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TEMPERATURE DIFFERENCES IN THE CEPHEID INSTABILITY STRIP REQUIRE DIFFERENCES IN THE PERIOD-LUMINOSITY RELATION IN SLOPE AND ZERO POINT

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ABSTRACT

A graphical and an algebraic demonstration is made to show why the slope and zero point of the Cepheid period-luminosity (P-L) relation is rigidly coupled with the slope and zero point of the Cepheid instability strip in the HR diagram. In this way it is shown why it is logically inconsistent to adopt a fixed P-L slope for all galaxies if the intrinsic color-period relations differ in slope for some of them. The graphical demonstration of this inconsistency uses an arbitrary (toy) ridgeline in the instability strip, while the algebraic demonstration uses the pulsation equation into which the *observed* P-L relations for the Galaxy and the LMC are put to predict the temperature zero points and slopes of the instability strips. Agreement between the predicted and the observed slopes in the instability strips argue that the observed P-L differences between the Galaxy and LMC are real. The direct evidence for different P-L slopes in different galaxies is displayed by comparing the Cepheid data in the Galaxy, the combined data in NGC 3351 and NGC 4321, in M31, LMC, SMC, IC 1613, NGC 3109, and in Sextans A+B. The P-L slopes for the Galaxy, NGC 3351, NGC 4321, and M31 are nearly identical and are the steepest in the sample. The P-L slopes decrease monotonically with metallicity in the order listed, showing that the P-L relation is not the same in different galaxies, complicating their use in calibrating the extragalactic distance scale.

Subject headings: Cepheids — distance scale

1. INTRODUCTION

There is evidence that the Cepheid period-luminosity relation is not universal but differs in slope and zero point from galaxy to galaxy at a level of up to ~0.3 mag as a function of period (Tammann & Reindl 2002; Tammann et al. 2002; Tammann et al. 2003, hereafter TSR03; Tammann et al. 2008, hereafter TSR08; Sandage et al. 2004, hereafter STR04; Sandage & Tammann 2006, for a review). Drastic as this conclusion is for studies of the extragalactic distance scale, it has been strengthened in confirming studies by Ngeow et al. (2003, 2005), Kanbur & Ngeow (2004), Ngeow & Kanbur (2004, 2005, 2006), and Koen et al. (2007), and from theoretical models as a function of chemical composition by many authors, starting perhaps with Cox (1959, 1980, p. 146) and including Christy (1966, 1972), Iben & Tuggle (1975), and Chiosi et al. (1992), and more recently Bono et al. (2000), Fiorentino et al. (2002), Marconi et al. (2005), and undoubtedly others.

These studies show that the position of the borders of the L, T_e instability strip in the HR diagram depends on chemical composition. If the strip borders vary in position and slope, so must the slope and zero point of the P-L relation, as worked through the pulsation equation in the following sections.

Despite this evidence, the conclusion that different P-L relations apply in different galaxies has recently been challenged in the literature. In these papers it is said that the slopes of the Cepheid P-L relations in other galaxies satisfy the slope of the P-L relation in the LMC and therefore that no slope differences with LMC have been demonstrated conclusively (Gieren et al. 2005a, 2005b, 2006; Pietrzynski et al. 2006; Benedict et al. 2007; van Leeuwen et al. 2007, are examples).

However, this claim sets aside the parallel evidence that the slope and zero point of the ridgelines of the Cepheid instability strips of the Galaxy, LMC, and SMC themselves differ in temperature at a given period (cf. Figs. 3 and 20 of STR04 for LMC and the Galaxy and Figs. 8 and 9 of Sandage et al. [2008] for SMC and the Galaxy), and hence in luminosity.

The purpose of this paper is to again remind us that the slope of the P-L relation is rigidly coupled with the slope of the instability strip via the Ritter (1879) pulsation condition that $P\rho^{1/2} =$ constant. We show that it is logically inconsistent to adopt a fixed P-L slope for all galaxies if the intrinsic color-period relations differ in slope for some of them. If the instability strip slope varies from galaxy to galaxy, so must the P-L slope.

