THE CARNEGIE HUBBLE PROGRAM: THE LEAVITT LAW AT 3.6 AND 4.5 μm IN THE MILKY WAY

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ABSTRACT

The Carnegie Hubble Program (CHP) is designed to calibrate the extragalactic distance scale using data from the post-cryogenic era of the Spitzer Space Telescope. The ultimate goal of the CHP is a systematic improvement in the distance scale leading to a determination of the Hubble constant to within an accuracy of 2%. This paper focuses on the measurement and calibration of the Galactic Cepheid period–luminosity (PL, Leavitt) relation using the warm Spitzer/IRAC 1 and 2 bands at 3.6 and 4.5 μm. We present photometric measurements covering the period range 4–70 days for 37 Galactic Cepheids. Data at 24 phase points were collected for each star. Three PL relations of the form \( M = a \log(P) - b \) are derived. The method adopted here takes the slope \( a \) to be \(-3.31\), as determined from the Spitzer Large Magellanic Cloud (LMC) data of Scowcroft et al. Using the geometric Hubble Space Telescope guide-star distances to 10 Galactic Cepheids, we find a calibrated 3.6 μm PL zero point of \(-5.80 \pm 0.03\). Together with our value for the LMC zero point, we determine a reddening-corrected distance modulus of \(18.48 \pm 0.04\) mag to the LMC. The mid-IR period–color diagram and the \([3.6]–[4.5]\) color variation with phase are interpreted in terms of CO absorption at 4.5 μm. This situation compromises the use of the 4.5 μm data for distance determinations.

Key words: infrared: stars – stars: variables: Cepheids

Online-only material: machine-readable table

1. INTRODUCTION

The Carnegie Hubble Program (CHP) is designed to reduce systematic uncertainties in the distance scale. The compelling reasons for doing so are provided in an overview by Freedman et al. (2011). The first phase of the CHP is a warm Spitzer legacy mission, the preliminary goal of which is to reduce the systematic uncertainties in \(H_0\) to 3% or better. The second phase will include observations from Gaia and the James Webb Space Telescope where the goal will be to push this number to 2%.

The warm Spitzer phase consists of observing Cepheids in the Milky Way (MW), Large Magellanic Cloud (LMC), Small Magellanic Cloud, and other Local Group galaxies (see Freedman et al. 2011 for a complete list) to calibrate the local distance scale in the mid-infrared (mid-IR). The program extends into the Hubble Flow by calibrating the mid-IR Tully–Fisher relation and farther to Type Ia supernova host galaxies observed as part of the Carnegie Supernova Project (Folatelli 2009; Contreras et al. 2010).

This paper presents warm Spitzer Infrared Array Camera (IRAC) channel 1 (3.6 μm) and channel 2 (4.5 μm) light curves for 37 Galactic Cepheids. Each star was observed at 24 phase points. The data are used to derive robust mean magnitudes and colors, and, with the adoption of Hubble Space Telescope (HST) parallaxes for 10 stars, an accurate calibration in the mid-IR. The absolute magnitudes give a distance to the LMC, which we believe is currently the value carrying the lowest systematic uncertainty. The calibrations and LMC distance values for a sample of Cepheids in Galactic clusters and for a sample with IRSB data are compared to the HST-based distance. A brief discussion of the observed period–color relationship and its interpretation in terms of CO affecting the 4.5 μm band is also given.

2. WARM SPITZER OBSERVATIONS

2.1. Target Selection

The 37 Cepheids in our sample have multiple distance and extinction estimates, and span a wide range of 4–70 days in period (Fernie et al. 1995; Tammann et al. 2003; Fouquè et al. 2007). The sample includes the majority of the nearest Cepheids; these should soon have high-precision parallaxes available from the Gaia mission (Windmark et al. 2011). Table 1 lists the target stars, the adopted reddening, and three measurements of distance for each star if available: direct parallax data from HST, distance moduli obtained from main-sequence fitting of their host clusters, and distances from Infrared Surface Brightness (IRSB) measurements; the latter two methods were converted to units of parallax for comparison. Reddening estimates from photometric and spectroscopic methods are listed in Table 2 as well as space reddenings determined from stars along the same line of sight. The average reddening of these methods was used in Table 1.

2.2. Observations

Observations were made using the Spitzer Space Telescope as part of a two-year Exploration Science Program, PID 60010: The Hubble Constant (Freedman et al. 2008). The warm Spitzer mission started in 2009 (Cycle-6) and the Galactic Cepheid observations were completed in early 2011. Each Cepheid was observed at 24 epochs, pre-selected and scheduled to fully sample the light curve (23 epochs for \(\zeta\) Gem). At each epoch, a nine-point dither pattern was used to mitigate array-dependent artifacts such as bad pixels and cosmic rays.
The majority of the data were taken using the sub-array mode of the IRAC\(^3\) (Fazio et al. 2004), with the shortest available frame time of 0.02 s (effective exposure time of 0.01 s). The sub-array mode outputs data from only one corner of the detector, in a 32\(\times\)32 pixel format, thus allowing the shortest possible exposure times. The observations of CF Cas were made using the full-array mode (0.4 s frame time, 0.2 s effective exposure time) because it is relatively faint compared to the other program stars.

The sub-array data are provided by the Spitzer Science Center (SSC) in two forms: as an image cube of 64 frames (each 32\(\times\)32 pixels) and as a single combined image; all further discussions to sub-array data refer to the combined form (\textit{sub2d} extensions). All data were retrieved in the basic calibrated data (BCD) format, and were reduced using the most recent pipeline (S18.18.0).

