The Cepheid Period-Luminosity Relation at Mid-Infrared Wavelengths: II. Second-Epoch LMC Data

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ABSTRACT

We present revised and improved mid-infrared Period-Luminosity (PL) relations for Large Magellanic Cloud (LMC) Cepheids based on double-epoch data of 70 Cepheids observed by Spitzer at 3.6, 4.5, 5.8 and 8.0 \( \mu \)m. The observed scatter at all wavelengths is found to decrease from \( \pm 0.17 \) mag to \( \pm 0.14 \) mag, which is fully consistent with the prediction that the total scatter is made up of roughly equal contributions from random sampling of the light curve and nearly-uniform samplings of stars across the instability strip. It is calculated that the Cepheids in this sample have a full amplitude of about 0.4 mag and that their fully-sampled, time-averaged magnitudes should eventually reveal mid-infrared PL relations that each have intrinsic scatter at most at the \( \pm 0.12 \) mag level, and as low as \( \pm 0.08 \) mag after correcting for the tilt of the LMC.

1. INTRODUCTION

In an earlier paper (Freedman et al. 2008, hereafter Paper I) we presented a preliminary calibration of the mid-infrared LMC Cepheid Period-Luminosity (PL) relations at 3.6, 4.5, 5.8 and 8.0 \( \mu \)m followed by an analysis of the wavelength dependence of the slopes and scatter in those relations. Those observations were derived from data serendipitously obtained by Spitzer during the course of the Surveying the Agents of a Galaxy’s Evolution (SAGE) Project (Meixner et al. 2006a). The main conclusion was that even single-phase data (for known Cepheids with published periods) provided PL relations that had a mean scatter of only
about $\pm 0.17$ mag, largely independent of wavelength. A plausible case was made that about
half of the scatter was due to the random-phase nature of single observations (sampling
light curves with a full amplitude of $0.3-0.4$ mag), and that the other half of the scatter
was being contributed by the intrinsic width of the instability strip. The latter was then
self-consistently estimated to have an edge-to-edge width of $0.3-0.4$ mag. Here we consider
the effects of doubling the number of observations of the same (fixed size) sample of 70
long-period LMC Cepheids as were examined in Paper I.

The second (and last) installment of the combined and revised catalog\footnote{Available from IRSA at \url{http://irsa.ipac.caltech.edu/data/SPITZER/SAGE/}} of point sources
in the LMC has been released by the SAGE team. We have taken 4-band photometry from
this catalog for epochs 1 and 2; the epoch 1 photometry was replaced by the SAGE team
for consistency. This provides us with 560 individual observations of 70 Cepheids spread
over 4 wavelengths and separated in time by about 7 months. The quoted precision of the
individual data points varies systematically with period/magnitude, ranging from $\pm 0.01$ mag
for the brightest (longest-period) Cepheids at about 80 days, up to $\pm 0.10$ mag for the faintest
(short-period) Cepheids in our sample at about 6 days. The individual observations for both
epochs are listed in Table 1, revising and updating our earlier tabulation in Freedman et al.
(2008).

Our sample is based on the Persson et al. (2004) subset of well-observed LMC Cepheids
selected to be uncrowded. Significantly larger samples (200 to nearly 600 stars, depending on
wavelength) have been studied by Ngeow & Kanbur (2008). Their analysis results in some
very different conclusions from ours. We comment briefly on these differences and explore
their probable origin at the end of Sections 2 and 3.

2. IRAC Mid-Infrared Period-Luminosity Relations

The four mid-IR period-luminosity relations, presenting all 560 random-phase observa-
tions of the 70 Cepheids, are given in Figures 1 and 2. Details of the SAGE observations
are given in Paper I; here we simply note that for some of the Cepheids the data for the
reprocessed photometry differs slightly from the previous release used in Paper I. In this
paper we use the most recently processed photometry for both epochs. The solid line gives
a least-squares fit to the plotted data. The dashed lines mark the two-sigma limits on the
scatter in each of the PL relations taken from Paper I. Despite the factor-of-two increase
in the number of observations it is interesting to note that virtually all of the new data
points fall within the previous limits. This was to be expected if the observed range of the

distribution is being defined by random sampling of finite-amplitude light curves. If the scatter were instead dominated by random errors in the photometry alone, the range would increase with sample size; it does not. We can then with some confidence go on to interpret the scatter physically.

Averaging the two-epoch photometry for individual Cepheids significantly decreases the scatter about the mean PL relation. This is because averaging brings us closer to the time-averaged mean magnitude of the individual Cepheids (by damping out the phase-induced excursions.)

How much of the total scatter is due to the random sampling of the light curves, and how much is due to the intrinsic width of the Cepheid instability strip, projected into the period-luminosity plane? In Paper I we suggested that the split was 50:50. We can now quantitatively test that prediction.

2.1. Period-Luminosity Fits

Weighted, least-squares, linear fits to each of the four mid-IR data sets are given in Section 3. The slopes, zero points, respective errors and $rms$ scatter, listed for each bandpass, are consistent with our previous results from Paper I. The slopes at each wavelength all have values of around -3.4, with a slight trend of increasingly negative values towards longer wavelengths. The scatter around each of the fits is relatively constant at $\pm 0.16-0.17$ mag; and from filter to filter the scatter of individual data points is highly correlated (see Figures 3-5 and discussion below).

