THE PERIOD-LUMINOSITY RELATION FOR THE LARGE MAGELLANIC CLOUD CEPHEIDS DERIVED FROM SPITZER ARCHIVAL DATA

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Received 2007 October 30; accepted 2008 January 9

ABSTRACT

Using Spitzer archival data from the SAGE (Surveying the Agents of a Galaxy’s Evolution) program, we derive the Cepheid period-luminosity (P-L) relation at 3.6, 4.5, 5.8, and 8.0 μm for Large Magellanic Cloud (LMC) Cepheids. These P-L relations can be used, for example, in future extragalactic distance scale studies carried out with the James Webb Space Telescope. We also derive Cepheid period-color (P-C) relations in these bands and find that the slopes of the P-C relations are relatively flat. We test the nonlinearity of these P-L relations with the F-statistical test and find that the 3.6, 4.5, and 5.8 μm P-L relations are consistent with linearity. However, the 8.0 μm P-L relation presents possible but inconclusive evidence of nonlinearity.

Subject headings: Cepheids — distance scale

1. INTRODUCTION

The Cepheid period-luminosity (P-L) relation is an important component in extragalactic distance scale and cosmological studies. The most widely used P-L relations in the literature are obtained from Large Magellanic Cloud (LMC) Cepheids in optical BVI (e.g., see Madore & Freedman 1991; Tanvir 1999; Udalski et al. 1999a; Sandage et al. 2004; Kanbur & Ngeow 2006) and near-infrared (NIR) JHK (e.g., see Madore & Freedman 1991; Gieren et al. 1998; Groenewegen 2000; Nikolaev et al. 2004; Persson et al. 2004; Ngeow et al. 2005) bands. In addition, there are also some LMC P-L relations obtained for MACHO V_{MACHO,MACHO} (Nikolaev et al. 2004; Ngeow et al. 2005) and EROS V_{EROS,EROS} (Bauer et al. 1999) bands. Recently, Ngeow & Kanbur (2007) applied a semiempirical approach to derive the LMC P-L relation in Sloan ugriz bands: still within optical and/or NIR regimes. Therefore, Cepheid P-L relations are well developed for wavelengths ranging from optical to NIR.

In contrast, there are currently no P-L relations available for wavelengths longer than the K band in the literature. The main motivation for having a P-L relation at these longer wavelengths is in order to apply it in future extragalactic distance scale studies. The Near-Infrared Camera (NIRCam) and the Mid-Infrared Instrument (MIRI), which are scheduled to be installed on the James Webb Space Telescope (JWST), will operate in the NIR and mid-infrared: a wavelength range of 0.6–5 and 5–27 μm, respectively. It is possible that extragalactic Cepheids will be discovered in this regime (e.g., see Madore & Freedman 1991; Tanvir 1999; Udalski et al. 1999a; Sandage et al. 2004; Kanbur & Ngeow 2006). The data are publicly available via the IRSA’s Gator Catalog Query.3 To find LMC Cepheids in the SAGE database, we first obtained the right ascension (R.A.) and declination (decl.) of the LMC Cepheids from the OGLE (Optical Gravitational Lensing Experiment; Udalski et al. 1999b) database. We only obtained the Cepheids that were classified as fundamental mode Cepheids (labeled as FU) from the OGLE database, where the classification was mainly based on the W_f P-L relation and the Fourier decomposition technique (Udalski et al. 1999b). The initial list of 771 Cepheids was cross-correlated with a list of “good” Cepheids given in Kanbur & Ngeow (2006). The details regarding selection criteria used to remove “bad” Cepheids, including possible overtone Cepheids, can be found in Kanbur & Ngeow (2006) and will not be repeated here. This left 627 OGLE LMC Cepheids. To increase the sample size and to extend the period coverage to longer period (OGLE Cepheids truncated at P ~ 30 days due to CCD saturation) we added non-OGLE Cepheids from the Sebo et al. (2002) catalog. As in previous studies (for example, see Udalski et al. 1999a; Kanbur & Ngeow 2006; Ngeow et al. 2005; Sandage et al. 2004, and references therein), we applied a period cut of P > 2.5 days to our sample to avoid possible nonlinearity. In § 2 we discuss our data selection. In § 3 we present our analysis and results for the P-L relations. In § 4 we show the P-C relations, the CMD, and the color-color plot for the Cepheids in our sample. Our conclusion is given in § 5. Extinction is ignored in this paper because it is expected to be negligible in the Spitzer IRAC bands (hereafter IRAC band).