\(^{3}\) The IRAC instrument handbook and ancillary data products are available at http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/.
The stellar flux in each image was measured using the Mosaicking and Point-source Extraction (MOPEX) package (Makovoz & Marleau 2005). The pipeline script *apex_user_list_Iframe.pl* (included with MOPEX) was used to perform profile fitting photometry. Uncertainty images were supplied to MOPEX using the square root of the input image frame.5 Once the first-pass fluxes had been obtained we processed the data to correct for three systematic effects. These are (1) the masking of saturated or markedly nonlinear pixels; (2) corrections for non-uniformity of response across individual pixels; and (3) correction for image persistence, in which a bright source will leave behind a trail of spurious flux as the telescope executes its dither pattern. The three effects are examined and the derived corrections are explained in detail in the Appendix.

The final stellar flux for each epoch is determined from the mean of the nine dithered flux measurements from MOPEX, modified by the three corrections. The random error is adopted as the dispersion of the nine measurements and the systematic error is taken as the zero-point error adopted by the SSC, viz., 0.016 mag for both [3.6] and [4.5] (Reach et al. 2005). Table 3 shows a sample of the IRAC photometric data (the magnitudes are named [3.6] and [4.5]) available for the 37 stars.6

### 4. RESULTS

#### 4.1. Mid-IR Light Curves for 37 Galactic Cepheids

Periods from the General Catalog of Variable Stars (Samus et al. 2009) were assumed. In the cases of U Car and V340 Nor, periods were computed using photometric data from Laney...
& Stobie (1992). Figure 1 presents the individual light and color curves (Vega magnitudes) for each Galactic Cepheid. Data points from Marengo et al. (2010) are shown as open triangles for comparison, when available. All are in good agreement except for U Car where the difference is likely due to a phase shift resulting from a period increase between the Laney & Stobie (1992) data and ours. All the light curves are plotted with the same magnitude range to emphasize relative changes in signal-to-noise ratio and amplitudes. The internal photometric precision is high, ranging from 0.004 to 0.029 mag. Interestingly, for the longer-period Cepheids, there is strong variation in the [3.6]–[4.5] color. This is due to the temperature-dependent carbon monoxide (CO) band in the [4.5] Channel, as will be discussed in Section 7.

Smooth light curves were generated using a Gaussian local estimation (GLOESS) algorithm. GLOESS is an interpolating method that uses second-order polynomials to fit the data locally throughout the cycle. The data points surrounding the point to be fit are assigned weights according to a Gaussian window function; weights depend on their distance (in phase) from the fit point. The method has been used to conveniently obtain mean magnitudes by Persson et al. (2004) and Scowcroft et al. (2011) for LMC Cepheids, and by Monson & Pierce (2011) for Galactic Cepheids. These data are uniformly sampled so the error on the mean is \( \sigma = A/N\sqrt{12} \), where \( A \) is the peak-to-peak amplitude of the light curve and \( N \) is the number of sample points; this is discussed in the Appendix of Scowcroft et al. (2011). The final total uncertainty in the mean magnitude turns out to be dominated by the systematic zero-point calibration of the Spitzer warm mission. Because the uncertainties in Channels 1 and 2 are correlated with each other, uncertainties in the color were also determined using the above equation. Table 4 gives the [3.6] and [4.5] IRAC intensity-mean magnitudes and colors for the 37 Cepheids.

### 4.2. Mid-IR Extinction Corrections

Before discussing the period–luminosity and period–color relationships, we shall need to correct for extinction. Compared to optical wavelengths, reddening, and extinction corrections are relatively small at mid-IR wavelengths. They must, nevertheless, be quantified and applied because values of \( A_V \) can exceed 3 mag in our sample. We adopted an extinction law for all stars that is applicable along average lines of sight through the diffuse interstellar medium. The extinction law of Indebetouw & van der Kruit (1977) is used:

\[
A_{\text{IR}} = A_V + K_{\text{IR}} \cdot A_V
\]

where \( A_{\text{IR}} \) is the extinction at mid-IR wavelengths, \( A_V \) is the visual extinction, and \( K_{\text{IR}} \) is the extinction coefficient for mid-IR wavelengths. The value of \( K_{\text{IR}} \) is determined from the extinction curve, which is assumed to be the same as that at optical wavelengths.

### Notes

4 Shown with the expected random errors from the averaging algorithm; see the text. The systematic errors are 0.016 mag for both the [3.6] and [4.5] data.

5 Because the errors in Channels 1 and 2 are correlated, the color error was calculated independently by using the error algorithm described in the text.
Figure 1. IRAC [3.6] and [4.5] light curves for 37 Galactic Cepheids. The error bars correspond to the random photometric error and the solid line is the GLOESS interpolated curve. Data points from Marengo et al. (2010) are overplotted as open triangles when available.

et al. (2005) combined with that of Cardelli et al. (1989) best fulfill this choice. The relations $A_{[3.6]}/AK = 0.56 \pm 0.06$ and $A_{[4.5]}/AK = 0.43 \pm 0.08$ (Indebetouw et al. 2005) were derived from field stars in the Galactic plane and are probably applicable to the Cepheids in this study.7

To scale the extinctions at $K$ to the reddenings $E(B-V)$ we used the extinction law derived by Cardelli et al. (1989): $A(\lambda)/A_V = a(x) + b(x)/R_V$, where $a = 0.574x^{1.61}$, $b = -0.527x^{1.61}$, $x = 1/\lambda$, and $R_V$ is the ratio of total-to-selective absorption ($R_V = A_V/E(B-V)$). Using a wavelength of $\lambda = 2.164 \mu m$ for the $K$ filter (actually $K_s$) as adopted by Indebetouw et al. (2005) and an average $R_V = 3.1$, we find $A_K/A_V = 0.117$. The combined relations yield a final total-to-selective extinction of $A_{[3.6]}/E(B-V) = 0.203$, $A_{[4.5]}/E(B-V) = 0.156$, and $E([3.6] - [4.5])/E(B-V) = 0.047$.