2.2. Correlations in the Scatter

In Figure 5 we show the highly correlated nature of the magnitude differences in a given band plotted against the magnitude differences for the same stars, but at the other wavelengths. Clearly the observed differences are not random noise, but rather due to the physically correlated changes generated by light variation of the Cepheids themselves. Since there appears to be no significant deviation from a one-to-one correspondence in these variations, this is consistent with the dominant contributor in each of these bands being due to radius variations, as expected at these long wavelengths (Madore & Freedman 1991).

If the magnitude differences in the two observations are purely a result of changes intrinsic to the Cepheid during its cycle then the distribution of those differences should be consistent with our expected mid-infrared light curve and that distribution should reach a
maximum at the full amplitude. Consulting the lower right panel in Figure 8 of Madore & Freedman (2005) which shows the marginalized distribution of amplitudes for a two-epoch, random sampling of a Cepheid light curves, shows that the expected distribution function should be triangular in form with its peak at zero difference between consecutive observations and its minimum at a value corresponding to (the unlikely, two-point, chance-sampling of) the full amplitude of the lightcurve. Examination of Figure 6 shows that the observed distributions of differences (upper histograms) correspond to this prediction and that the most probable amplitude for these Cepheids at all wavelengths is 0.4-0.5 mag. The lower portion of the main plot showing each of the individual differences (with symbols encoded by wavelength) indicates that there may be a slow decline of mean/maximum amplitude with decreasing period from a maximum amplitude of 0.5 mag around 40 days, falling to a maximum amplitude of 0.3 mag below 10 days.

We are now in a position to test the assumption made in Paper I that the measured variance in the single-phase PL relation is shared equally between the random sampling of the instability strip and the phase sampling of the individual light curve where the width of the instability strip (0.40 mag) contributes a scatter of ±0.12 mag and the amplitudes of the individual Cepheids (also 0.4 mag peak-to-peak) contribute another ±0.12 mag of scatter.

That is, if $\sigma_1$ is the scatter around the PL relation measured for the single-epoch data, and $\sigma_2$ is the scatter measured for the time-averaged two-epoch data then:

$$\sigma_1^2 = \sigma_{strip}^2 + \sigma_{cepheid}^2$$

$$\sigma_2^2 = \sigma_{strip}^2 + \sigma_{cepheid}^2 / 2$$

Thus

$$\sigma_{cepheid}^2 = 2(\sigma_1^2 - \sigma_2^2)$$

and

$$\sigma_{strip}^2 = 2\sigma_2^2 - \sigma_1^2$$

Converting observed scatter to intrinsic width (i.e., \(\sigma_{strip} \times \sqrt{N}\)) gives strip widths of 0.36, 0.37, 0.36 and 0.37 mag at 3.6, 4.5, 5.8 and 8.0 µm, respectively, and average Cepheid amplitudes of 0.43, 0.45, 0.43 and 0.43 mag in those same respective bandpasses. These amplitudes correspond well to the independently-estimated amplitudes derived from the magnitude-difference histograms discussed above.

What this means in practice is that, given the choice between observing more Cepheids or observing more phase points for the same set of Cepheids in order to reduce the error on the distance modulus, increasing the number of observations per Cepheid is initially
more effective given the larger amplitude of the stars compared to the intrinsic width of the instability strip. The advantage of numbers of observations over numbers of stars is about 3:2 in the variance, which scales inversely with $N$.

The short-wavelength residuals reported by Ngeow & Kanbur (2008) based on a completely different and considerably larger sample of 200 to 600 LMC Cepheids (depending on the wavelength), are significantly smaller than the values given here. For instance, they give (their Tables 2 & 4) a scatter about the mean of $\pm 0.10$ mag for the 3.6 and 4.5$\mu$m PL relations. Following the line of argument given above such small scatter (if real) would reduce both the amplitudes and the width of the instability strip to implausibly small values. Our data do not support those conclusions. It is possible that the procedures used by Ngeow & Kanbur in an attempt to remove outliers resulted in this remarkably low dispersion.

3. Absolute Calibration

In keeping with Paper I, we adopt a true distance to the Large Magellanic Cloud of $(m-M)_0 = 18.50$ mag and a mean reddening to the Cepheids of $E(B-V) = 0.10$ mag (Freedman et al., 2001). Applying this correction for the true distance modulus and applying extinction corrections (0.04 to 0.01 mag), we derive the following updated absolute calibrations for the Cepheid Period-Luminosity relations at mid-infrared wavelengths:

$$< M >_{3.6} = -3.40 (\log(P) - 1.0) \pm 0.02 - 5.81 \pm 0.03 \quad \sigma_{3.6} = \pm 0.135$$

$$< M >_{4.5} = -3.35 (\log(P) - 1.0) \pm 0.02 - 5.76 \pm 0.03 \quad \sigma_{4.5} = \pm 0.141$$

$$< M >_{5.8} = -3.44 (\log(P) - 1.0) \pm 0.03 - 5.81 \pm 0.04 \quad \sigma_{5.8} = \pm 0.137$$

$$< M >_{8.0} = -3.49 (\log(P) - 1.0) \pm 0.03 - 5.81 \pm 0.04 \quad \sigma_{8.0} = \pm 0.139$$

The last entry in each line is the scatter measured about the preceding regression line. The above-quoted slopes and their generally monotonic increase with wavelength (consistent with and confirming Figure 4, Paper I) are in conflict with the generally lower values and especially the puzzling reversal of the slopes with wavelength given by Ngeow & Kanbur (2008). We speculate that their increased sample size brings with it crowding and other photometric errors that affect their solutions. Certainly the dramatic increase in dispersion
around their solutions at longer wavelengths must be the result of photometric uncertainties and not due to (or expected from) physical processes intrinsic to the Cepheids themselves.