2. DATA SELECTION

SAGE (Surveying the Agents of a Galaxy’s Evolution; Meixner et al. 2006)2 is a program to survey the LMC using the Spitzer satellite. As a result it has detected about 4 million sources in the LMC with Spitzer’s IRAC instrument (with an angular resolution of ~2′). The data are publicly available via the IRSA’s Gator Catalog Query.3 To find LMC Cepheids in the SAGE database, we first obtained the right ascension (R.A.) and declination (decl.) of the LMC Cepheids from the OGLE (Optical Gravitational Lensing Experiment; Udalski et al. 1999b) database. We only obtained the Cepheids that were classified as fundamental mode Cepheids (labeled as FU) from the OGLE database, where the classification was mainly based on the W_f P-L relation and the Fourier decomposition technique (Udalski et al. 1999b). The initial list of 771 Cepheids was cross-correlated with a list of “good” Cepheids given in Kanbur & Ngeow (2006). The details regarding selection criteria used to remove “bad” Cepheids, including possible overtone Cepheids, can be found in Kanbur & Ngeow (2006) and will not be repeated here. This left 627 OGLE LMC Cepheids. To increase the sample size and to extend the period coverage to longer period (OGLE Cepheids truncated at P ~ 30 days due to CCD saturation) we added non-OGLE Cepheids from the Sebo et al. (2002) catalog. As in previous studies (for example, see Udalski et al. 1999a; Kanbur & Ngeow 2006; Ngeow et al. 2005; Sandage et al. 2004, and references therein), we applied a period cut of P > 2.5 days to our sample to avoid

1 See the links given in http://www.stsci.edu/jwst/instruments/.

2 See http://sage.stsci.edu/index.php.

3 See http://irsa.ipac.caltech.edu/applications/Gator/.
TABLE 1
SEARCH RESULTS FROM THE SAGE DATABASE

| Parameter          | SAGE Catalog | SAGE Archive |
|--------------------|--------------|--------------|
| \(N_{\text{total}}\) | 886          | 912          |
| \(N_{\text{nomatch}}\) | 13           | 4            |
| \(N_{\text{nomatch}}\) | 724          | 733          |
| \((d) \text{ (arcsec)}\) | 0.777 ± 0.015 | 0.773 ± 0.014 |
| \((\Delta\text{R.A.}) \text{ (arcsec)}\) | 0.575 ± 0.020 | 0.582 ± 0.019 |
| \((\Delta\text{decl.}) \text{ (arcsec)}\) | -0.088 ± 0.014 | -0.092 ± 0.013 |

3. THE PERIOD-LUMINOSITY RELATION

Initial plots of the P-L relations for all matched sources display a tight P-L relation with some obvious outliers. These outliers are probably due to the mismatch of the Cepheids with the input SAGE database, blending of other sources along the line of sight, or other physical reasons. These reasons are difficult to track down because we only have the data from the publicly available database and not the source images. Therefore, we apply an iterative outlier removal algorithm (the \(\sigma\)-clipping algorithm, as in Udalski et al. 1999a) to remove the outliers. For each iteration, P-L relations are fitted to the data and outliers located more than 2.5 \(\sigma\) away from the fitted regression lines are removed, where \(\sigma\) is the dispersion of the regression lines. This process is repeated several times until the solutions from the regression become stable. The rejected outliers are represented as open squares in Figure 2.