Differences in the instability strip colors of the Galaxy and SMC were first set out by Gascoigne & Kron (1965). They were made secure as temperature differences by Laney & Stobie (1986) and have now been made definitive by the new CCD data by Udalski et al. (1999a, 1999b) for LMC and SMC and by Berdnikov et al. (2000) for the Galaxy, as summarized for the Galaxy and LMC in Figure 20 of STR04.

In § 2 we show the pulsation equation graphically and demonstrate from it the stated premise; a slope difference in the ridgeline of the instability strip leads to a slope difference in the P-L relation. The graphical solution here is parallel to the algebraic demonstration given elsewhere (TSR03, § 7.3; STR04, § 8) and made more explicit in § 3 here.

2. A GRAPHICAL SOLUTION BASED ON THE LINES OF CONSTANT PERIOD IN THE HR DIAGRAM

In an obvious way the Ritter $P\rho^{1/2}$ pulsation condition can be put into the observable parameters of period, luminosity, mass, and temperature by also using the Stefan-Boltzmann blackbody radiation condition that $L \sim R^2 T_e^4$. The Ritter plus blackbody condition is improved by model calculations for real stars by using details of the pulsating stellar atmosphere structure, leading to the more precise pulsation equation of $P(L, M, T_e)$.

As in previous papers we again use the van Albada & Baker (1973) pulsation equation. Although it was calculated by them to apply to the lower mass RR Lyrae stars, comparisons show that their predicted P-L relation is nearly identical with many other pulsation equations calculated for higher mass Cepheids. Examples are the equations by Iben & Tuggle (1975, their eq. [3]), Chiosi et al. (1992, their eq. [5]), Simon & Clement (1993, their eq. [2]), and Saio & Gautschy (1998). The near identity among the equations is discussed in Sandage et al. (1999, hereafter SBT99).

The pulsation equation by van Albada & Baker (1973) is

$$\log P = 0.84 \log L_{\rm bol} - 0.68 \log \mathcal{M} - 3.48 \log T_e + 11.502. \quad (1)$$

It can be made into an equation, $P(L, T_e)$, for the lines of constant period in the HR diagram once a mass-luminosity relation for Cepheids is used to eliminate mass from equation (1).

Observational determinations of many Cepheid masses are not available, and we must rely on theoretical mass values from calculated evolution tracks that pass through the instability strip. A summary of such tracks is given in Tables 1–5 of SBT99 for tracks calculated from the Geneva models, in Table 11 for the Padua tracks, and Table 12 for the Saio-Gautschy tracks. Detailed references for these models are in SBT99. The models of Marconi et al. (2005) for solar metallicity and by Bono et al. (2000) for lower metallicities were also studied.

From all the models, normalized at $\log \mathcal{M} = 0.84$ at $\log L = 3.80$, we have adopted

$$\log \mathcal{M} = 0.300 \log L_{\rm bol} - 0.300 \quad (2)$$

from the tracks. This is everywhere within $\Delta \log \mathcal{M} = 0.03$ dex of the Geneva and Padua tables in SBT99 for all metallicities.

Putting equation (2) into equation (1) gives the equation of the lines of constant period to be

$$\log L_{\rm bol} = 5.472 \log T_e + 1.572 \log P - 18.406. \quad (3)$$

This produces a family of lines in the $\log L$, $\log T_e$ HR diagram as $\log P$ is varied.

Figure 1 shows such a family for $\log P$ values of 0.4, 0.7, 1.0, 1.3, and 1.6. The ridgeline instability strip for the Galaxy is shown, using its equation of $\log T_e = -0.054 \log L + 3.922$ from STR04, their Figure 20. The blue and red strip borders are arbitrarily drawn parallel to the Galaxy ridgeline using a temperature width of $\Delta \log T_e = 0.06$ from the Galaxy ridgeline. This is slightly wider than is observed (Fig. 20 of STR04), but is drawn to accommodate the dashed strip line of a toy galaxy shown with the equation $\log T_e = -0.100 \log L + 4.103$.