However, we note that there is still two additional sources of identifiable variance in these solutions: (1) back-to-front geometric effects due to the tilt of the LMC and (2) a spread of metallicity amongst the LMC Cepheids themselves. The analysis of Persson et al. (2004), given in their Table 6, clearly indicates that tilt contributes about ±0.08 mag of scatter to all solutions using this Cepheid sample. Removing that geometric term would suggest that the underlying (time-averaged) mid-infrared PL relations have an intrinsic scatter of ±0.08 mag. The compilation of measured atmospheric metallicities of individual LMC Cepheids by Romaniello et al. (2008) shows a spread of 0.5 dex in [Fe/H]. Any impact of this dispersion of metallicity on the mid-infrared magnitudes of these LMC Cepheids must be fully contained within the ±0.08 mag of residual scatter. However this scatter cannot be totally due to metallicity since there must ultimately be contributions due to mean-radius and mean-temperature variations of the Cepheids across the instability strip. Each of these second-order effects and any others that have not yet been explicitly considered (residual crowding effects and unresolved binary stars in the sample, for example) all must be contained in the residual scatter of ±0.08 mag.

4. Conclusions and Future Prospects

The total magnitude width of the LMC Cepheid instability strip at mid-infrared wavelengths is found to be 0.36 mag (uncorrected for the LMC tilt). This translates into an \( \text{rms} \) scatter of ±0.11 mag around any one of the four time-averaged, mid-infrared PL relations. In order to obtain a distance modulus statistically good to ±0.01 mag would require a sample of approximately 100 Cepheids. We further calculate that the average mid-IR amplitude of Cepheids in our sample is (peak-to-peak) 0.43 mag. To obtain time-averaged mean magnitudes for individual Cepheids good to ±0.02 mag would then require on the order of 36 randomly-phased observations.

Testing the mid-infrared PL relations for their sensitivity to metallicity, and providing an absolute calibration that is independent of the LMC distance scale are the obvious next steps in this process. However, Spitzer alone is certainly capable of detecting Cepheids out to 1-2 Mpc using reasonable (1-2 hour) integration times, but crowding from AGB and extended-AGB stars is likely to be the real limiting factor. Applications to galaxies appreciably beyond the Local Group and their use in shoring up the extragalactic distance scale must await JWST.
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Figure Captions