Figure 2 displays the P-L relations in the IRAC bands, and Table 2 presents the results from fitted regression lines after outliers have been removed. When fitting the P-L relations, we do not stipulate constraints that the number of Cepheids should be the same in all four bands and/or a given Cepheid be detected in all four bands because the number of Cepheids in the 8.0 \(\mu\)m band is much smaller than in other bands. Table 2 finds that the IRAC band P-L relations obtained using data from the SAGE catalog and archive are in very good agreement. A small discrepancy is seen for the 8.0 \(\mu\)m P-L relation, perhaps due both to the different numbers of Cepheids in the two catalogs (there are \(\sim 48\%\) more Cepheids from the SAGE archive than in the SAGE catalog), and also to the lack of Cepheids fainter than \(m = 14\) mag in the SAGE catalog (Fig. 2, lower left panel). In Figure 3, we give the reported 1 \(\sigma\) errors on the magnitudes as a function of magnitude from the SAGE database. This figure clearly shows the truncation of \(m = 14\) at 8.0 \(\mu\)m for our Cepheid sample in the SAGE catalog. Furthermore, there is a clear cutoff of the 1 \(\sigma\) errors for the 8.0 \(\mu\)m band data\(^5\) from the SAGE catalog, which is absent in other panels in Figure 3. The lack of \(m_{8.0} > 14\) mag and the cutoff of the 1 \(\sigma\) errors at the 8.0 \(\mu\)m band could be due to the more stringent criteria for the SAGE catalog than the SAGE archive (see Meixner et al. 2006 and the SAGE document given in footnote 4).

\(^5\) This cutoff is still visible if we include a large number of non-Cepheid data from the SAGE catalog.

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\(^4\) See http://irsa.ipac.caltech.edu/applications/Gator/GatorAid/SAGE/SAGE... SSCdatadocument.. delivered.pdf.
these reasons we only consider the data from the SAGE archive in the rest of this paper.

Figure 4 presents the residual plots from the fitted P-L relation in each bands. The residuals for the 3.6, 4.5, and 5.8 μm bands are more or less evenly distributed around the regression lines. However, the residuals for the 8.0 μm band exhibit a deficit on one side of the regression at log $P$ $\approx$ 1.0. This could suggest that the 8.0 μm band P-L relation may not be linear, and this will be investigated further in § 3.4. Interestingly, the smallest dispersion of the P-L relations seems to occur at log $P$ $\approx$ 1.0 in all four bands.

### 3.1. Sensitivity of the P-L Relations with Various Period Cuts

Even though period cut of log $P$ $\approx$ 0.4 has been applied to our sample to avoid the contamination of overtone Cepheids at the short-period end (see § 2), the short-period Cepheids in our sample may still be influenced by the overtone Cepheids, the increasing sensitivity of blending and the increasing of measurement errors in the IRAC band (as shown in Fig. 3) for the faint (hence short-period) Cepheids. These may bias the P-L relations in comparison to those presented in Table 2, and a cut at a longer period may be required to avoid the bias due to these effects. In Figure 5 we present the slopes and zero points of the fitted P-L relations with various period cuts from log $P$ $\approx$ 0.4 to 0.9 to our sample. This figure suggests that the slopes and zero points of the fitted P-L relations with various period cuts from log $P$ $\approx$ 0.65 will not greatly affect the results presented in Table 2, and the various sources that could bias the P-L relations may not be important. However, at log $P$ $\approx$ 0.65, the number of Cepheids in the sample decreases to $\sim$50% in the 3.6, 4.5, and 5.8 μm bands and to $\sim$23% in the 8.0 μm band. Hence, we retain our results given in Table 2 in this paper.

