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Period-luminosity relations for Galactic Cepheid variables with independent distance measurements.

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ABSTRACT

In this Letter, we derive the period-luminosity (PL) relation for Galactic Cepheids with recent independent distance measurements from open cluster, Barnes-Evans surface brightness and interferometry techniques. Our PL relation confirms the results of Tammann et al. (2003), which showed that the Galactic Cepheids follow a different PL relation than 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 level. We apply this Galactic PL relation to find the distance to NGC 4258. Our result of $\mu_o = 29.44 \pm 0.06(\mathrm{random\ error}) mag.$ agree at $\sim 1\sigma$ level with the geometrical distance of $\mu_{geo} = 29.28 \pm 0.15 mag.$ from water maser measurements.

Key words: Cepheids – Stars: fundamental parameters

1 INTRODUCTION

Recently, Tammann et al. (2003, hereafter T03) derived the Galactic PL relation by combining the Galactic Cepheids with independent distance measurements from open clusters/associations (Feast 1999) and from the Barnes-Evans (BE) surface brightness techniques (Gieren et al. 1998). The resulting Galactic PL relations in T03 are steeper than the LMC PL relations commonly applied in distance scale applications (as in, e.g., Freedman et al. 2001). Similar conclusions are also reported in Fouqué et al. (2003).

The need for using the Galactic PL relation as a fundamental calibrating relation has become more desirable in recent years (Feast 2003; Fouqué et al. 2003; Kanbur et al. 2003; Tammann et al. 2003; Thim et al. 2003), because of the following two main reasons: (a) The average value of metallicity (defined as $12 + \log[O/H]$) in target galaxies of H_o Key Project is about $8.84 \pm 0.31 dex$ (Freedman et al. 2001), which is closer to the standard Solar value of $8.87 \pm 0.07 dex$ (Grevesse et al. 1996) than the LMC value of $8.50 \pm 0.08 dex$ (see reference in Ferrarese et al. 2000); and (b) There is evidence that LMC PL relation is broken at 10 days (Tammann et al. 2002; Kanbur & Ngeow 2003), i.e., the short ($<$ 10days) and long period Cepheids in the LMC follow different PL relations. Due to these reasons, the calibrated Galactic PL relation will become important in future distance scale studies.

In this Letter, we derive the Galactic PL relation from Cepheids with independent distance measurements. Our analysis of the Galactic PL relation is similar to T03 but different in the following aspects:

(i) In addition to the Cepheids from Feast (1999) and Gieren et al. (1998) that are used in T03, we include other recent distance measurements to the Galactic Cepheids that are available in the literature (see Section 2 for details). These include seven additional Cepheids that are not included in T03 sample.

(ii) As most of the Cepheids we considered here have more than one independent distance measurement, we took the standard weighted-mean of the available distances as the final adopted distance to derive the PL relation.

2 GALACTIC CEPHEIDS WITH INDEPENDENT DISTANCE MEASUREMENT

We collected the Galactic Cepheids with recent distance measurements from the literature, which include:

(i) Distances from Open Cluster techniques: These distances are adopted from table 3 of T03, where the authors adopted a distance modulus for the Pleiades of $\mu_{Pleiades} = 5.61 \pm 0.03$ (Stello & Nissen 2001). Feast (1999) estimated that the uncertainty associated with cluster distance moduli is $\sim$ 0.15-0.20$mag.$ (see, e.g., Romeo et al. 1989), hence we assign an uncertainty of 0.20$mag.$ to the open cluster distance moduli in Table 1. We also include other open cluster distances from Hoyle et al. (2003) in column 5 of Table 1.

(ii) Distances from BE surface brightness techniques:

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These distances are adopted from table 5 of Gieren et al. (1998). We also include the updated version from Fouqué et al. (2003), with additional data that are not included in Gieren et al. (1998)[1]. The uncertainties of the distance moduli are also given in these papers. Note that T03 only included the distances from Gieren et al. (1998) but not from Fouqué et al. (2003). We also include the latest distance measurements with BE techniques from Barnes et al. (2003), who used a Bayesian statistical approach in their analysis.

(iii) Distances from interferometry techniques: Currently, there are only three Cepheids with distance measurements from interferometry, which include: η AQL, ζ GEM (Lane et al. 2002) and δ CEP (Nordgren et al. 2002).