For this demonstration the slope of the ridgeline instability strip L-T_e relation has been put larger than that for the Galaxy to show how the ridgeline relations cut the lines of constant period at different L values (at fixed period) for the Galaxy and the toy if the L-T_e slopes differ. This, of course, is the crux of the demonstration that the P-L and L-T_e relations are rigidly coupled. The toy galaxy strip (Fig. 1, *dashed line*) has arbitrarily been made to intersect the Galaxy strip at $\log P = 1.3$ to ensure that the separate P-L relations also cross at this period in this demonstration.

The ridgeline P-L relations are derived in an obvious way by reading the $\log L$ (ordinate) values at the intersections of the instability strip with the constant period lines for both the Galaxy and the toy model. The premise in the title that the resulting ridgeline P-L relations obtained for the Galaxy and the toy in this way must differ is obvious from this construction. For $\log L < 4.0$, the instability strip has higher temperatures for the toy model than for the Galaxy at a given period. Hence, the intersection of the ridgeline strip with the constant period lines occurs at brighter luminosities for the toy than for the Galaxy, giving a P-L relation for the toy model that is brighter than for the Galaxy for all periods smaller than $\log P = 1.3$. The opposite is true for $\log P > 1.3$. Hence the P-L relations will have different slopes, as was to be shown.

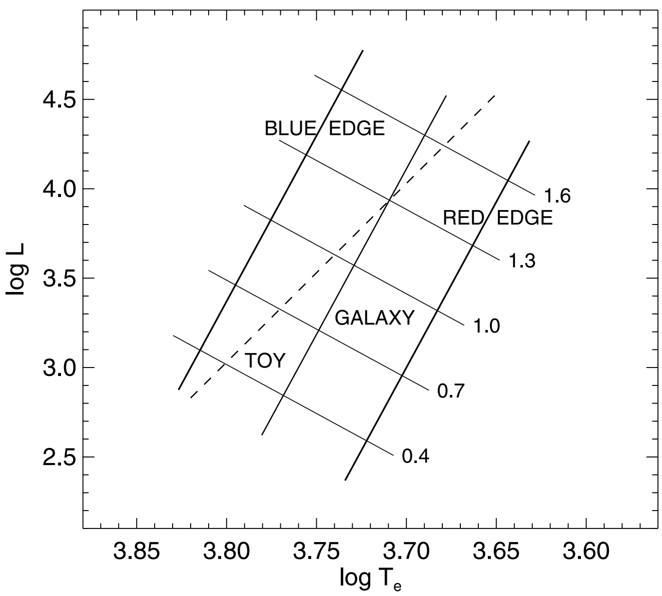

FIG. 1.—Schematic HR diagram in the vicinity of the Cepheid instability strip. The central line is the observed ridgeline for the Galaxy taken from Fig. 20 of STR04 whose equation is arbitrarily put at $\log T_e = -0.054 \log L_V + 3.922$. The dashed line is for a toy galaxy whose ridgeline equation is $\log T_e = -0.100 \log L_V + 4.103$. The borders of the instability strip are put parallel to the Galaxy ridgeline. Lines of constant period, calculated from eq. (3), are marked with their $\log P$ values (in days).

The discussion here in words could complete the promised demonstration. However, to make the point more explicit, even to the point of pedantry, Figure 2 displays the two different P-L relations obtained by reading Figure 1 in this way. The slope values for the Galaxy and the toy are marked in the figure, based on the adopted instability equations adopted for Figure 1.