Use of the Indebetouw et al. (2005) mid-IR extinction law might be questioned on general grounds. Three stars have $E(B-V) > 1$, above which the corrections will begin to introduce systematic errors. For example, measured values of $A_{[3.6]}/AK$ range from 0.41 (Chapman et al. 2009) to 0.64 (Flaherty et al. 2007). Toward the Galactic center Nishiyama et al. (2009) obtain $0.50 \pm 0.01$. For V367 Sct ($E(B-V) = 1.231$) the total range in $A_{[3.6]}$ is 0.10 mag. The uncertainties

7 Following Indebetouw et al. (2005) we use $K$ to mean the $K_s$ filter of the 2MASS survey.

8 See www.pas.rochester.edu/~emamajek/memo_ir_reddening.html for a summary.
in $E(B - V)$ are all $\leq 0.03$ mag except for GY Sge, where $\sigma(E(B - V)) = 0.17$. This value introduces uncertainties of 0.035 and 0.027 mag into the 3.6 and 4.5 $\mu$m magnitudes, respectively. Finally, if the uncertainty in $A_{[3.6]} / E(B - V)$ is as large as 0.05 (see above), the corresponding corrections will remain negligibly small.

5. PERIOD–LUMINOSITY RELATIONS
AT 3.6 AND 4.5 $\mu$m

We now present the period–luminosity (PL) relations for the 37 Cepheids in our sample. Table 1 shows that the sample may be divided into three subsamples, depending on the origin of their distance measurements. Henceforth we consider each subsample separately, as the three methodologies for distance determinations are quite different. In Section 5.2, we discuss in detail three weighting techniques for the data points. In the following sections, we have adopted unweighted fits in finding slopes and zero points.

5.1. The Three Subsamples

Of the 37 Cepheids, 10 have direct geometric parallaxes determined from HST guide camera data (Benedict et al. 2007) and therefore have the most accurate distance determinations currently available. The data for the sample are provided in Table 5. Figure 2 shows the data and zero-point fit using uniform weighting; the distance uncertainties are displayed for reference as error bars. The data include the final de-reddened [3.6] and [4.5] mag, the final adopted distance moduli, extinctions, and absolute magnitudes. Following Benedict et al. (2007) we have applied Lutz–Kelker–Hanson corrections (Lutz & Kelker 1973; Hanson 1979, LKH) to these parallaxes; the corrections
are systematic and range from $-0.02$ to $-0.15$ mag with uncertainties of $\pm 0.01$ mag. For completeness we include in Table 6 and Figure 3 the corresponding data for the HST sample without LKH corrections.

Of the 37 Cepheids, 18 are likely to be members of star clusters or associations for which distance moduli have been estimated from main-sequence (MS) fitting (Turner & Burke 2002; Turner 2010; Majaess et al. 2011, 2012a, 2012b). Table 7 lists the data and Figure 4 shows the forced LMC slope and zero-point fit for the uniformly weighted data. The Cepheids CEa and CEb Cas are presumably at the same distance as CF Cas by virtue of common membership in the cluster NGC 7790 and although separated by only 1\,"0 they were easily split using point response function (PRF) photometry and they have been included in the sample.

Of the 37 Cepheids, 32 have distance determinations based on the IRSB technique (Storm et al. 2011b, and references therein). Table 8 contains the data and Figure 5 shows the fit and zero point for uniformly weighted data; W Sgr was rejected from the analysis due to its relatively high uncertainty.

Each of the data subsamples were fit using a PL relationship of the form: $M = a \log P - 1 + b$. As will be shown below we find no statistically significant difference between the slope of the $[3.6]$ PL of $-3.31 \pm 0.05$ for the LMC and that of the HST parallax sample. We thus adopt the LMC slope for the PL fit and re-determine zero points for each subsample. The magnitude residuals from the PL fits are highly correlated with each other, suggesting that the widths of the PL relations are not driven by random photometric errors. Rather, the correlated scatter is most...
Figure 1. (Continued)
likely some combination of deterministically correlated (unit slope) distance errors and the intrinsic (correlated) positions of these Cepheids in the instability strip (IS). If the IS is represented by a rectangular distribution (i.e., it is uniformly filled and has hard limits at the blue and red edges) then the peak-to-peak width in the residuals can be interpreted as the width of the IS or at least an upper limit, which in the HST subsample is ~0.4 mag.
5.2. Dependence of PL Relations and Uncertainties on Weighting Techniques

The PL relations were fit to each of the three subsamples using multiple weighting schemes and also by further restricting the subsamples by period cuts. The final uncertainty in absolute magnitude for an individual Cepheid is dominated by the uncertainty in its distance. In deriving a PL relation, however, an additional spread is caused by the finite width of the IS, and biases in the PL slope and zero point may result depending on how the strip is filled. To investigate these uncertainties and their effects on the derived PL fits, we applied different weighting schemes. In addition, for each of the data sets, we investigated different period cuts so that the Galaxy data sets more closely matched the period range of the LMC sample, viz., 6–60 days. Finally, a fixed slope determined from the LMC data was force fitted to the Galactic data to determine only the Galactic zero point. The data were fit using a PL relationship of the form $M = a(\log P - 1) + b$. Table 8 presents the results using three different weighting methods for the data in this analysis.

The first weighting method applies a uniform uncertainty of 0.1 mag to each Cepheid, the purpose of which is to provide results presumably less biased by Cepheids which may have underestimated distance uncertainties. The second method applies traditional weights as $\sigma^{-2}$ to the absolute magnitudes. The third method falls between the first two in that it assumes an intrinsic scatter in the IS. In this case, an additional uncertainty of 0.1 mag is added in quadrature to each individual uncertainty. The value of 0.1 mag is adopted from the average rms scatter of the LMC data points around the best fit.