### 3.2. Random Phase Correction and the P-L Relations in the IRAC Band

In optical bands accurate mean magnitudes from the light curves are used to fit for the P-L relations. In contrast, the magnitudes obtained from the SAGE database are flux averaged over several observations (see Meixner et al. 2006 for the details of the SAGE observing strategy). Since information regarding the

| Band   | Slope  | Zero Point  | $\sigma$ | $N$ |
|--------|--------|-------------|---------|-----|
| 3.6 μm | $-3.265 \pm 0.017$ | 15.947 ± 0.012 | 0.104   | 613 |
| 4.5 μm | $-3.211 \pm 0.017$ | 15.922 ± 0.012 | 0.104   | 618 |
| 5.8 μm | $-3.158 \pm 0.027$ | 15.840 ± 0.022 | 0.169   | 534 |
| 8.0 μm | $-3.031 \pm 0.048$ | 15.609 ± 0.049 | 0.183   | 215 |

| Band   | Slope  | Zero Point  | $\sigma$ | $N$ |
|--------|--------|-------------|---------|-----|
| 3.6 μm | $-3.263 \pm 0.016$ | 15.945 ± 0.012 | 0.104   | 628 |
| 4.5 μm | $-3.221 \pm 0.017$ | 15.927 ± 0.012 | 0.103   | 635 |
| 5.8 μm | $-3.173 \pm 0.028$ | 15.850 ± 0.022 | 0.175   | 561 |
| 8.0 μm | $-3.091 \pm 0.039$ | 15.684 ± 0.036 | 0.193   | 319 |

Note.—The parameter $\sigma$ is the dispersion of the P-L relation.
time of observation of each data point is not available to us, these averaged magnitudes may not necessarily correspond to the mean magnitudes of the Cepheids. Nevertheless, it is well known that the amplitude of Cepheid light curves decreases as wavelength increases. From Figure 6 it can be seen that the amplitude decreases from the $B$ to $J$ band and flattens out at the $H$ and $K$ band. Extrapolating this trend to longer wavelengths may imply that the amplitudes in the IRAC bands could either be the same as in $HK$ band or become smaller or larger as wavelength increases. Therefore, we assume that the amplitudes will be small and these “random-phased” magnitudes are close to the mean magnitudes in those bands. In $JHK$ bands there are well-developed methods to estimate the mean magnitudes from single-epoch (or a few epochs) random phase observations, as presented in Nikolaev et al. (2004) and Soszynski et al. (2005). However, both methods require either the epoch of observation to be known or the existence of a template constructed from well-observed light curves. Clearly, both requirements are not present for the data that we studied in this paper. Nevertheless, the use of random phase $JHK$ magnitudes from single-epoch observations to derive the P-L relation has a precedent in the literature (see, for example, Groenewegen 2000).

The influence of (single-epoch) random phase magnitudes is expected to be minimal in the $K$ band. In order to test the validity of this assumption we use 2MASS $K$-band data that are available from the SAGE database. We repeat the fitting of the $K$-band P-L relation in the same way as for the IRAC bands. The results are presented in Table 3. We compare our $K$-band P-L relations with the $K$-band LMC P-L relation that is given in Fouqué et al. (2007). There are two main reasons for selecting the P-L relation from Fouqué et al. (2007) for our comparison. First, Cepheids used in Fouqué et al. (2007) are entirely based on the OGLE sample. This is similar to our sample that consists mostly of OGLE Cepheids. Second, random phase correction with the method described in Soszynski et al. (2005) and extinction correction have been applied to the 2MASS $K$-band data used in Fouqué et al. (2007). This is in contrast to the data used in this paper.

Table 3 reveals that without applying any random phase correction, the slope of the $K$-band P-L relation from the SAGE database is identical to the $K$-band P-L relation given in Fouqué et al. (2007). This suggests that the random phase correction may not have a large influence on the $K$-band slope, probably due to the small amplitude in the $K$ band. The difference between the Fouqué et al. (2007) P-L relation zero points and the results found with the SAGE database is $\sim 0.06$ mag. Assuming that the mean extinction toward the LMC is $\sim 0.10$ mag (for example, see Freedman et al. 2001) and using the total-to-selective extinction ($R$) of 0.38 in the $K$ band (Fouqué et al. 2007), then about $-0.04$ mag of the $-0.06$ mag difference can be explained as due to the extinction. Therefore, we believe that the IRAC-band P-L

![Fig. 3](image-url)  
**Fig. 3.**— Plots of the $1\sigma$ errors on the magnitudes as reported in the SAGE database vs. the magnitudes. Left and right panels are for the SAGE catalog and SAGE archive, respectively. The open squares and filled circles are for the rejected outliers and the remaining data points, respectively.