**Fig. 1** – Random-phase (3.6 and 4.5µm) IRAC Period-Luminosity relations for LMC Cepheids plotted over the log(P) range 0.7 to 1.8. Observations of the same star seen at different epochs are joined by solid vertical lines. The solid line is a weighted least-squares fit to the data. The broken lines represent ±2σ (typically ±0.33 mag) bounds on the instability strip taken from the single-phase data fits, consistent with Paper I. Note that virtually all of the new data points fall within the old boundaries: despite a factor of two increase in numbers of data points the range does not appear to increase. The sizes of the plotted symbols are comparable to the typical photometric error on a mid-range Cepheid, i.e., ±0.05 mag at log(P) = 1.3. A magnitude error of ±0.05 mag is shown in the lower right corner of each figure; at the shortest periods the reported errors on a single observation can be as high as ±0.10 mag.
Fig. 2 – The same as Figure 1 except that the plots are for 5.8 and 8.0 μm IRAC data.
Fig. 3 – Time-Averaged (3.6 and 4.5\(\mu\)m) IRAC Period-Luminosity relations for LMC Cepheids plotted over the log(P) range 0.7 to 1.8. Only two epochs contributed to the average, nevertheless the scatter drops measurably from around ±0.165 mag to about ±0.140 mag (see Section 3). The solid line is a weighted least-squares fit to the data. The thick broken lines are the ±2\(\sigma\) (typically ±0.28 mag) bounds on the instability strip taken from fits to the plotted time-averaged datasets. The thin dashed lines are the two-sigma bounds on the instability strip from Figures 1 & 2. The shrinkage between the two limits is significant and is interpreted in the text. The sizes of the plotted symbols are comparable to the typical photometric error on a mid-range Cepheid, i.e., ±0.05 mag at log(P) = 1.3. A magnitude error of ±0.05 mag is shown in the lower right corner of each figure; at the shortest periods the reported errors on a single observation can be as high as ±0.10 mag.
Fig. 4 – Time-averaged (5.8 and 8.0µm) IRAC Period-Luminosity relations for LMC Cepheids plotted over the log(P) range 0.7 to 1.8; otherwise see caption to Figure 3.
Fig. 5 – Correlated residuals from the PL and (upper left panel) PC fits. Deviations of individual phase points from the mean PL regression are shown to be highly correlated across the respective bandpasses. A unit-slope line is shown for reference, and scatter around that line is seen to be consistent with the photometric errors (typically $\pm 0.05$ mag) quoted for the individual observations. Maximum (correlated) excursions have an upper bound of $\pm 0.4$ mag which is probably representative of the full amplitude of Cepheids at these wavelengths. The upper left panel is illustrative of the lack of any significant correlation between magnitude and color residuals, primarily because there is no statistically significant change (with phase) in the colors of these Cepheids at mid-IR wavelengths. A typical (two-sigma) error bar is shown in the lower righthand corner of this plot: the change in magnitude for a given star is statistically significant, the change in color is not.
Fig. 6 – The absolute values of magnitude differences between the two epochs for the same star as a function of the period. Filled circles are 3.6\(\mu\)m amplitudes, open circles are 4.5\(\mu\)m data. Crosses and squares are magnitude differences for 6.8 and 8.0\(\mu\)m data, respectively. Note the possible increase in the maximum difference as a function period, consistent with the scaled upper envelope to the optical Period-Amplitude relation from Schaltenbrand & Tammann (1970), shown the series of broken straight lines. The histograms in the upper part of the figure represent the marginalized and binned amplitude data for each of the four IRAC bands increasing in wavelength from left to right. As predicted from simulations (Madore & Freedman 2005), the form of the histograms should be triangular, as is observed; and the x intercept should be the full amplitude of the variable star. Each of the histograms is consistent with an amplitude of 0.4 mag, as independently calculated from the change in residuals around the PL relation, discussed in Section 2.2.
| Cepheid | log(P) (days) | 3.6μm (mag) | 4.5μm (mag) | 5.8μm (mag) | 8.0μm (mag) |
|---------|--------------|-------------|-------------|-------------|-------------|
| HV 872  | 1.475        | 11.174      | 11.245      | 11.167      | 11.129      |
|         |              | 0.034       | 0.033       | 0.041       | 0.053       |
| HV 872  | 1.475        | 11.397      | 11.481      | 11.373      | 11.350      |
|         |              | 0.023       | 0.026       | 0.032       | 0.046       |
| HV 873  | 1.536        | 10.764      | 10.891      | 10.740      | 10.701      |
|         |              | 0.040       | 0.035       | 0.034       | 0.052       |
| HV 873  | 1.536        | 10.733      | 10.773      | 10.721      | 10.658      |
|         |              | 0.034       | 0.029       | 0.040       | 0.057       |
| HV 875  | 1.482        | 11.062      | 11.011      | 11.030      | 11.027      |
|         |              | 0.034       | 0.025       | 0.034       | 0.034       |
| HV 875  | 1.482        | 11.020      | 10.971      | 10.946      | 10.939      |
|         |              | 0.039       | 0.031       | 0.039       | 0.038       |
| HV 876  | 1.356        | 11.579      | 11.687      | 11.624      | 11.527      |
|         |              | 0.037       | 0.032       | 0.055       | 0.063       |
| HV 876  | 1.356        | 11.537      | 11.538      | 11.516      | 11.575      |
|         |              | 0.036       | 0.038       | 0.040       | 0.076       |
| HV 877  | 1.655        | 10.584      | 10.687      | 10.606      | 10.571      |
|         |              | 0.035       | 0.036       | 0.039       | 0.050       |
| HV 877  | 1.655        | 10.595      | 10.687      | 10.634      | 10.542      |
|         |              | 0.040       | 0.027       | 0.033       | 0.041       |
| HV 878  | 1.367        | 11.387      | 11.387      | 11.277      | 11.318      |
|         |              | 0.035       | 0.041       | 0.042       | 0.041       |
| HV 878  | 1.367        | 11.373      | 11.471      | 11.375      | 11.402      |
|         |              | 0.041       | 0.037       | 0.041       | 0.057       |
| HV 879  | 1.566        | 10.718      | 10.801      | 10.725      | 10.708      |
|         |              | 0.024       | 0.024       | 0.031       | 0.035       |
| HV 879  | 1.566        | 10.904      | 10.821      | 10.824      | 10.811      |
|         |              | 0.037       | 0.023       | 0.041       | 0.032       |
| HV 882  | 1.503        | 11.087      | 11.139      | 11.014      | 10.969      |
|         |              | 0.032       | 0.033       | 0.039       | 0.046       |
| Cepheid | log(P) (days) | 3.6μm (mag) | 4.5μm (mag) | 5.8μm (mag) | 8.0μm (mag) |
|---------|--------------|-------------|-------------|-------------|-------------|
| HV 882  | 1.503        | 11.315      | 11.338      | 11.215      | 11.163      |
|         |              | 0.053       | 0.034       | 0.036       | 0.050       |
| HV 887  | 1.161        | 12.288      | 12.217      | 12.213      | 12.223      |
|         |              | 0.052       | 0.074       | 0.065       | 0.056       |
| HV 887  | 1.161        | 12.235      | 12.238      | 12.233      | 12.197      |
|         |              | 0.039       | 0.042       | 0.050       | 0.057       |
| HV 889  | 1.412        | 11.189      | 11.342      | 11.228      | 11.119      |
|         |              | 0.042       | 0.060       | 0.050       | 0.053       |
| HV 889  | 1.412        | 11.226      | 11.267      | 11.253      | 11.170      |
|         |              | 0.058       | 0.043       | 0.048       | 0.053       |
| HV 891  | 1.235        | 11.734      | 11.721      | 11.788      | 11.652      |
|         |              | 0.041       | 0.042       | 0.049       | 0.059       |
| HV 891  | 1.235        | 12.036      | 12.082      | 12.055      | 12.034      |
|         |              | 0.051       | 0.047       | 0.070       | 0.058       |
| HV 892  | 1.204        | 12.155      | 12.148      | 12.096      | 12.194      |
|         |              | 0.048       | 0.038       | 0.042       | 0.066       |
| HV 892  | 1.204        | 11.982      | 11.959      | 11.930      | 11.967      |