5.3. PL Slopes

The IRSB slopes closely match the HST slopes, which is not surprising because the most recent IRSB distances used a projection factor ($p$-factor) calibrated using the HST parallaxes (but without LKH corrections) as priors. The IRSB slope is better constrained because of sample size, but is still dependent on the adopted $p$-factor. The effect of varying the weighting method is most noticeable in the Cluster MS fits where the slopes differ by more than 2σ between the first two methods, and converges to within 1σ of the HST, IRSB, and LMC slopes using the third weighting method. As discussed by Turner (2010) some long-period Cepheids populate the blue edge of the IS and can bias the slope, so it is necessary to include an estimate of the intrinsic width of the IS to reduce the bias. The benefit of the third weighting method is that the intrinsic width of the IS is included as well as individual uncertainties for each Cepheid. As can be seen in Table 9 the slopes for all three methods agree very well.
with each other using the softened weights. Since the slope from each method agrees with that of the LMC, we chose to adopt the better-determined LMC slope and to redetermine the zero points for both the [3.6] and [4.5] PL relations. This decision is further backed by recent studies that find near-identical PL slopes for the MW and LMC in the near-infrared (Storm et al. 2011a).

### 5.4. PL Intercepts

As mentioned above, some of the long-period Cepheids occupy the blue edge of the IS and although we forced a fixed (LMC) slope, the zero point can now be slightly biased if the entire sample does not uniformly populate the IS. We therefore limit ourselves to adopt zero points from the uniformly weighted fits. This effectively assumes the width of the IS is the only source of uncertainty and can be treated as equal for each Cepheid. We also chose to make use of the entire period range which provides a larger sample and will more uniformly populate the IS. With these choices in hand, we now have zero points of _HST_ (without LKH) = \(-5.80 \pm 0.03\), _HST_ (without LKH) = \(-5.74 \pm 0.03\), _MS_ = \(-5.75 \pm 0.05\), and IRSB = \(-5.74 \pm 0.02\). We note again the agreement between the _HST_ (without LKH) and IRSB zero points as must be the case (see above). The average LKH correction is \(-0.06\) mag, which if applied to the IRSB calibration would shift the [3.6] IRSB PL zero point to \(-5.80 \pm 0.03\) mag. Because they are calibrated using the _HST_ parallaxes the IRSB zero point does not offer an independent baseline measurement; however, it does sample the IS better and since it yields the same zero point and scatter, it indicates that the _HST_ data are not too affected by paucity.

The Cluster Cepheids do offer an independent check of the zero point and they appear to confirm the _HST_ (without LKH) zero point. We note, however, that the outliers V Vul and TW Nor are more than 10% discrepant compared to their IRSB distances and rejecting them would change the Cluster zero point to \(-5.79\) mag in agreement with LKH. This is in agreement with the Ngewo (2012) results which also find a 0.04 mag relative offset between their derived Wesenheit PL distances to the Storm et al. (2011b) IRSB and Turner (2010) Cluster samples. Based on

### Table 9  Period–Luminosity (Leavitt) Laws

| Galaxy | Sample | Band | N   | weights= 1/0.12 | weights= 1/σM | weights = 1/(σM^2 + 0.12^2) |
|--------|--------|------|-----|----------------|--------------|-----------------------------|
| MW     | π_HST  | [3.6] | 10  | -3.40 ± 0.12   | -5.81 ± 0.04 | -3.35 ± 0.22                |
| MW     | π_HST 6 ≤ P ≤ 60 | [3.6] | 5   | -3.33 ± 0.18   | -5.82 ± 0.05 | -3.33 ± 0.35                |
| MW     | π_HST no LKH | [3.6] | 10  | -3.40 ± 0.12   | -5.75 ± 0.04 | -3.33 ± 0.22                |
| MW     | π_HST no LKH 6 ≤ P ≤ 60 | [3.6] | 5   | -3.27 ± 0.12   | -5.78 ± 0.05 | -3.27 ± 0.35                |
| MW     | π_MAS 6 ≤ P ≤ 60 | [3.6] | 18  | -3.00 ± 0.07   | -5.75 ± 0.02 | -3.43 ± 0.08                |
| MW     | π_MAS 6 ≤ P ≤ 60 | [3.6] | 11  | -3.30 ± 0.12   | -5.68 ± 0.03 | -3.19 ± 0.10                |
| MW     | π_IRSB 6 ≤ P ≤ 60 | [3.6] | 36  | -3.42 ± 0.05   | -5.73 ± 0.02 | -3.42 ± 0.09                |
| LMC    | π_HST 6 ≤ P ≤ 60 | [3.6] | 80  | -3.31 ± 0.05   | 12.70 ± 0.02 | -3.37 ± 0.07                |
| MW     | π_HST 6 ≤ P ≤ 60 | [3.6] | 10  | -5.80 ± 0.03   |              |                            |
| MW     | π_HST 6 ≤ P ≤ 60 | [3.6] | 5   | -5.82 ± 0.04   |              |                            |
| MW     | π_HST no LKH | [3.6] | 10  | -5.74 ± 0.03   |              |                            |
| MW     | π_HST no LKH | [3.6] | 5   | -5.77 ± 0.04   |              |                            |
| MW     | π_MAS 6 ≤ P ≤ 60 | [3.6] | 18  | -5.75 ± 0.02   |              |                            |
| MW     | π_MAS 6 ≤ P ≤ 60 | [3.6] | 11  | -5.67 ± 0.03   |              |                            |
| MW     | π_IRSB 6 ≤ P ≤ 60 | [3.6] | 36  | -5.74 ± 0.02   |              |                            |
| LMC    | π_IRSB 6 ≤ P ≤ 60 | [3.6] | 26  | -5.77 ± 0.02   |              |                            |

Notes. The form of the PL relation used in these fits is \( M = a(\log P - 1) + b \). The values in bold indicate our adopted PL slope and zero points. To eliminate asymmetric rounding errors when reporting two significant figures in the zero points a floor rounding function was used which rounds toward negative infinity rather than away from zero.

a The LMC sample does not contain Cepheids with periods less than six days. The LMC data are discussed in Scowcroft et al. (2011).

b Force fit the LMC slope from the unweighting method to find the zero point.
Figure 2. Leavitt PL relations for the HST Calibrators in the Galaxy at 3.6 (upper plot) and 4.5 μm (lower plot). The data have been corrected for Lutz–Kelker–Hanson bias. The relations are shown as solid lines, which were determined using a fixed slope found from the LMC data and a zero point found from the HST parallaxes (Benedict et al. 2007); the ±2σ boundaries are shown as dotted lines. The highly correlated magnitude residuals are plotted in the inset, showing that the peak-to-peak width of the IS as defined by the HST Galactic Calibrators is less than 0.4 mag.