3. THE ALGEBRAIC SOLUTION USING DATA FROM THE GALAXY AND THE LMC

We can apply the pulsation equation directly to show the algebraic solution for the same problem using real data, both for the equations of the instability strips of the Galaxy and LMC and the observed P-L relations. The demonstration made here uses the equations for observed P-L relations from STR04 in their equation (17) for the Galaxy and their equations (12) and (13) for the LMC. These are put into equation (1), which, together with the adopted mass-luminosity equation (2), gives a predicted $\log T_e$, $\log L$ instability ridgeline relation. This predicted line is then compared with the observed instability strip equations shown in Figure 20 of STR04.

We have used an explicit bolometric correction to change the $\log L_V$ values obtained from the observations into $\log L_{\rm bol}$ required in equations (1) and (2), and back to $\log L_V$ to compare the predictions from the pulsation equation with the observations.

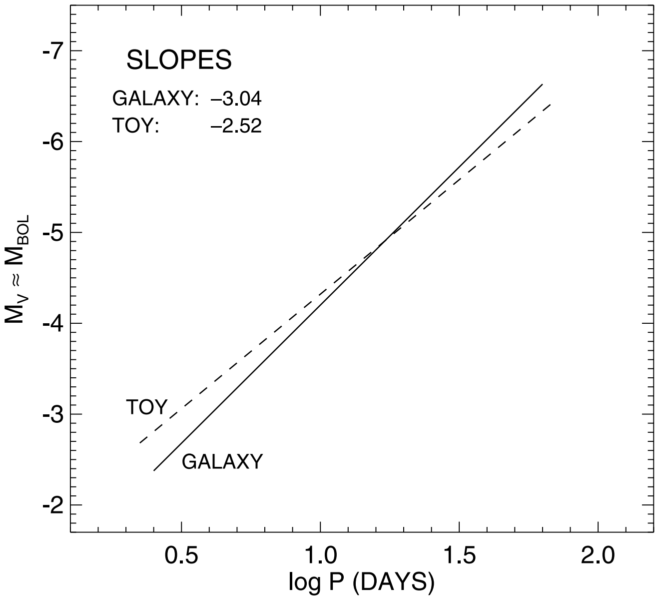

FIG. 2.—Two P-L relations for the two ridgelines in Fig. 1, determined from the intersections of the ridgelines of the Galaxy and the toy galaxy with the lines of constant period in Fig. 1. The absolute magnitudes along the ordinate are transferred from Fig. 1 by $M_V = -2.5 \log L_{\rm bol} + 4.75$ where the bolometric correction in V is adopted to be zero.

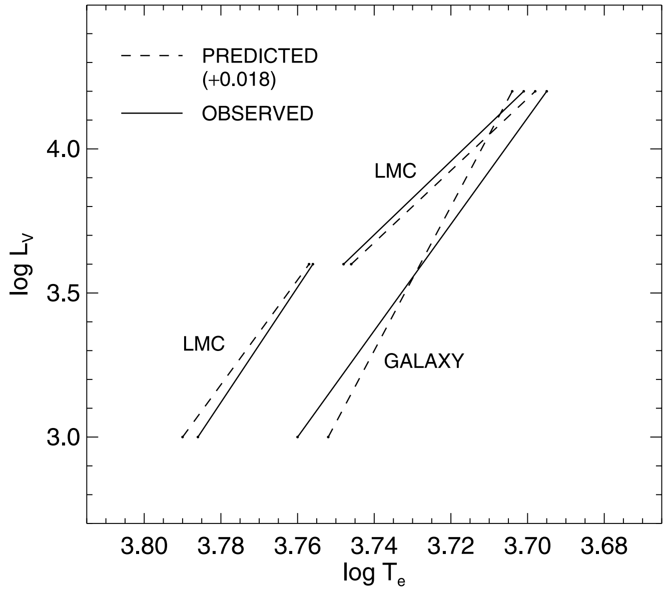

FIG. 3.—Algebraic demonstration of the rigid coupling between the slopes of the instability strip and the slope of the P-L relation required by the pulsation equation. Predicted (*dashed lines*) slopes and zero points for these instability strip ridgelines in the Galaxy and the LMC are compared with the observed (*solid lines*) lines from Fig. 20 of STR04. The predictions are made by inserting the equations of the observed P-L relations for the Galaxy and the LMC into the pulsation eq. (1). The predicted zero points are moved by 0.018 in $\log T_e$, hotter.