|         |              | 0.038       | 0.033       | 0.051       | 0.056       |
| HV 893  | 1.325        | 11.730      | 11.705      | 11.674      | 11.706      |
|         |              | 0.051       | 0.037       | 0.065       | 0.053       |
| HV 893  | 1.325        | 11.697      | 11.776      | 11.684      | 11.675      |
|         |              | 0.044       | 0.042       | 0.056       | 0.051       |
| HV 899  | 1.492        | 11.350      | 11.464      | 11.359      | 11.275      |
|         |              | 0.032       | 0.039       | 0.049       | 0.049       |
| HV 899  | 1.492        | 11.213      | 11.219      | 11.153      | 11.137      |
|         |              | 0.035       | 0.042       | 0.068       | 0.041       |
| HV 900  | 1.677        | 10.324      | 10.350      | 10.311      | 10.186      |
|         |              | 0.027       | 0.029       | 0.034       | 0.044       |
| HV 900  | 1.677        | 10.382      | 10.441      | 10.353      | 10.263      |
|         |              | 0.023       | 0.029       | 0.028       | 0.043       |
| Cepheid | log(P) (days) | 3.6\(\mu\)m (mag) | 4.5\(\mu\)m (mag) | 5.8\(\mu\)m (mag) | 8.0\(\mu\)m (mag) |
|---------|---------------|----------------------|----------------------|----------------------|----------------------|
| HV 901  | 1.266         | 11.870               | 11.919               | 11.910               | 11.773               |
|         |               | 0.039                | 0.040                | 0.044                | 0.071                |
| HV 901  | 1.266         | 12.213               | 12.202               | 12.198               | 12.037               |
|         |               | 0.028                | 0.026                | 0.041                | 0.041                |
| HV 904  | 1.483         | 11.386               | 11.331               | 11.318               | 11.271               |
|         |               | 0.025                | 0.021                | 0.036                | 0.035                |
| HV 904  | 1.483         | 11.171               | 10.976               | 11.001               | 10.937               |
|         |               | 0.045                | 0.038                | 0.042                | 0.034                |
| HV 909  | 1.575         | 10.951               | 10.981               | 10.943               | 10.922               |
|         |               | 0.036                | 0.040                | 0.039                | 0.047                |
| HV 909  | 1.575         | 10.661               | 10.686               | 10.586               | 10.580               |
|         |               | 0.042                | 0.041                | 0.040                | 0.039                |
| HV 914  | 0.838         | 13.046               | 13.052               | 13.145               | 12.927               |
|         |               | 0.034                | 0.051                | 0.05                 | 0.097                |
| HV 914  | 0.838         | 13.226               | 13.204               | 13.195               | 13.320               |
|         |               | 0.042                | 0.036                | 0.095                | 0.109                |
| HV 971  | 0.968         | 12.808               | 12.806               | 12.808               | 12.795               |
|         |               | 0.042                | 0.053                | 0.082                | 0.088                |
| HV 971  | 0.968         | 12.638               | 12.504               | 12.588               | 12.552               |
|         |               | 0.048                | 0.038                | 0.061                | 0.080                |
| HV 932  | 1.123         | 12.213               | 12.167               | 12.165               | 11.935               |
|         |               | 0.039                | 0.050                | 0.068                | 0.145                |
| HV 932  | 1.123         | 12.415               | 12.458               | 12.313               | 12.057               |
|         |               | 0.031                | 0.040                | 0.051                | 0.103                |
| HV 953  | 1.680         | 10.159               | 10.219               | 10.167               | 10.135               |
|         |               | 0.030                | 0.032                | 0.043                | 0.041                |
| HV 953  | 1.680         | 10.266               | 10.364               | 10.234               | 10.185               |
|         |               | 0.037                | 0.029                | 0.033                | 0.043                |
| HV 997  | 1.119         | 12.403               | 12.550               | 12.484               | 12.376               |
|         |               | 0.043                | 0.041                | 0.071                | 0.065                |
| Cepheid | \( \log(P) \) (days) | 3.6\( \mu \)m (mag) | 4.5\( \mu \)m (mag) | 5.8\( \mu \)m (mag) | 8.0\( \mu \)m (mag) |
|---------|----------------------|---------------------|---------------------|---------------------|---------------------|
| HV 997  | 1.119                | 12.233              | 12.229              | 12.177              | 12.175              |
|         | 0.032                | 0.038               | 0.053               | 0.059               |
| HV 1002 | 1.484                | 10.900              | 10.930              | 10.898              | 10.814              |
|         | 0.032                | 0.030               | 0.046               | 0.036               |
| HV 1002 | 1.484                | 11.204              | 11.257              | 11.141              | 11.120              |
|         | 0.037                | 0.041               | 0.037               | 0.046               |
| HV 1003 | 1.387                | 11.511              | 11.499              | 11.502              | 11.483              |
|         | 0.034                | 0.033               | 0.044               | 0.061               |
| HV 1003 | 1.387                | 11.505              | 11.453              | 11.530              | 11.469              |
|         | 0.043                | 0.033               | 0.042               | 0.051               |
| HV 1005 | 1.272                | 11.787              | 11.780              | 11.722              | 11.741              |
|         | 0.032                | 0.028               | 0.038               | 0.045               |
| HV 1005 | 1.272                | 12.120              | 12.162              | 12.035              | 12.137              |
|         | 0.035                | 0.049               | 0.057               | 0.073               |
| HV 1006 | 1.153                | 12.113              | 12.205              | 12.152              | 12.020              |
|         | 0.047                | 0.040               | 0.067               | 0.053               |
| HV 1006 | 1.153                | 12.114              | 12.214              | 12.056              | 12.054              |
|         | 0.052                | 0.059               | 0.066               | 0.058               |
| HV 1013 | 1.383                | 11.515              | 11.598              | 11.508              | 11.412              |
|         | 0.024                | 0.026               | 0.031               | 0.038               |
| HV 1013 | 1.383                | 11.611              | 11.606              | 11.590              | 11.506              |
|         | 0.041                | 0.033               | 0.051               | 0.057               |
| HV 1019 | 1.134                | 12.262              | 12.279              | 12.240              | 12.348              |
|         | 0.043                | 0.042               | 0.054               | 0.099               |
| HV 1019 | 1.134                | 12.316              | 12.287              | 12.310              | 12.365              |
|         | 0.038                | 0.031               | 0.052               | 0.064               |
| HV 1023 | 1.424                | 11.306              | 11.445              | 11.334              | 11.249              |
|         | 0.035                | 0.031               | 0.037               | 0.044               |
| HV 1023 | 1.424                | 11.174              | 11.275              | 11.196              | 11.150              |
|         | 0.027                | 0.036               | 0.041               | 0.050               |
Table 1—Continued

