pg 117
 Groenewegen, M. A. T., Romaniello, M., Primas, F., Mottini, M., 2004, A&A, 420, 655

¹<http://www.astro.utoronto.ca/DDO/research/cepheids/>

- Heacox, W., 2004, in *Variable Stars in the Local Group*, ed. Kurtz & Pollard, ASP Conf. Series Vol. 310, pg 547
- Hoyle, F., Shanks, T., Tanvir, N., 2003, MNRAS, 345, 269
- Kanbur, S., Ngeow, C., Nikolaev, S., Tanvir, N., Hendry, M., 2003, A&A, 411, 361
- Kennicutt, R., Stetson, P., Saha, A., et al., 1998, ApJ, 491, 181
- Kervella, P., Nardetto, N., Bersier, D., Mourard, D., Coudé du Foresto, V., 2004, A&A, 416, 941
- Kochanek, C., 1997, ApJ, 491, 13
- Lane, B., Creech-Eakman, M., Nordgren, T., 2002, ApJ, 573, 330
- Leonard, D., Kanbur, S., Ngeow, C., Tanvir, N., 2003, ApJ, 594, 247
- Madore, B., Freedman, W., 1998, ApJ, 492, 110
- Mignard, F., 2005, ESA SP-576, this volume
- Ngeow, C., Kanbur, S., 2003, MNRAS, 349, 1130
- Nordgren, T., Lane, B., Hindsley, R., Kervella, P., 2002, AJ, 123, 3380
- Perryman, M.A.C., 2005, ESA SP-576, this volume
- Romaniello, M., Primas, F., Mottini, M., Groenewegen, M. A. T., 2004, in *Variable Stars in the Local Group*, ed. Kurtz & Pollard, ASP Conf. Series Vol. 310, pg 426
- Sakai, S., Ferrarese, L., Kennicutt, R., Saha, A., 2004, ApJ, 608, 42
- Sasselov, D., Beaulieu, J. P., Renault, C., et al., 1997, A&A, 324, 471
- Storm, J., Carney, B., Gieren, W., et al., 2004, A&A, 415, 531
- Stothers, R., 1988, ApJ, 329, 712
- Tammann, G. A., Sandage, A. & Reindl, R., 2003, A&A, 404, 423
- Turner, D., 1988, in *The Extragalactic Distance Scale*, Ed. van den Bergh, S. & Pritchet, C., ASP Conf. Series Vol. 4, pg. 178
- Turner, D., Pedreros, M. & Walker, A., 1998, AJ, 115, 1958
- Turner, D. & Burke, J., 2002, AJ, 124, 2931
- Udalski, A., Szymański, M., Kubiak, M., et al., 1999, AcA, 49, 201
- Zwillinger, D., Kokoska, S., 2000, *Standard Probability and Statistics Tables and Formulae.*, Chapman & Hall/CRC, 1st Ed.