![Fig. 4](image-url)  
**Fig. 4.**— Residuals from the P-L relations given in Table 2 (SAGE archive) as a function of period.
relations presented here will not be strongly influenced by the lack of random phase or extinction corrections.

3.3. Comparison of P-L Relations at Different Bands

It has been well documented in the literature that the slopes of the P-L relation become progressively steeper from the $B$ to $K$ band, while at the same time the dispersion of the P-L relation decreases (see, for example, Madore & Freedman 1991; Berdnikov et al. 1996; Caputo et al. 2000; Fiorentino et al. 2002, 2007). This is expected in part due to the blackbody curves with Cepheid-like temperatures. From $L \propto R^2 T^4$, the temperature variation will dominate the luminosity variation in the optical bands (see, for example, Cox 1980) and extends to $JH$ band or even the $K$ band. In contrast, at the $K$ band and/or the wavelengths longer than the $K$ band, the radius variation will dominate the temperature variation. Since the period-radius (P-R) relation is independent of wavelength, the slope of the P-L relation is expected to reach a maximum value at some characteristic wavelength and remain constant as the wavelength increases. Similarly, the dispersion is expected to reach a minimum at the same characteristic wavelength and remain steady at longer wavelengths. In Figure 7 we compare the slope, the zero point, and the dispersion of the P-L relation at various bands. For illustration purposes, we adopt the empirical $BVI$- and $JHK$-band P-L relations from Sandage et al. (2004) and Persson et al. (2004), respectively. To extend to longer wavelengths, we also add P-L relations in the IRAC bands from Table 2 (with results from the SAGE archive) in this figure.

Figure 7 attests to the fact that the slope of the P-L relation is the steepest around the K to 4.5 $\mu$m band region and becomes shallower at longer wavelengths. In contrast, the zero point of the P-L relation is a monotonic function of wavelength. The dispersion of the P-L relation displays a similar trend to the slope: the dispersion reaches a minimum around the $K$ and 4.5 $\mu$m bands and subsequently increases for longer wavelengths. A polynomial function in the form of $Y(\lambda) = d_0 + \sum_{i=1}^{4} d_i \times [\log_{10}(\lambda)]^i$ was used to fit the data points in Figure 7. Here $Y$ represents either the P-L slopes, zero points, or dispersion. From the polynomial fits, the steepest P-L slope of $-3.266$ seems to be located at a wavelength of $\sim 2.7$ $\mu$m. The minimum dispersion of $\sim 0.109$

![Fig. 6.— Typical ratio of the light-curve amplitude ($A$) as a function of wavelength, using the $V$-band amplitude as a reference (hence, the ratio for $V$ band is 1). The amplitude ratios are from Freedman (1988) for the $B$ band, Tanvir (1997) and Ngeow et al. (2003) for the $I$ band, and Soszyński et al. (2005) for the $JHK$ band. There are two points for $JHK$ band because Soszyński et al. (2005) separated out the amplitude ratios at two period ranges.](image)

**TABLE 3**

| Source                  | Slope   | Zero Point | $\sigma$ | $N$ |
|-------------------------|---------|------------|----------|-----|
| SAGE catalog            | $-3.231 \pm 0.021$ | $16.050 \pm 0.016$ | 0.140 | 634 |
| SAGE archive            | $-3.229 \pm 0.021$ | $16.048 \pm 0.016$ | 0.141 | 642 |
| Fouque et al. (2007)    | $-3.228 \pm 0.028$ | $15.989 \pm 0.006$ | 0.136 | 529 |

Note.— The parameter $\sigma$ is the dispersion of the P-L relation.
occurs at the same wavelength. This suggests that the P-L relations from K band to 3.6 \(\mu m\) band will provide a more accurate distance scale measurement than the optical bands. However, observations from optical bands are still required to detect Cepheid variables. Furthermore, the bottom panel of Figure 7 implies that the dispersions at 3.6 and 4.5 \(\mu m\) bands are similar to the \(JHK\) bands, suggesting also that omission of random phase corrections may not be too serious an oversight.