The selected Galactic Cepheids and the corresponding distances from these sources are summarized in Table 1[2]. Since these distances are from independent measurements, we can take the weighted-mean among the available distances. We did not include the distances from *Hipparcos* because the errors in the distance moduli, after converted from parallax, are large (see, e.g., Madore & Freedman 1998).

In this work, we exclude all the possible non-fundamental mode Cepheids as mentioned in T03, which include: EV SCT, V1726 CYG, SZ TAU, QZ NOR, α UMi and V367 SCT. We further exclude EU TAU from Barnes et al. (2003) because it is a first-overtone Cepheid. Note for LS PUP which is not classified as "DCEP" in General Catalogue of Variable Stars (Kholopov et al. 1998). We also exclude this Cepheid though it is included in T03 sample. The additional Cepheids included in our sample are labelled in Table 1. The values of $\log(P)$, $(B-V)_o$ color, $E(B-V)$[3], and the mean B, V and I band[4] magnitudes for these Cepheids are all taken from T03. The absorption-to-reddening coefficient R for individual Cepheids are derived using the prescription given in T03[5]: $R_V = 3.17(\pm0.13) + 0.44[(B-V)_o - 0.78] + 0.05[E(B-V) - 0.42]$, $R_B = R_V + 1.00$ and $R_I = R_V - 1.28$.

3 PERIOD-LUMINOSITY RELATION

The B, V and I band extinction-corrected absolute magnitudes for the 46 Cepheids in Table 1 can be calculated by adopting the weighted-mean distance moduli, as given in last column of Table 1, and fitted with least-squared regressions (see, e.g., Press et al. 1992) to obtain the PL relation.

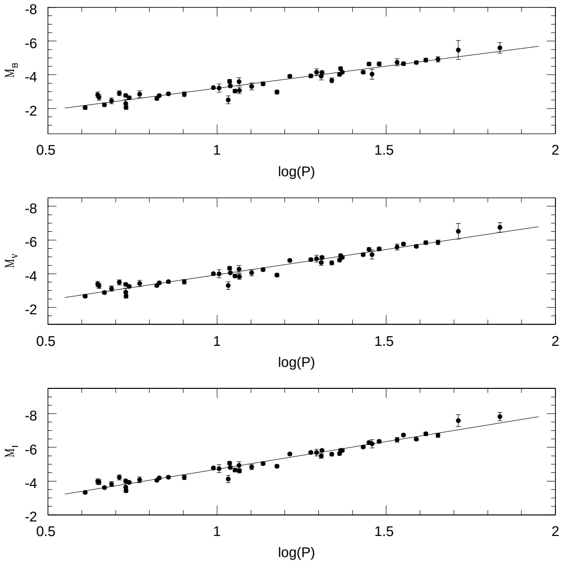

Figure 1. Galactic PL relation in B (top panel), V (middle panel) and I (bottom panel) band. The solid lines are the fitted PL relations, as given in equation (1)-(3). The error bars include the errors in distance modulus, errors in extinction and an error estimation of $0.05 mag.$ in mean magnitudes.

The plots of the fitted Galactic PL relations are presented as solid lines in Figure 1, with the following expressions:

$$M_B = -2.613(\pm0.122)\log(P) - 0.590(\pm0.143), \sigma = 0.272 \quad (1)$$

$$M_V = -3.002(\pm0.112)\log(P) - 0.934(\pm0.131), \sigma = 0.250 \quad (2)$$

$$M_I = -3.291(\pm0.107)\log(P) - 1.410(\pm0.126), \sigma = 0.239 \quad (3)$$

The error bars in Figure 1 are obtained from the quadrature sum of the error estimations in distance modulus (given in last column of Table 1), extinction (adopted from Fernie et al. (1995) database[6]) and mean magnitudes. We assign a conservative error of $0.05 mag.$ to the mean magnitudes, which is reasonable because the mean magnitudes are derived from the accurate and reliable light curves (Berdnikov et al. 2000).