The bolometric corrections are interpolated from Table 6 of SBT99 for the appropriate metallicities and surface gravities of the Cepheids. The turbulent velocity was assumed to be 1.7 km s^{-1}. The surface gravities vary with radius, mass, and luminosity and therefore with period as a surrogate as $\log g = -1.09 \log P + 2.64$ (eq. [49] of STR04). The metallicities are assumed to be $[{\rm A/H}] = 0.00$ for the Galaxy and -0.5 for LMC. The mass is from equation (2). The obvious arithmetic is not shown.

The resulting predictions of the instability strip ridgeline equations are these:

$$\log T_e(\text{predicted}) = -0.040 \log L_V + 3.854 \quad (4)$$

for the Galaxy at all periods,

$$\log T_e(\text{predicted}) = -0.056 \log L_V + 3.941 \quad (5)$$

for $P < 10$ days for the LMC, and

$$\log T_e(\text{predicted}) = -0.081 \log L_V + 4.020 \quad (6)$$

for $P > 10$ days, also for the LMC.

Note that the break in the $T_e - L$ instability strip relation at $P = 10$ days in equations (5) and (6) is mirrored in the break in the P-L LMC relations given in equations (12) and (13) of STR04, and shown as Figure 4 there.

For comparison with the predictions in equations (4)–(6) here, the *observed* ridgelines of the strips in the Galaxy and the LMC, taken from the insert equations shown in Figure 20 of STR04, are

$$\log T_e(\text{observed}) = -0.054 \log L_V + 3.922 \quad (7)$$

for the Galaxy at all periods,

$$\log T_e(\text{observed}) = -0.050 \log L_V + 3.936 \quad (8)$$

for $P < 10$ days, and

$$\log T_e(\text{observed}) = -0.078 \log L_V + 4.029 \quad (9)$$

for $P > 10$ days for the LMC.

The near agreement of the predicted slopes of the instability strips in equations (4)–(6) with the observed slopes in equations (7)–(9) is the demonstration we are seeking. The agreement is good, but there is a disagreement in the temperature zero points between equations (4)–(6) and equations (7)–(9) by $\Delta \log T_e = 0.018$ dex. The predicted temperatures are cooler than those observed. However, the difference is remarkably small, given the approximations we have made in the bolometric corrections, in the adopted temperature scale of SBT99, their Table 6, and in the adopted van Albada-Baker theoretical zero point in equation (1).

The temperature offset could be made zero if the zero point of the mass in equation (2) would be made smaller by 0.09 dex, but then the evolution mass would differ from the pulsation mass by this amount. This is the expression of the previous well-known mass "problem" which is solved here by the temperature shift, which can, of course, be solved in other ways (e.g., Bono et al. 2000).

In this regard, it is useful to remark that many of the temperature scales in the current literature, for example as summarized by Sekiguchi & Fukugita (2000) or by Cacciari et al. (2005) and including the one in SBT99 that we have used here, differ among themselves by as much as 0.025 dex in $\log T_e$ at fixed $B - V$. This, then, is the temperature uncertainty in the temperature zero point in Figure 20 of STR04. Our shifting of the predicted temperature relative to the observed temperatures in Figure 3 by 0.018 dex is not excessive.