Figure 3. Leavitt PL relations for the HST Calibrators in the Galaxy at 3.6 (upper plot) and 4.5 μm (lower plot). The data have not been corrected for Lutz–Kelker–Hanson bias. The relations are shown as solid lines, which were determined using a fixed slope found from the LMC data and a zero point found from the HST parallaxes (Benedict et al. 2007); the ±2σ boundaries are shown as dotted lines. The highly correlated magnitude residuals are plotted in the inset, showing that the peak-to-peak width of the IS as defined by the HST Galactic Calibrators is less than 0.4 mag.

Figure 4. Leavitt PL relations for the Cluster Cepheids in the Galaxy at 3.6 (upper plot) and 4.5 μm (lower plot). The relations are shown as solid lines, which were determined using a fixed slope found from the LMC data. The ±2σ boundaries are shown as dotted lines. The highly correlated magnitude residuals are plotted in the inset, showing that the peak-to-peak width of the IS as defined by the Cluster Galactic Calibrators is less than 0.8 mag.

Figure 5. Leavitt PL relations for the IRSB Cepheids in the Galaxy at 3.6 (upper plot) and 4.5 μm (lower plot). The relations are shown as solid lines, which were determined using a fixed slope found from the LMC data. The ±2σ boundaries are shown as dotted lines. The highly correlated magnitude residuals are plotted in the inset, showing that the peak-to-peak width of the IS as defined by the IRSB Galactic Calibrators is less than 0.6 mag.
of A points are defined at log $P = 0.1$ (Freedman & Madore 2010) and using the extinction law discussed in Section 4.2 (which yields a total LMC extinction $E_B$. By adopting a net extinction to the LMC of $18.6 \pm 0.01$ mag (Benedict et al. 2007).

We note that the scatter in the HST data is less than the average uncertainty assigned to the HST parallaxes and that we have chosen to adopt this (smaller) empirical scatter as a measure of the total zero-point uncertainty.

6. THE DISTANCE TO THE LMC

As will be discussed in Section 7, the 4.5 $\mu$m data are likely to be affected by CO absorption while the 3.6 $\mu$m data are not (see also Freedman et al. (2012)). Consequently, we have adopted the absolute PL zero point from the HST Leavitt Law at 3.6 $\mu$m ($-5.80 \pm 0.03$ mag) and compare that with the apparent zero point of the LMC PL relationship ($12.70 \pm 0.02$ mag); both zero points are defined at log $P = 1.0$ and the PL relations are parallel to each other. We found no measurable metallicity effects for the MW and LMC Cepheids at 3.6 $\mu$m for which there are spectroscopic [Fe/H] values (Freedman et al. 2012, Figure 2). By adopting a net extinction to the LMC of $E(B-V) = 0.1$ (Freedman & Madore 2010) and using the extinction law discussed in Section 4.2 (which yields a total LMC extinction of $A_{3.6} = 0.02$ mag), we find a distance modulus $(m-M)_{3.6}$ for the LMC of $18.48 \pm 0.04$ mag.

Alternatively, we followed a multi-wavelength approach to solve for reddening and distance modulus simultaneously (Freedman & Madore 2010). The multi-wavelength photometry for the LMC are taken from: Udalski et al. 1999 ($B$, $V$, and $I_C$), Persson et al. 2004 ($J$, $H$, and $K_s$), and Scowcroft et al. 2011 (3.6) and (4.5)). The Galactic Cepheid photometry were compiled from the literature (Berdnikov 2008; Barnes et al. 1997; Laney & Stobie 1992; Welch et al. 1984; Monson & Pierce 2011) and average magnitudes were found in the same manner as discussed in 4.1; see Table 10. The multi-wavelength PL relations are shown in Figure 6 and summarized in Table 11. The slopes were found by fitting the LMC data in the period range 3.8–60 days; a universal slope is considered. The Galactic zero points were found using the LMC slopes at each wavelength using only the HST parallax Cepheids; see 5.4 for details. The apparent distance moduli are plotted against inverse wavelength in Figure 7. The standard extinction law from Cardelli et al. (1989) was fit to the data to find the true LMC distance modulus of $18.48 \pm 0.03$ and average LMC reddening of $E(B-V) = 0.12 \pm 0.01$ mag. The $K_s$ and [4.5] data were excluded from the fit due to the effect of CO in those bands. This supersedes the value of $18.39 \pm 0.06$ found in Freedman & Madore (2010) and is in excellent agreement with other independent measures recently reviewed by Walker (2011) who finds a composite distance modulus of $18.48 \pm 0.05$ and Laney et al. (2012) who find a red clump distance of $18.47 \pm 0.02$.