| Cepheid | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|---------|---------------|-------------|-------------|-------------|-------------|
| HV 2244 | 1.145         | 12.321      | 12.333      | 12.367      | 12.273      |
|         | 0.052         | 0.043       | 0.065       | 0.064       |
| HV 2244 | 1.145         | 12.241      | 12.174      | 12.173      | 12.165      |
|         | 0.045         | 0.031       | 0.058       | 0.062       |
| HV 2251 | 1.446         | 11.094      | 11.011      | 11.011      | 11.019      |
|         | 0.027         | 0.045       | 0.037       | 0.042       |
| HV 2251 | 1.446         | 11.110      | 11.176      | 11.151      | 11.088      |
|         | 0.031         | 0.036       | 0.032       | 0.030       |
| HV 2257 | 1.594         | 10.985      | 11.011      | 10.914      | 10.907      |
|         | 0.038         | 0.041       | 0.039       | 0.048       |
| HV 2257 | 1.594         | 10.521      | 10.590      | 10.526      | 10.526      |
|         | 0.044         | 0.031       | 0.036       | 0.046       |
| HV 2260 | 1.114         | 12.458      | 12.457      | 12.399      | 12.463      |
|         | 0.041         | 0.035       | 0.045       | 0.051       |
| HV 2260 | 1.114         | 12.797      | 12.808      | 12.870      | 12.684      |
|         | 0.065         | 0.039       | 0.080       | 0.090       |
| HV 2270 | 1.134         | 12.398      | 12.309      | 12.305      | 12.265      |
|         | 0.047         | 0.034       | 0.063       | 0.068       |
| HV 2270 | 1.134         | 12.318      | 12.308      | 12.293      | 12.174      |
|         | 0.054         | 0.029       | 0.055       | 0.058       |
| HV 2282 | 1.166         | 12.082      | 12.087      | 11.989      | 12.063      |
|         | 0.066         | 0.042       | 0.051       | 0.068       |
| HV 2282 | 1.166         | 12.128      | 12.125      | 12.120      | 12.144      |
|         | 0.051         | 0.041       | 0.059       | 0.069       |
| HV 2291 | 1.349         | 11.902      | 11.863      | 11.821      | 11.792      |
|         | 0.040         | 0.046       | 0.066       | 0.052       |
| HV 2291 | 1.349         | 11.478      | 11.499      | 11.462      | 11.434      |
|         | 0.035         | 0.041       | 0.045       | 0.037       |
| HV 2294 | 1.563         | 10.526      | 10.494      | 10.422      | 10.477      |
|         | 0.047         | 0.035       | 0.043       | 0.047       |
| Cepheid | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|---------|--------------|-------------|-------------|-------------|-------------|
| HV 2294 | 1.563        | 10.808      | 10.765      | 10.726      | 10.759      |
|         |              | 0.035       | 0.029       | 0.044       | 0.036       |
| HV 2324 | 1.160        | 12.159      | 12.133      | 12.087      | 12.130      |
|         |              | 0.048       | 0.036       | 0.051       | 0.056       |
| HV 2324 | 1.160        | 12.325      | 12.276      | 12.215      | 12.313      |
|         |              | 0.046       | 0.040       | 0.056       | 0.077       |
| HV 2337 | 0.837        | 13.159      | 13.189      | 13.251      | 13.195      |
|         |              | 0.046       | 0.068       | 0.072       | 0.113       |
| HV 2337 | 0.837        | 13.230      | 13.194      | 13.070      | 13.321      |
|         |              | 0.051       | 0.070       | 0.088       | 0.129       |
| HV 2338 | 1.625        | 10.759      | 10.688      | 10.711      | 10.690      |
|         |              | 0.026       | 0.037       | 0.042       | 0.038       |
| HV 2338 | 1.625        | 10.370      | 10.445      | 10.389      | 10.347      |
|         |              | 0.028       | 0.020       | 0.031       | 0.031       |
| HV 2339 | 1.142        | 12.315      | 12.245      | 12.267      | 12.247      |
|         |              | 0.045       | 0.035       | 0.066       | 0.073       |
| HV 2339 | 1.142        | 12.101      | 12.084      | 12.078      | 12.113      |
|         |              | 0.029       | 0.025       | 0.042       | 0.054       |
| HV 2352 | 1.134        | 12.257      | 12.277      | 12.223      | 12.295      |
|         |              | 0.082       | 0.034       | 0.066       | 0.090       |
| HV 2352 | 1.134        | 12.393      | 12.341      | 12.298      | 12.337      |
|         |              | 0.041       | 0.027       | 0.065       | 0.062       |
| HV 2405 | 0.840        | 13.402      | 13.335      | 13.344      | 13.366      |
|         |              | 0.047       | 0.036       | 0.073       | 0.101       |
| HV 2405 | 0.840        | 13.250      | 13.296      | 13.109      | 13.171      |
|         |              | 0.039       | 0.041       | 0.079       | 0.097       |
| HV 2369 | 1.684        | 10.190      | 10.168      | 10.128      | 10.125      |
|         |              | 0.039       | 0.036       | 0.035       | 0.049       |
| HV 2369 | 1.684        | 10.133      | 10.169      | 10.109      | 10.083      |
|         |              | 0.038       | 0.029       | 0.040       | 0.044       |
| Cepheid | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|---------|--------------|-------------|-------------|-------------|-------------|
| HV 2432 | 1.038        | 12.459      | 12.438      | 12.530      | 12.414      |
|         |              | 0.069       | 0.038       | 0.068       | 0.072       |
| HV 2432 | 1.038        | 12.488      | 12.352      | 12.389      | 12.482      |
|         |              | 0.045       | 0.043       | 0.059       | 0.083       |
| HV 2527 | 1.112        | 12.669      | 12.610      | 12.562      | 12.530      |
|         |              | 0.028       | 0.043       | 0.043       | 0.078       |
| HV 2527 | 1.112        | 12.461      | 12.519      | 12.447      | 12.402      |
|         |              | 0.036       | 0.033       | 0.071       | 0.066       |
| HV 2538 | 1.142        | 12.219      | 12.245      | 12.153      | 12.083      |
|         |              | 0.030       | 0.020       | 0.046       | 0.038       |
| HV 2538 | 1.142        | 12.204      | 12.318      | 12.298      | 12.201      |
|         |              | 0.034       | 0.028       | 0.033       | 0.053       |
| HV 2549 | 1.209        | 11.738      | 11.759      | 11.738      | 11.718      |
|         |              | 0.039       | 0.041       | 0.056       | 0.056       |
| HV 2549 | 1.209        | 11.797      | 11.819      | 11.757      | 11.757      |
|         |              | 0.030       | 0.028       | 0.052       | 0.046       |
| HV 2579 | 1.128        | 12.104      | 12.121      | 12.078      | 12.075      |
|         |              | 0.038       | 0.034       | 0.056       | 0.079       |
| HV 2579 | 1.128        | 12.263      | 12.159      | 12.138      | 12.193      |
|         |              | 0.051       | 0.031       | 0.058       | 0.051       |
| HV 2580 | 1.228        | 11.721      | 11.821      | 11.763      | 11.707      |
|         |              | 0.028       | 0.023       | 0.032       | 0.038       |
| HV 2580 | 1.228        | 11.717      | 11.727      | 11.711      | 11.618      |
|         |              | 0.038       | 0.034       | 0.054       | 0.048       |
| HV 2733 | 0.941        | 12.856      | 12.820      | 12.848      | 12.812      |
|         |              | 0.050       | 0.039       | 0.057       | 0.092       |
| HV 2733 | 0.941        | 12.814      | 12.828      | 12.823      | 12.900      |
|         |              | 0.036       | 0.033       | 0.058       | 0.065       |
| HV 2749 | 1.364        | 11.720      | 11.768      | 11.690      | 11.543      |
|         |              | 0.045       | 0.039       | 0.058       | 0.063       |
Table 1—Continued