The observed (*solid lines*) and the predicted (*dashed lines shifted by* 0.018 dex *in* $\log T_e$) instability strips for the Galaxy and the LMC are shown in Figure 3. The agreement is satisfactory, showing again that differences in the instability strip loci causes differences in the slopes of the P-L relations. Hence the claims in

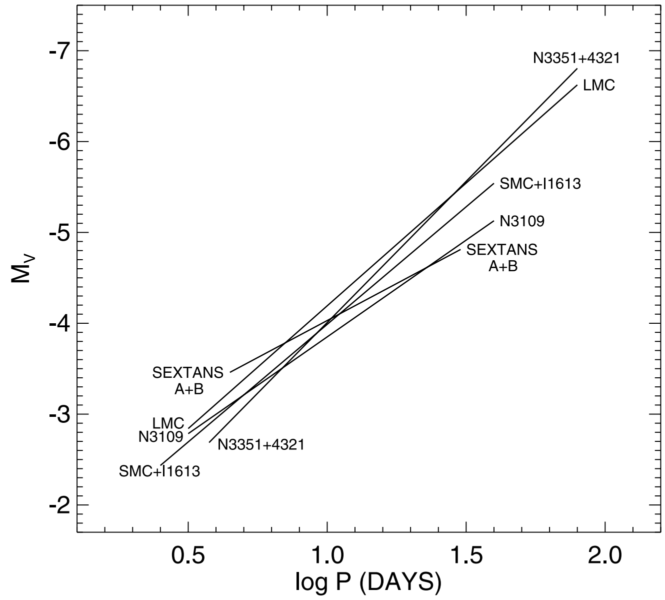

FIG. 4.—Observed ridgelines of the P-L relations for eight galaxies listed in Table 1. The P-L relation for the Galaxy (not shown) is nearly identical with the combined NGC 3351 and NGC 4321 line and has the steepest slope. The agreement between the Galaxy and the combined NGC 3351 and NGC 4321 slopes argues for the correctness of the steep slope for the Galaxy P-L relation.

the current literature, cited in § 1, that a universal slope exists for the Cepheid P-L relation are inconsistent with Figures 1–3 which show different positions of the instability strip in different galaxies.

In this section we could have made the calculation in the reverse way by adopting the observed L-T_e instability strip equation from Figure 20 of STR04 to predict the P-L relation as was done in Figures 1 and 2 here for the toy model. The results would, of course, have been the same. We chose to do it this way to make the demonstration in both ways.

4. SUMMARY OF OBSERVED P-L SLOPE DIFFERENCES IN SELECTED GALAXIES

The arguments given in the previous sections rely on knowledge of the temperatures of the instability strips. These can only be measured using reddening corrected colors, and these are reliable only if the reddening of the individual Cepheids can be determined by some method other than by using a fiducial period-color (P-C) relation. The reason is that if the temperatures of the instability strips differ from galaxy to galaxy, presumably because of chemical composition differences, the P-C relations will also differ. There will be no correct fiducial P-C template from which to determine the reddening if the chemical compositions vary greatly, and the reddenings will therefore be indeterminate.

Presently, it is only the Galaxy, LMC, and SMC that can be subjected to the analysis given here because it is only for these galaxies that the reddening of their Cepheids have been determined by methods other than by comparing with some adopted fiducial P-C relation.

However, for some galaxies with enough Cepheids, and where the differential reddening between the Cepheids is small enough to be ignored, comparison of the P-L slopes can be made directly from the data. The result for the Galaxy, NGC 3351, NGC 4321, LMC, SMC, IC 1613, NGC 3109, and Sextans A and B is shown in Figure 4. The adopted data for the P-L relations are in Table 1. The equations for the apparent magnitude and absolute magnitude P-L relations are $V^0 = a \log P + b$, and $M_V^0 = a \log P + c$. Column (2) is the log of the oxygen-to-hydrogen ratio from Table 5 of TSR08. Columns (3) and (4) show the observed slope a and its error of the apparent magnitude P-L relation taken from Table 5 of TSR08. Column (5) lists the apparent magnitude P-L intercept, b, as observed. Column (6) lists the $(m - M)^0$ distance modulus adopted in TSR08. The absolute magnitude P-L relation is in column (7), which is column (5) minus column (6). The literature source is in column (8). The resulting P-L relations, calculated from the a and c values in Table 1, are shown in Figure 4. The slopes for the NGC 3351/ NGC 4321 combination and the Galaxy are the steepest of those shown, and are similar. That of the LMC is next steepest.