7. PERIOD–COLOR RELATIONSHIPS

7.1. The Period–Color Diagram

CO absorption in the 4.5 $\mu$m band for cooler stars produces a significant period–color relation that moves the mean [3.6]–[4.5] color toward the blue at cooler temperatures, and longer periods. This effect is driven, as is the case for the light curve color variations (see below), by the temperature dependence of CO dissociation and not by the thermal color–temperature which has little effect on the slope of the continuum at these long wavelengths. The [3.6]–[4.5] period–color relation is shown in Figure 8 and the weighted least-squares fit to the de-reddened data (omitting Y Oph) is [3.6]–[4.5] LMC = $-0.09(\pm 0.01)(\log P - 1.0) - 0.03(\pm 0.01)$. For comparison, the LMC period–color relation is [3.6]–[4.5] LMC = $-0.09(\pm 0.01)(\log P - 1.0) + 0.01(\pm 0.01)$ (Scowcroft et al. 2011). The slopes of these fits are consistent, but the zero points differ by $0.04 \pm 0.01$ mag.
Table 10
Multi-wavelength Parameters for Galactic Cepheids

| Cepheid | log $P$ | $E$ | $\pi$ (mas) | $(m - M)$ | LKH | $m_B$ | $m_V$ | $m_I$ | $m_J$ | $m_H$ | $m_K$ | $m_{[3.6]}$ | $m_{[4.5]}$ |
|---------|---------|-----|------------|-----------|-----|------|------|------|------|------|------|-----------|-----------|
| $\ell$ Car | 1.551 | 0.154 ± 0.011 | 2.01 ± 0.20 | 8.48 ± 0.22 | −0.08 | 4.986 | 3.722 | 2.552 | 1.674 | 1.198 | 1.076 | 0.925 | 1.047 |
| $\zeta$ Gem | 1.007 | 0.018 ± 0.007 | 2.78 ± 0.18 | 7.78 ± 0.14 | −0.03 | 4.701 | 3.839 | 3.107 | 2.585 | ... | 2.114 | 2.025 | 2.037 |
| $\beta$ Dor | 0.993 | 0.058 ± 0.009 | 3.14 ± 0.16 | 7.52 ± 0.11 | −0.02 | 4.542 | 3.741 | 2.939 | 2.376 | 2.020 | 1.948 | 1.858 | 1.871 |
| W Sgr | 0.881 | 0.109 ± 0.007 | 2.28 ± 0.20 | 8.21 ± 0.19 | −0.06 | 5.412 | 4.665 | 3.846 | 3.252 | 2.952 | 2.828 | 2.721 | 2.719 |
| X Sgr | 0.846 | 0.227 ± 0.013 | 3.00 ± 0.18 | 7.61 ± 0.13 | −0.03 | 5.299 | 4.550 | 3.649 | 2.916 | 2.626 | 2.636 | 2.423 | 2.409 |
| Y Sgr | 0.761 | 0.203 ± 0.007 | 2.13 ± 0.29 | 8.36 ± 0.30 | −0.15 | 6.595 | 5.738 | 4.789 | 4.086 | 3.690 | 3.609 | 3.486 | 3.483 |
| $\delta$ Cep | 0.730 | 0.073 ± 0.007 | 3.66 ± 0.15 | 7.18 ± 0.09 | −0.01 | 4.602 | 3.955 | 3.168 | 2.689 | 2.378 | 2.310 | 2.221 | 2.217 |
| FF Aql | 0.650 | 0.204 ± 0.008 | 2.81 ± 0.18 | 7.76 ± 0.14 | −0.03 | 6.135 | 5.372 | 4.488 | 3.864 | 3.565 | 3.475 | 3.378 | 3.353 |
| T Vul | 0.647 | 0.073 ± 0.008 | 1.90 ± 0.23 | 8.61 ± 0.26 | −0.12 | 6.385 | 5.747 | 5.015 | 4.546 | 4.256 | 4.192 | 4.114 | 4.111 |
| RT Aur | 0.571 | 0.058 ± 0.011 | 2.40 ± 0.19 | 8.10 ± 0.17 | −0.05 | 6.050 | 5.468 | 4.730 | 4.251 | 3.982 | 3.924 | 3.853 | 3.849 |

Table 11
Multi-wavelength Period–Luminosity Relations for the LMC and MW

| Filter | $\lambda$ (\textmu m) | $\mu$ LMC | $\mu$ MW | $A_\lambda$ |
|--------|-----------------|-----------|-----------|------------|
| $B$    | 0.44            | 384       | 15.60 ± 0.03 | 0.42 |
| $V$    | 0.55            | 388       | 14.81 ± 0.02 | 0.31 |
| $I_C$  | 0.80            | 392       | 13.93 ± 0.01 | 0.20 |
| $J$    | 1.24            | 82        | 13.26 ± 0.02 | 0.15 |
| $H$    | 1.66            | 82        | 12.90 ± 0.02 | 0.12 |
| $K_s$  | 2.16            | 82        | 12.80 ± 0.02 | 0.11 |
| [3.6]  | 3.55            | 80        | 12.70 ± 0.02 | 0.11 |
| [4.5]  | 4.49            | 80        | 12.69 ± 0.02 | 0.11 |

Notes. The form of the PL relation is: $M_L = a(\log P - 1) + b$. The LMC slope is used to constrain the MW zero point. The apparent distance moduli ($\mu$) are found by differencing the LMC and MW zero points and the extinction ($A_\lambda$) is the solution from Figure 7.

Figure 8. Galactic period–color relation. The solid circles are the de-reddened colors for the 37 Cepheids in this study; see Tables 1 and 4. The solid line is the fit to all the data except Y Oph. The broken lines are theoretical trends from Ngeow (2012).

Ngeow et al. (2012) have presented a number of models for theoretical PC diagrams in the mid-IR. Their summary tables give slopes and zero points for several models of the PLs and [3.6]–[4.5] color covering a range of helium and metal abundance. Several of their model PCs are plotted with the data in Figure 8. Comparison of the theoretical slope of the [3.6]–[4.5] PC diagram shows reasonably good agreement with the Galaxy color data for a helium abundance of $Y = 0.31$.