Figure 7 provides evidence that the slopes and dispersions for the 3.6 and 4.5 \(\mu m\) band P-L relations are consistent both with each other and with the \(K\)-band P-L relation. However, the slopes and dispersions for the 5.8 and 8.0 \(\mu m\) band P-L relations are shallower and larger, respectively, than the theoretical expectation outlined previously. There are two possible causes for this. The first possibility is that measurement errors become larger toward the faint end of the 5.8 and 8.0 \(\mu m\) band P-L relations, as suggested in Figure 3. The second possibility is that the number of Cepheids in these two bands is less than those in the 3.6 and 4.5 \(\mu m\) bands. This is especially true for the 8.0 \(\mu m\) band. Figure 8 presents the period distribution for our Cepheid sample: fewer Cepheids are detected when compared to the 3.6 and 4.5 \(\mu m\) bands.

![Comparison of the slopes (top), the zero points (ZP; middle), and the dispersions (bottom) for the empirical LMC P-L at different bands. The IRAC band data points are from the SAGE archive results as given in Table 2. The dashed curves are the polynomial fits to the data points.](image)

**Fig. 7.**—Comparison of the slopes (top), the zero points (ZP; middle), and the dispersions (bottom) for the empirical LMC P-L at different bands. The IRAC band data points are from the SAGE archive results as given in Table 2. The dashed curves are the polynomial fits to the data points.

3.4. Nonlinearity of the P-L Relations

A number of recent studies have strongly suggested the LMC P-L relation in optical bands is nonlinear, in the sense that the relation can be broken into two P-L relations separated at/around 10 days (Tammann & Reindl 2002; Kanbur & Ngeow 2004, 2006; Sandage et al. 2004; Ngeow et al. 2005, 2008; Ngeow & Kanbur 2006a, 2006b; Kanbur et al. 2007b). In NIR, Ngeow et al. (2005, 2008) found that the \(JHG\)-band LMC P-L relations are nonlinear but the \(K\)-band LMC P-L relation is marginally linear. Ngeow & Kanbur (2006b) outline a blackbody argument for their result that the P-L relation could be linear in \(K\) band but not in the optical and/or \(JH\) band. One possibility is that the temperature variation in Cepheid atmospheres, modulated at certain phases, periods, and metallicities by the stellar photosphere-hydrogen ionization front interaction (Kanbur et al. 2004, 2007a; Kanbur & Ngeow 2006), is responsible for the observed nonlinear P-L relation. Since the temperature variation for a blackbody with Cepheid-like temperatures is minimal or even negligible at longer wavelengths, it is expected that the P-L relation becomes linear for wavelengths longer than the \(K\) band. Therefore, another main motivation for this paper is to study the linearity/nonlinearity of the LMC P-L relations in the IRAC band.

To test the nonlinearity of the P-L relations, we apply the \(F\)-test as in our previous studies (Kanbur & Ngeow 2004, 2006; Ngeow et al. 2005). The detailed description and formalism of the \(F\)-test can be found in Weisberg (1980), Kanbur & Ngeow (2004), and Ngeow et al. (2005) and will not be repeated here. Simply speaking, in our \(F\)-test, the null hypothesis is that the data can be fitted with a single regression line, and the alternate hypothesis is that two regression lines separated at 10 days are needed to fit the data. In our test, we set \(p(F)\), the probability of the observed \(F\)-value under the null hypothesis, to be 0.05 (equivalently at the 95% confidence level). This corresponds to \(F \sim 3\) for our data. Hence, the 5.8 \(\mu m\) band, Figure 8 also suggests that, for \(\log P < 0.5\), fewer Cepheids are detected when compared to the 3.6 and 4.5 \(\mu m\) bands.
TABLE 4