The slope of the Galaxy P-L relation in TSR03 and STR04 is based on averaging the results using the moving atmosphere method (the Baade-Becker-Wesselink procedure) and the independent main-sequence fitting method. Nevertheless, the resulting slope of the P-L slope has been questioned as being too steep (Gieren et al. 2005b; van Leeuwen et al. 2007). However, the slopes of the NGC 3351 and NGC 4321 combined P-L relation, and that of M31 by Vilardell et al. (2007) are equally steep as for the Galaxy. The M31 slope by Vilardell et al. of -2.91 ± 0.21 has been redetermined by TSR08. The original slope by Vilardell and collaborators was based on $E(B - V)$values using the LMC P-C relation rather than the more correct higher metallicity P-C relation for the Galaxy. The resulting $E(B - V)$values turns out to depend on period as a further complication. But even discounting

TABLE 1

OBSERVED $(\text{P-L})_V$ RELATIONS FOR TEN GALAXIES WITH DIFFERENT CHEMICAL COMPOSITIONS

Name (1)	[O/H] (2)	a (3)	V slope error (4)	b (5)	$(m - M)^0$ (6)	c (7)	References (8)
Galaxy	8.60	−3.09	0.09	. . .	. . .	−0.91	1
NGC 3351/4321	⟨8.80⟩	−3.15	0.37	Mean	Mean	−0.90	2
M31	8.66	−2.92	0.21	. . .	24.43	. . .	3
LMC	8.34	−2.70	0.03	17.05	18.54	−1.49	4
SMC	7.98	−2.59	0.05	17.53	18.93	−1.40	5
IC 1613	7.86	−2.67	0.12	23.08	24.35	−1.27	6
NGC 3109	8.06	−2.13	0.18	23.73	25.45	−1.72	7
Sextans A+B	7.52	−1.59	0.39	23.10	25.80	−2.40	8

NOTE.—Col. (4): The rms errors are from TSR08 (their Table 5). They have been calculated by us and differ slightly from those given by the original authors because of differences in the samples used.

REFERENCES.—(1) STR04, eq. [17]; (2) TSR08, Fig. 2; (3) Vilardell et al. 2007; (4) STR04, eq. [8]; (5) TSR08, eq. [5]; (6) Antonello et al. 2006; (7) Pietrzynski et al. 2006, Fig. 4; (8) Piotto et al. 1994.

the M31 case, the steep slope for NGC 3351 and NGC 4321 from TSR08 (their Fig. 2), supports the Galaxy slope that we derived in STR04 and its difference from the P-L slope in LMC.

Because of frequent statements in the literature that the slope of the LMC P-L relation fits the data in other galaxies despite differences in the metallicity, one could question the significance of the slope differences in column (3) of Table 1, yet the rms errors in the slopes listed in Table 1 are small for the Galaxy, LMC, SMC, and IC 1613, averaging ± 0.07.

The slope differences in Table 1 are significant at greater than the 3 σ level for these galaxies. The rms errors for NGC 3351/NGC 4321, NGC 3109, and Sextans A+B are larger, averaging ± 0.30. Nevertheless, the slope difference between the Galaxy and NGC 3109 at 0.96 and between the Galaxy and Sextans A+B at 1.50 are significant at 4 σ.

Nevertheless, these formal values, significant as they are, are misleading. They are not the best illustration of the problem. Most important for the extragalactic distance scale is the deviation of the longest period Cepheids from some fiducial P-L relation. This is large for the long period Cepheids that are invariably used for the most distant sample.