| Cepheid | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|----------|---------------|-------------|-------------|-------------|-------------|
| HV 2749  | 1.364         | 11.763      | 11.645      | 11.616      | 11.598      |
|          |               | 0.032       | 0.038       | 0.043       | 0.070       |
| HV 2793  | 1.283         | 11.529      | 11.626      | 11.561      | 11.516      |
|          |               | 0.031       | 0.044       | 0.053       | 0.055       |
| HV 2793  | 1.283         | 11.699      | 11.784      | 11.621      | 11.644      |
|          |               | 0.047       | 0.036       | 0.048       | 0.062       |
| HV 2836  | 1.244         | 11.962      | 12.037      | 11.908      | 12.055      |
|          |               | 0.031       | 0.034       | 0.061       | 0.053       |
| HV 2836  | 1.244         | 11.953      | 12.109      | 11.973      | 11.943      |
|          |               | 0.037       | 0.041       | 0.057       | 0.064       |
| HV 2854  | 0.936         | 12.942      | 12.886      | 12.940      | 12.880      |
|          |               | 0.029       | 0.029       | 0.048       | 0.067       |
| HV 2854  | 0.936         | 12.779      | 12.743      | 12.684      | 12.798      |
|          |               | 0.034       | 0.028       | 0.051       | 0.072       |
| HV 5655  | 1.153         | 12.167      | 12.185      | 12.115      | 12.109      |
|          |               | 0.050       | 0.040       | 0.054       | 0.065       |
| HV 5655  | 1.153         | 12.120      | 12.150      | 12.149      | 12.110      |
|          |               | 0.038       | 0.030       | 0.044       | 0.035       |
| HV 6065  | 0.835         | 13.201      | 13.257      | 13.162      | 13.331      |
|          |               | 0.036       | 0.040       | 0.076       | 0.105       |
| HV 6065  | 0.835         | 13.414      | 13.365      | 13.310      | 13.285      |
|          |               | 0.033       | 0.045       | 0.078       | 0.101       |
| HV 6098  | 1.384         | 11.168      | 11.134      | 11.135      | 11.151      |
|          |               | 0.027       | 0.027       | 0.028       | 0.032       |
| HV 6098  | 1.384         | 11.189      | 11.126      | 11.086      | 11.089      |
|          |               | 0.035       | 0.037       | 0.044       | 0.046       |
| HV 8036  | 1.453         | 11.224      | 11.316      | 11.215      | 11.293      |
|          |               | 0.041       | 0.043       | 0.043       | 0.053       |
| HV 8036  | 1.453         | 11.360      | 11.466      | 11.385      | 11.287      |
|          |               | 0.042       | 0.025       | 0.055       | 0.038       |
Table 1—Continued