3.1 Comparison to the published PL relation

We selected the recent PL relations from the literature that give both V and I band PL relations to be compared with our results. The selected PL relation, along with our results, are given in Table 2. These include the LMC PL relation adopted by Freedman et al. (2001), and the Galactic PL relations derived in Gieren et al. (1998, GAL-G98), Fouqué et al. (2003, GAL-F03) and Tammann et al. (2003, GAL-T03). From the table, it can be seen that our results are consistent with the GAL-G98 and GAL-F03 PL relation. However there is some discrepancy between our results and GAL-T03. In this situation, we can use the t-statistical test (see, e.g., Zwillinger & Kokoska 2000) to assess the difference in slopes under the null hypothesis that the slopes are the

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[1] It is possible that the Gieren et al. (1998) data and the Fouqué et al. (2003) data are not totally independent. However, the results are very similar to the results in Section 3 if we exclude Gieren et al. (1998) data in obtaining the weighted-mean distances as given in the last column of Table 1.

[2] T03 only used the distance moduli in column 2 & 3, but not the distance moduli in column 4 & 5 of Table 1, in their study.

[3] $E(B-V)_{corr}$ in T03.

[4] There is no mean I band values for η AQL, δ CEP and ζ GEM in T03, hence we adopted the I band mean magnitudes from Lanoix et al. (1999).

[5] There are other formulae for the R_V available in the literature. We choose the formula of R_V from T03 in order to be consistent to the work of T03. The detailed study of the sensitivity of PL relation on the selected R_V will address in a future paper.

[6] `http://ddo.astro.utoronto.ca/cepheids.html`

Table 1. Distances to Galactic Cepheids.

Cepheid	$\mu_o(O.C.)$[a]	$\mu_o(G98)$[a]	$\mu_o(F03)$[a]	$\mu_o(other)$[a]	$\mu_o(w.m.)$[a]
η AQL[f]	···	···	6.986 ± 0.052	7.526 ± 0.217[b]	7.015 ± 0.051
RX AUR[f]	···	···	···	11.101 ± 0.204[c]	11.101 ± 0.204
U CAR	11.46	11.069 ± 0.038	10.972 ± 0.032	···	11.019 ± 0.024
VY CAR	11.63	11.419 ± 0.043	11.501 ± 0.022	···	11.485 ± 0.019
WZ CAR	···	12.980 ± 0.135	12.918 ± 0.066	···	12.930 ± 0.059
l CAR	···	8.941 ± 0.053	8.989 ± 0.032	···	8.976 ± 0.027
CEa CAS	12.69	···	···	12.58 ± 0.14[d]	12.616 ± 0.115
CEb CAS	12.69	···	···	12.58 ± 0.14[d]	12.616 ± 0.115
CF CAS	12.69	···	···	12.58 ± 0.14[d]	12.616 ± 0.115
DL CAS	11.22	···	···	10.94 ± 0.14[d]	11.032 ± 0.115
KN CEN	···	12.911 ± 0.060	13.124 ± 0.045	···	13.047 ± 0.036
XX CEN	···	10.847 ± 0.065	11.116 ± 0.023	···	11.086 ± 0.022
V CEN	9.17	9.302 ± 0.024	9.175 ± 0.063	···	9.284 ± 0.022
VW CEN	···	13.014 ± 0.042	12.803 ± 0.039	···	12.901 ± 0.029
δ CEP[f]	···	···	7.084 ± 0.044	7.173 ± 0.048[b]	7.125 ± 0.032
X CYG[f]	···	···	10.421 ± 0.016	10.209 ± 0.055[c]	10.404 ± 0.015
ζ GEM[f]	···	···	···	7.794 ± 0.228[b]	7.794 ± 0.228
Z LAC[f]	···	···	11.637 ± 0.055	···	11.637 ± 0.055
CV MON	11.22	10.901 ± 0.046	10.988 ± 0.034	11.34 ± 0.21[d]	10.968 ± 0.027
T MON	11.14	10.576 ± 0.067	10.777 ± 0.053	10.580 ± 0.068[c]	10.682 ± 0.035
UU MUS	···	12.260 ± 0.092	12.589 ± 0.084	···	12.439 ± 0.062
S NOR	9.85	9.918 ± 0.025	9.908 ± 0.032	···	9.914 ± 0.020
TW NOR	11.47	···	···	11.33 ± 0.18[d]	11.393 ± 0.134
U NOR	···	10.769 ± 0.067	10.716 ± 0.060	···	10.740 ± 0.045
V340 NOR	11.17	11.498 ± 0.130	11.145 ± 0.185	11.18 ± 0.12[d]	11.276 ± 0.074
BF OPH	···	9.496 ± 0.110	9.271 ± 0.034	9.265 ± 0.192[c]	9.290 ± 0.032
UY PER	11.78	···	···	···	11.780 ± 0.200
AQ PUP	···	12.750 ± 0.038	12.522 ± 0.045	···	12.655 ± 0.029
BN PUP	···	12.924 ± 0.051	12.950 ± 0.050	···	12.937 ± 0.036
VZ PUP	···	13.551 ± 0.036	13.083 ± 0.057	···	13.418 ± 0.030
RS PUP	11.28	···	11.622 ± 0.076	11.160 ± 0.290[c]	11.555 ± 0.069
KQ SCO	12.36	···	···	···	12.360 ± 0.200
RY SCO	···	10.469 ± 0.042	10.516 ± 0.034	9.911 ± 0.147[c]	10.479 ± 0.026
RU SCT	11.60	···	···	11.36 ± 0.20[d]	11.480 ± 0.141
GY SGE	12.65	12.939 ± 0.071[e]	···	···	12.650 ± 0.200
BB SGR	9.11	9.238 ± 0.022	9.519 ± 0.028	9.805 ± 0.181[c]	9.348 ± 0.017
U SGR	9.07	8.869 ± 0.015	8.871 ± 0.022	9.137 ± 0.158[c]; 9.08 ± 0.18[d]	8.873 ± 0.012
WZ SGR	11.26	11.262 ± 0.021	11.287 ± 0.047	12.001 ± 0.169[c]; 11.18 ± 0.16[d]	11.274 ± 0.019
CS VEL	12.59	12.713 ± 0.144	···	···	12.671 ± 0.117
RY VEL	···	12.100 ± 0.050	12.019 ± 0.032	···	12.043 ± 0.027
RZ VEL	11.19	11.169 ± 0.025	11.020 ± 0.029	···	11.106 ± 0.019
SW VEL	12.08	11.989 ± 0.056	11.998 ± 0.025	···	11.998 ± 0.023
T VEL	···	10.094 ± 0.023	9.802 ± 0.060	···	10.057 ± 0.021
S VUL	13.24	13.731 ± 0.095[e]	···	···	13.240 ± 0.200
T VUL[f]	···	···	···	8.920 ± 0.146[c]	8.920 ± 0.146
SV VUL	11.83	12.325 ± 0.072[e]	···	11.331 ± 0.081[c]; 10.93 ± 0.21[d]	11.348 ± 0.071