We make the point with the NGC 3109 data here because Pietrzynski et al. (2006) suggest that the V and I P-L relations show no systematic difference with the LMC P-L relation when the σ uncertainties between LMC and NGC 3109 are combined. However, there is clearly a difference at the long period end when the Galaxy P-L relations in V and I are overlaid on Figure 4 of Pietrzynski et al. with slopes of -3.09 in V and -3.35 in I for the Galaxy and -2.13 in V and -2.40 in I and using $(m - M)^0 = 25.45$ for NGC 3109. The NGC 3109 Cepheids average 0.38 mag fainter than in the Galaxy in V and 0.25 mag fainter in I at $\log P = 1.4$. The same differences exist between NGC 3109 and the LMC because the P-L relations of LMC and the Galaxy cross at $\log P = 1.4$ (see Fig. 4). The differences are striking and are greater than the scatter in Figure 4 of Pietrzynski et al. The problem with relying only on the formal least-squares solutions for the slope to prove or disprove P-L differences is that the result is influenced by short period Cepheids in the nearby galaxies with $\log P < 1$ which are not used in the *HST* data for the more distant program galaxies.

One can also question the accuracies of the listed [O/H] abundances in Table 1. The systematic errors in them are of the order of 0.2–0.3 dex (Díaz et al. 2000; Bresolin et al. 2005; Bono et al. 2008) in absolute value, but the variation between galaxy to galaxy is smaller. For example, there is no question that the metallicities for LMC and SMC are smaller than for the Galaxy by differential values of about 0.4 and 0.7 in [Fe/H], but the absolute values may not be known to within about 0.3 dex. Hence, the ordering of the metallicity variations in Table 1 is probably correct on the whole, as plotted in Figure 4 of TSR08. Nevertheless the errors in the slopes and metallicities in Table 1 here and Table 5 of TSR08 can move each point in Figure 4 of TSR08 quite a bit, yet the combined evidence makes a flat relation (no correlation of the P-L slope with metallicity) unlikely.

There are, however, concerns. The galaxies, except for NGC 3351/ NGC 4251 and M31, are in Table 1 either because they have reddening values determined independently of some adopted fiducial universal P-C relation, or because, for dwarf galaxies, the reddenings are negligible. NGC 3351, NGC 4321, and M31 are included because they are relatively nearby; hence, their Cepheids are available over a wide range of periods, ensuring high weight in the determination of the P-L slope. And, because they are giant galaxies of high metallicity, we make the usual assumption that the Galactic P-C relation applies to them.

Other more distant high metallicity galaxies have poorly determined slopes due to the lack of short period Cepheids in their databases. Hence, high metallicity galaxies are underrepresented in Table 1. However, the metal-poor galaxies here represent a more complete distance limited sample, and they have a reasonable number of Cepheids where the absorption is not a major problem. Among them, there is no galaxy, so far, with a steep P-L relation.

So far only one set of Cepheids with Galactic metallicity is known, i.e., those in the inner field of NGC 4258 (Macri et al. 2006; TSR08), that define within small errors a P-L slope as flat as LMC Cepheids. This shows that the scatter in slope of high-metallicity Cepheids may be larger than exhibited in Table 1, but it does not question the general trend of low-metallicity Cepheids to have flat P-L relations.

Figure 4 here, similar in principle to Figure 5 in TSR08, together with Figure 3 here, is our chief case for nonunique P-L relations between galaxies of different chemical compositions. The complications that this portends for determining the scale of extragalactic distances from Cepheids to within $\sim$15%, unless special corrections for the difference are applied, is discussed elsewhere (Saha et al. 2006; Sandage et al. 2006; TSR08). The difference between our distant scale and that of Freedman et al. (2001) and Riess et al. (2005) by about 15% (our scale is longer) is almost entirely due to the difference in the Cepheid P-L relations that have been adopted by each group.

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