7.2. Color Curves and CO Absorption Models

As pointed out in Section 4.1, the [3.6]–[4.5] color is characterized by systematic variations through the cycle. The color amplitude is also closely related to period, the longer-period stars having the largest variations. This effect, in complete analogy with the cause of the period–color relation, is again due to CO absorption in the 4.5 \textmu m band, as discussed by Scowcroft et al. (2011) and Marengo et al. (2010). The color variation extends only toward bluer colors from a baseline red color limit of ~0.01 mag; this can be seen Figure 9. The blue extent (blue indicating more absorption at 4.5 \textmu m) increases with period as the Cepheids reach intrinsically cooler temperatures. The effect of CO has only recently been observed over entire Cepheid pulsation cycles (see also Scowcroft et al. 2011).

To quantify the behavior of both the overall PC relation and the color curves, we have computed several synthetic spectra using appropriate Kurucz stellar models (Kurucz 1993; Castelli & Kurucz 2003; Sbordone et al. 2004; Sbordone 2005). Figure 10 shows the results. They indicate that at temperatures greater than approximately 6000 K absorption due to CO is nearly non-existent. As the temperature falls below 6000 K CO absorption in the 4.5 \textmu m band sets in, leading to the diminished flux observed in the 4.5 \textmu m light curve. The result is that the color curves should have larger amplitudes for Cepheids with longer periods, as they reach intrinsically cooler temperatures. This is precisely the behavior exhibited in the observed color curves. For the shorter-period Cepheids the color amplitude is diminished because these Cepheids are intrinsically hotter and...
Figure 9. De-reddened color vs. period. The red extent of each Cepheid is well defined near 0.01 mag. The blue extent increases with period due to CO molecular absorption in Cepheids that reach intrinsically cooler temperatures. The CO remains dissociated over a longer portion of the pulsation cycle.

Part of the systematic offset in the PC fits (Galaxy versus LMC) is plausibly explained by the difference in metal abundance between the two galaxies. Figure 10 shows that this shift should amount to ~0.02 mag offset per 0.5 dex change in metal abundance. Other effects such as rotation may also play a role, and in any case we are dealing with a very small effect.

8. SUMMARY

In this work, we have presented the first results from the Galactic Cepheid campaign of the CHP. Light curves created from uniformly spaced observations with high-precision photometry yield intensity-mean magnitudes for 37 Galactic Cepheids spanning a range of periods from 4 to 70 days.

Using the precise geometric parallax measurements from Benedict et al. (2007) we have found a Galactic zero point (set to log $P = 1.0$) for the 3.6 $\mu$m period–luminosity (Leavitt) law of $-5.80 \pm 0.03$ mag. Comparing this to the LMC zero point we find an LMC distance modulus of 18.48 $\pm$ 0.04 mag, which is confirmed using a multi-wavelength analysis. The uncertainty represents a factor of two improvement over previous Key Project measurements (Freedman & Madore 2010) and will be made stronger with future geometric parallaxes to the full sample from Gaia. The implications of this revised LMC distance modulus on the Key Project distances are discussed in Freedman et al. (2012).

The well-sampled light curves reveal a strong color variation for Cepheids with periods longer than 10 days. A second and related result is a clear period–color relation. Both correlations are caused by enhanced temperature-sensitive CO absorption at 4.67 $\mu$m in longer-period, intrinsically cooler Cepheids.

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APPENDIX

CORRECTIONS FOR SYSTEMATIC EFFECTS ON THE PHOTOMETRY

Saturated pixels. The first step in the reduction is to find and mask markedly nonlinear or saturated pixels. This is particularly important for stars as bright as the Cepheids in this program. Our routine works as follows: MOPEX fits the profile by masking unwanted pixels, and by assigning weights using the uncertainty image. Saturated pixels (near the center of the point-spread function (PSF)) will tend to have lower dispersions and hence artificially high weights (in the limit of complete saturation the dispersion will be zero). We found valid upper thresholds by experiment: the dispersions for the nine dither positions of a saturated star were found as a function of threshold level and the best level chosen. The final upper threshold values were 10,000 and 12,000 DN for the 3.6 and 4.5 $\mu$m bands, respectively. These were lower than those recommended in the IRAC Handbook.

Figure 10. Left: synthetic spectra showing the onset of CO molecular absorption in the IRAC Channel 2 bandpass. Right: the synthetic color, normalized to zero at 7000 K, for the generated model spectra. The color trends to the blue at cooler temperatures, a result of the CO molecular absorption.
Point response profiles and pixel phase corrections. Each stellar profile was fit with a PRF profile, a procedure that minimizes the residual between the input frame and a standard PRF supplied by MOPEX. Rather than having a functional form, the PRF is a look-up table containing different representations of a point source at various pixel phases. These are the distances from the center of the stellar profile to the center of the nearest (integer valued) pixel. This complication arises because pixels do not have uniform response across them. The pixel phase correction (PPC) was included in the PRF tables provided by the SSC for the cold mission. This was not the case for the warm mission. The correction for an arbitrary profile was thus determined using all the data to find an empirical PPC as follows. For every nine-point dither pattern constituting a measurement one has an average count, and nine deviations from that count. (The deviations arise from the pixel phase variation.) The left-hand side of Figure 11 shows all those deviations plotted as a function of pixel phase. The total number of points is $9 \times 24 \times 37$ (9 dither positions per measurement, 24 light curve points per star, 37 stars). The strong correlation represents the residual PPC, which is easily removed to yield corrected data. The correction is of the form $f_{\text{ppc}} = u + v((1/\sqrt{2\pi}) - p)$, where $p = \sqrt{(x - \text{nint}(x))^2 + (y - \text{nint}(y))^2}$ is the pixel phase.\(^9\) The right-hand side of Figure 11 shows the results of applying the above correction to the data points on the left-hand side. The results are seen to be satisfactory.

The PRF photometry methods correct for several other systematic effects.