[a] $\mu_o(O.C.)$ = open cluster distance from Feast (1999); $\mu_o(G98)$ = distance from Gieren et al. (1998); $\mu_o(F03)$ = distance from Fouqué et al. (2003); $\mu_o(other)$ = distance from other sources; $\mu_o(w.m.)$ = the weighted-mean distance for the entries in column 2 to 5, when available.

[b] Distance measurements from interferometry. See text for details.

[c] Distance measurements from Barnes et al. (2003). See text for details.

[d] Open cluster distances from Hoyle et al. (2003).

[e] These distance moduli are not used in both Gieren et al. (1998) and Tammann et al. (2003) as they appear to be outliers in the PL plots. These Cepheids also have variable periods. We exclude these distances in obtaining the weighted-mean distance.

[f] These Cepheids are not included in Tammann et al. (2003).

Table 2. Comparison of various PL relation[a].

PL relation	N	a_V	b_V	σ_V	a_I	b_I	σ_I	Ref.[b]
LMC	~ 650	-2.760 ± 0.030	-1.458 ± 0.020	0.160	-2.962 ± 0.020	-1.942 ± 0.010	0.110	1
GAL-G98	28	-3.037 ± 0.138	-1.021 ± 0.040	0.209	-3.329 ± 0.132	-1.435 ± 0.037	0.194	2
GAL-F03	32	-3.06 ± 0.11	-0.989 ± 0.034	$\cdots$	-3.24 ± 0.11	-1.550 ± 0.034	$\cdots$	3
GAL-T03	53	-3.141 ± 0.100	-0.826 ± 0.119	0.24	-3.408 ± 0.095	-1.325 ± 0.114	0.23	4
GAL-Here	46	-3.002 ± 0.112	-0.934 ± 0.131	0.250	-3.291 ± 0.107	-1.410 ± 0.126	0.239	5

[a] $M_{V,I} = a_{V,I}\log(P) + b_{V,I}$, and $\sigma_{V,I}$ is the rms dispersion. For LMC PL relation, assume $\mu_{LMC} = 18.50mag$.