F-Test Results of the P-L Relations in IRAC Band

| Band       | $P < 10$ days | $P > 10$ days |
|------------|---------------|---------------|
|            | Slope$_S$     | Zero Point$_S$| $\sigma_S$ | $N_S$ | Slope$_L$     | Zero Point$_L$| $\sigma_L$ | $N_L$ | $F$  | $p(F)$ |
| 3.6 $\mu$m | $-3.309 \pm 0.030$ | $15.971 \pm 0.019$ | 0.101 | 550 | $-3.287 \pm 0.079$ | $15.986 \pm 0.099$ | 0.126 | 78 | 1.78 | 0.170 |
| 4.5 $\mu$m | $-3.255 \pm 0.029$ | $15.946 \pm 0.019$ | 0.100 | 558 | $-3.331 \pm 0.079$ | $16.076 \pm 0.098$ | 0.122 | 77 | 2.81 | 0.061 |
| 5.8 $\mu$m | $-3.121 \pm 0.058$ | $15.817 \pm 0.039$ | 0.176 | 471 | $-3.212 \pm 0.093$ | $15.893 \pm 0.118$ | 0.175 | 90 | 0.55 | 0.579 |
| 8.0 $\mu$m | $-2.858 \pm 0.094$ | $15.517 \pm 0.069$ | 0.191 | 232 | $-3.364 \pm 0.114$ | $16.018 \pm 0.143$ | 0.186 | 87 | 5.90 | 0.003 |

Note.—The parameter $\sigma$ is the dispersion of the P-L relation.

Fig. 9.—P-C relations from the matched sources in the SAGE archive after the removal of the outliers.
TABLE 5
P-C RELATIONS IN IRAC BAND

| Color   | Slope    | Zero Point | $\sigma$ | $N$  |
|---------|----------|------------|----------|------|
| $m_{3.6} - m_{4.5}$ | -0.044 ± 0.010 | 0.017 ± 0.007 | 0.061 | 595  |
| $m_{3.6} - m_{5.8}$ | -0.048 ± 0.024 | 0.050 ± 0.019 | 0.137 | 504  |
| $m_{3.6} - m_{6.0}$ | -0.108 ± 0.038 | 0.190 ± 0.034 | 0.171 | 287  |
| $m_{4.5} - m_{5.8}$ | -0.008 ± 0.025 | 0.039 ± 0.019 | 0.140 | 512  |
| $m_{4.5} - m_{6.0}$ | -0.057 ± 0.038 | 0.169 ± 0.034 | 0.170 | 291  |
| $m_{5.8} - m_{6.0}$ | -0.104 ± 0.038 | 0.186 ± 0.035 | 0.181 | 298  |

Note.—The parameter $\sigma$ is the dispersion of the P-C relation.

$F > 3$ indicates that the null hypothesis can be rejected at the 95% confidence level or more for the P-L relation under scrutiny.

In Table 4 we present the results from the $F$-test for the P-L relations in the IRAC band. The $F$-test results indicate that the P-L relation is linear in the 3.6, 4.5, and 5.8 $\mu$m bands but not in the 8.0 $\mu$m band. The linearity of the P-L relation in the 3.6, 4.5, and 5.8 $\mu$m bands is expected from the blackbody argument as outlined previously. However, it is important to point out that the linearity/nonlinearity of the P-L relation in these bands does not necessarily imply that the P-L relation in the optical bands will be linear/nonlinear. The apparently nonlinear 8.0 $\mu$m P-L relation is puzzling. Removing the longest period Cepheid in the 8.0 $\mu$m band sample still leaves a nonlinear result with an $F$-value of 5.04. The relatively small number of Cepheids in the 8.0 $\mu$m band (see Fig. 8) may cause the apparent nonlinear result, although the $F$-test is sensitive to this. The similar trends of the 1 $\sigma$ measurement error plot, as shown in Figure 3, and the similar dispersions for the P-L relations in the 5.8 and 8.0 $\mu$m band, suggest that the lack of short-period Cepheids in the 8.0 $\mu$m band may be the reason for the nonlinear result, because the $F$-test result finds that the 5.8 $\mu$m P-L relation is linear. It is still inconclusive whether the 8.0 $\mu$m P-L relation is truly nonlinear or not, and more data are needed in the future work to solve this problem.