1. The fits have slightly different coefficients for saturated and unsaturated data, a systematic effect that probably arises from centroid offsets in masking central pixels. The coefficients were confirmed by masking non-saturated data.
2. The PRF varies across the array, but a fixed PRF was used for the sub-array data, located at column 233, row 35. For the full frame data (CF Cas) a lookup table was used to find the nearest PRF at each position.
3. MOPEX reports fluxes at the center of pixel flux and is normalized to a radius of 10 pixels, i.e., the IRAC standard aperture. Because the flux reported is that for a pixel phase of zero, an additional correction factor ($f_{\text{corr}}$) is applied to bring the flux to the average pixel phase, which corresponds to where the flux zero points were defined.

Finally, the flux is placed on the standard Vega magnitude system by dividing by the photometric flux zero points ($z_p$); $280.9 \pm 4.1$ and $179.7 \pm 2.6$ [Jy], for [3.6] and [4.5], respectively (Reach et al. 2005). The final-corrected magnitude ($m$) is found from the PRF flux ($F_{\text{PRF}}$), which is reported in $\mu$Jy, by the following equation:

\begin{equation}
m = m_0 - 2.5 \log \left( \frac{F_{\text{PRF}}}{z_p} \right)
\end{equation}

\(^9\) This equation is taken from the IRAC Handbook. The coefficients guarantee that the average deviation is zero and thus the correction does not introduce a spurious shift in the average measurement.
Figure 12. Dither time series of PSF-subtracted images for one epoch of RT Aur showing the nine dither positions (Channel 1). RT Aur has been fit using MOPEX and the model fit was subtracted leaving the residual. In these frames (ordered 1–9), it is possible to see the latent image of the star trail as the telescope slewed into position at time-stamp 1. The trail is nearly dissipated by time-stamp 9; but new latent images are formed at the location of each of the previous dithers. By time-stamp 9 the previous 8 latent images reveal the full Reuleaux dither pattern as a faint afterglowing latent triangle.

Table 12

| Channel Criterion | \(u\) | \(v\) | \(f_{\text{corr}}\) | \(z_p\) |
|-------------------|------|------|----------------|-----|
| Ch 1. non-saturated | 1.000 | 0.080 | 1.021 | 280.9 ± 4.1 |
| Ch 1. saturated | 1.000 | 0.000 | 1.021 | 280.9 ± 4.1 |
| Ch 2. non-saturated | 1.000 | 0.025 | 1.012 | 179.7 ± 2.6 |
| Ch 2. saturated | 0.965 | −0.050 | 1.012 | 179.7 ± 2.6 |

Note. A source is considered saturated if 1 or more pixels were masked during the PRF fitting procedure; see the text.

Relation:

\[ m = -2.5 \log \left( \frac{F_{\text{PRF}} \cdot 10^{-6}}{f_{\text{corr}} \cdot f_{\text{ppc}} \cdot z_p} \right). \]

Table 12 contains the constants for each channel.

Image persistence or latency. The sub-array data were taken with short exposure times on bright objects, and with short settling times between dithers. As a consequence, the data are prone to short-term image persistence from previous dithers and observations; see Figure 12. A multi-stage process was undertaken to mitigate image persistence for each frame. First, the stellar profile was fit in each of the nine dithered frames using the PRF-fitting algorithm in the MOPEX script described above.

The residual images were averaged together using a nearest neighbor weighting scheme for each dither position. Lowest weights were given to future frames and higher weights were given to the most recent frames to create an approximate map of the image persistence at each dither position. The persistence maps were then subtracted from the original data leaving only the source; see Figure 13. Note that this process simply describes creating a local background frame by combining dithered frames where the source(s) has been modeled and subtracted rather than masked. Each background/persistence-subtracted image was passed through the MOPEX pipeline to perform a second and final PRF fit.

The latency can affect aperture photometry measurements by nearly 5% in the short (0.02 s) sub-array data. The effect is larger for shorter exposure times when there is less time for the latency to dissipate. One advantage of the PRF-fitting algorithm is that it tends to ignore the latent pixels when fitting a PRF. After the latent image subtraction the PRF photometry changes by less than 1%.

Photometry checks. As a check of the photometric fidelity the standard star HD165459 was processed in the manner described above for various exposure times in sub-array and full-array mode resulting in non-saturated and saturated data. To quantify the effect of persistence both aperture and PRF photometry
were performed on the standard star both prior to, and after, the persistence correction. Prior to the correction, the aperture photometry was consistently reporting 5%–15% higher flux than expected for the shortest exposure times while after the persistence correction the aperture photometry was typically only 0%–5% higher than expected. The PRF photometry was relatively unaffected by the persistence correction, changing by less than 1% before and after the persistence correction. The standard star comparisons represent the worse case scenario since the long exposures (saturated data) were taken just prior to the short exposures and subsequently suffered from a relatively large amount of persistence. The final PRF photometry results for the non-saturated standard data are $6.588 \pm 0.007$ mag and $6.571 \pm 0.008$ mag and $6.587 \pm 0.014$ mag and $6.564 \pm 0.017$ mag for the saturated data. Both are in good agreement with the standard magnitudes of $6.593 \pm 0.029$ mag and $6.575 \pm 0.028$ mag found by Reach et al. (2005) for the Cepheids, the difference in PRF photometry before and after the persistence correction was also less than 1%; except for $\ell$ Car, the most severely saturated star in our sample, in which case the difference was 6% and 3% in Channels 1 and 2. We report here the final PRF photometry resulting from a persistence-subtracted image.

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Figure 13. Image persistence mitigation for Channel 1. Top left: original BCD image of the Galactic Cepheid RT Aur. Top middle: residual image after preliminary PRF fitting. Top right: persistence map created from weighted average of nine dithered residual images. Bottom left: original BCD with background/persistence map subtracted. Bottom middle: the uncertainty map with background pixels masked and only the core region used for PRF fitting. Bottom right: final residual image after persistence map was subtracted. The same procedure was followed for Channel 2, although the latency effect was negligible.
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