[b] Reference: [1] Freedman et al. (2001); [2] Gieren et al. (1998); [3] Fouqué et al. (2003); [4] Tammann et al. (2003); [5] This work.

same. The results show that the null hypothesis cannot be ruled out with 95% confidence level. Hence our results are also consistent with the GAL-T03 PL relation.

Since the PL relation is shown to be different in the LMC and Galaxy by T03 (also in Fouqué et al. 2003 and Kanbur & Ngeow 2003), we verify this result by comparing our Galactic PL relation to the LMC counterpart. For our Galactic PL relation, the difference in the V and I band slopes is: $\Delta a_V = 0.242 \pm 0.116$ and $\Delta a_I = 0.329 \pm 0.109$, which are more than 2σ results. We also apply the t-statistical test to test for the equality in the slopes of the Galactic and LMC PL relation. The results show that the slopes in the Galactic and LMC PL relation are inconsistent at more than a 95% confidence level. Therefore, Cepheids in the Galaxy and the LMC do follow a different PL relation.

4 THE DISTANCE TO NGC 4258

The Galactic PL relation presented in the previous section can be used to find the distance to NGC 4258, because the metallicity in this galaxy is $8.85 \pm 0.06dex$ (see reference in Newman et al. 2001), which is closer to the Solar value. Furthermore, there is an accurate geometrical distance measurement to NGC 4258 using the water maser in the inner disk of this galaxy (Herrnstein et al. 1999). The measured geometrical distance is $7.2 \pm 0.5Mpc$, corresponding to $\mu_{geo} = 29.28 \pm 0.15mag$.

There are 15 Cepheids discovered with *HST* observations by Newman et al. (2001), where we adopted the periods and the mean V and I band magnitudes (from ALLFRAME photometry) for these Cepheids. The distance modulus to NGC 4258 can be obtained using the prescription given in Kanbur et al. (2003). We did not include the metallicity correction because it is small (Kanbur et al. 2003). The results are given in Table 3, using the different PL relations in Table 2. This shows that the distance to NGC 4258 is consistent with these different PL relations. However, the median distance modulus of $29.44mag.$ is still $\sim 1\sigma$ away from the water maser distance[7]. This could be due in part to the small number of Cepheids discovered in NGC 4258 (Newman et al. 2001). The on-going Cycle 12 *HST* observations of NGC 4258 (Program ID: 9810; P.I.: L. Greenhill) that proposed to discover $\sim$ 100 Cepheids in this galaxy would help to solve the discrepancy between the Cepheid distance and water maser distance.

Table 3. Distances to NGC 4258 with different PL relation.

PL Relation	μ_V	μ_I	μ_o^a
LMC	29.90 ± 0.07	29.71 ± 0.05	29.44 ± 0.06^b
GAL-G98	29.80 ± 0.07	29.65 ± 0.05	29.43 ± 0.06
GAL-F03	29.79 ± 0.07	29.66 ± 0.05	29.46 ± 0.06
GAL-T03	29.73 ± 0.07	29.63 ± 0.05	29.50 ± 0.06
GAL-Here	29.67 ± 0.07	29.58 ± 0.05	29.44 ± 0.06

[a] $\mu_o = \mu_V - 2.45(\mu_V - \mu_I)$, without metallicity correction. The errors are random error only.

[b] The metallicity correction using the LMC PL relation to this galaxy is $\delta_z = +0.07mag$. (Freedman et al. 2001; Newman et al. 2001). Then the metallicity-corrected distance modulus becomes $29.51 \pm 0.06mag$.

5 CONCLUSION

By using the recent independent distance measurements to 46 Galactic Cepheids, we derive the Galactic PL relation in B, V and I bands. Our analysis differs from that in T03 due to the following aspects: (a) we include other recent independent distance measurements; and (b) we took the weighted-mean to the available distances. The results confirm that the Galactic PL relations are steeper than the LMC counterparts (Fouqué et al. 2003; Tammann et al. 2003). Application of the Galactic PL relation to determine the distance of NGC 4258 show that there is still a $\sim 1\sigma$ discrepancy in distance with the water maser measurements. The Galactic PL relation can be improved if there are more independent distance measurements to the Galactic Cepheids in the future, such as the Cycle 12 *HST* observations of the nearby Cepheids with astrometric measurements (10 Cepheids from Program 9879 with P.I. of G. Benedict and 9 Cepheids from Program 9888 with P.I. of H. Bond).

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