| Cepheid   | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|-----------|---------------|-------------|-------------|-------------|-------------|
| HV 12471  | 1.200         | 12.044      | 12.129      | 12.030      | 12.007      |
|           |               | 0.040       | 0.035       | 0.053       | 0.067       |
| HV 12471  | 1.200         | 12.253      | 12.339      | 12.256      | 12.223      |
|           |               | 0.034       | 0.041       | 0.060       | 0.057       |
| HV 12505  | 1.158         | 12.416      | 12.453      | 12.533      | 12.460      |
|           |               | 0.036       | 0.035       | 0.085       | 0.074       |
| HV 12505  | 1.158         | 12.539      | 12.499      | 12.407      | 12.646      |
|           |               | 0.044       | 0.036       | 0.061       | 0.085       |
| HV 12656  | 1.127         | 12.339      | 12.299      | 12.289      | 12.301      |
|           |               | 0.048       | 0.037       | 0.058       | 0.067       |
| HV 12656  | 1.127         | 12.217      | 12.187      | 12.145      | 12.198      |
|           |               | 0.056       | 0.041       | 0.054       | 0.078       |
| HV 12700  | 0.911         | 12.910      | 12.908      | 12.989      | 12.899      |
|           |               | 0.043       | 0.044       | 0.073       | 0.085       |
| HV 12700  | 0.911         | 12.900      | 12.914      | 12.873      | 12.996      |
|           |               | 0.035       | 0.030       | 0.066       | 0.071       |
| HV 12724  | 1.138         | 12.326      | 12.365      | 12.338      | 12.316      |
|           |               | 0.051       | 0.039       | 0.064       | 0.071       |
| HV 12724  | 1.138         | 12.492      | 12.566      | 12.463      | 12.443      |
|           |               | 0.046       | 0.040       | 0.073       | 0.063       |
| HV 12815  | 1.416         | 11.063      | 11.125      | 11.059      | 11.007      |
|           |               | 0.038       | 0.034       | 0.042       | 0.038       |
| HV 12815  | 1.416         | 11.054      | 11.079      | 11.004      | 11.053      |
|           |               | 0.030       | 0.024       | 0.029       | 0.033       |
| HV 12816  | 0.973         | 12.897      | 12.844      | 12.901      | 12.956      |
|           |               | 0.052       | 0.034       | 0.075       | 0.077       |
| HV 12816  | 0.973         | 12.826      | 12.789      | 12.877      | 12.765      |
|           |               | 0.035       | 0.036       | 0.061       | 0.085       |
| HV 13048  | 0.836         | 13.084      | 13.088      | 13.067      | 13.054      |
|           |               | 0.034       | 0.032       | 0.059       | 0.075       |
| Cepheid   | log(P) (days) | 3.6µm (mag) | 4.5µm (mag) | 5.8µm (mag) | 8.0µm (mag) |
|-----------|---------------|--------------|--------------|--------------|--------------|
| HV 13048  | 0.836         | 13.217       | 13.197       | 13.060       | 13.058       |
|           | 0.044         | 0.044        | 0.090        | 0.093        |              |
| HV 2279   | 0.839         | 13.409       | 13.459       | 13.363       | 13.378       |
|           | 0.047         | 0.047        | 0.100        | 0.146        |              |
| HV 2279   | 0.839         | 13.346       | 13.472       | 13.463       | 13.186       |
|           | 0.067         | 0.059        | 0.105        | 0.109        |              |
| HV 886    | 1.380         | 11.488       | 11.550       | 11.481       | 11.450       |
|           | 0.034         | 0.033        | 0.048        | 0.055        |              |
| HV 886    | 1.380         | 11.667       | 11.232       | 11.552       | 11.585       |
|           | 0.039         | 0.035        | 0.052        | 0.055        |              |
| HV 12747  | 0.556         | 14.205       | 14.251       | 14.527       | 14.051       |
|           | 0.044         | 0.058        | 0.174        | 0.185        |              |
| HV 12747  | 0.556         | 14.224       | 14.193       | 14.135       | 13.999       |
|           | 0.034         | 0.041        | 0.091        | 0.999        |              |