4. THE PERIOD-COLOR RELATION, THE COLOR-COLOR PLOT, AND THE CMD

In addition to the P-L relations derived in previous sections, the SAGE archive also permits the derivation of P-C relations, color-color plots, and the CMD. The resulting P-C relations from the data are presented in Figure 9 and Table 5, while the color-color plots and CMD are presented in Figures 10 and 11, respectively.

The IRAC band P-C relations are found to be relatively flat as compared to the P-C relations in the optical band, with the mean color being close to zero (especially for the $m_{4.5} - m_{5.8}$ P-C relation). This is not a surprise given that the slopes and the zero points of the P-L relations in these bands are similar (see Table 2 and Fig. 7). In fact blackbody curves with Cepheid-like temperatures predict the P-C relation should vanish at these bands. Table 5 also finds that some P-C relations are identical to each other, including the $m_{3.6} - m_{5.8}$ and $m_{5.8} - m_{8.0}$ pair, and the $m_{3.6} - m_{4.5}$, $m_{3.6} - m_{5.8}$, and $m_{5.8} - m_{8.0}$ P-C relations. Furthermore, all P-C relations presented in Figure 9 display a very tight sequence for Cepheids with log $P \gtrsim 1.0$. This is also seen in the CMD. In Table 6 we present the P-C relations separated at 10 days. The flatness of the P-C slope, the mean color of zero, and the small dispersion of the P-C relation are clearly evident from this table for Cepheids with period longer than 10 days.

At the short-period end of the P-C relations, the dispersion of the P-C relations gets broader (except for the $m_{3.6} - m_{4.5}$ P-C relation) as period decreases. This feature is also seen from Figure 11 toward the faint end of the CMD. Probably this could be due to the relatively large measurement errors at the faint (or short-period) end, because the measurement errors in color can reach up to $\sim 0.3$ mag, as suggested from Figure 3. In addition, Figures 9 and 11 imply a lack of detections for the matched sources near log $P \sim 0.5$, especially for the P-C relations that include the 8.0 $\mu$m band. This could cause the short-period P-C relations to deviate from flatness and mean zero color as given in Table 6. Because of these reasons, we did not test the nonlinearity of the P-C relations with the $F$-test.

Nevertheless, the CMD presented in Figure 11 finds that the instability strip for LMC Cepheids is well defined in the IRAC band, especially with the $m_{3.6} - m_{4.5}$ color. The tightness of the $m_{3.6} - m_{4.5}$ color is also reflected in Figure 10, where the spread out of $m_{5.8} - m_{6.0}$ color is mainly from the short-period Cepheids. The well-occupied regions of the Cepheids in Figure 10 and the well-defined CMD suggest that Figures 10 and 11 can be used to identify Cepheids in future studies.

5. CONCLUSION

In this paper we derive P-L relations for LMC Cepheids in IRAC 3.6, 4.5, 5.8, and 8.0 $\mu$m bands. These P-L relations can be potentially applied to future extragalactic distance scale studies with, for example, the JWST. The data are taken from Spitzer’s archival database from the SAGE program. After properly removing the outliers, the fitted P-L relations are presented in Table 2. We have tested the P-L relations with various period cuts and found that our results are insensitive to period cuts up to log $P_{cut} \sim 0.65$. We also argue that the random phase corrections may not be important for IRAC band P-L relations. When comparing P-L relations from B to 8.0 $\mu$m bands, the slope of the P-L relation appears to be the steepest around $K$ band to 3.6 $\mu$m band, while the dispersion of the P-L relation reaches a minimum between those bands. The shallower slopes and larger P-L dispersions in the 5.8 and 8.0 $\mu$m bands are in contrast to the theoretical expectation. This could be due to the smaller number of Cepheids and larger measurement errors toward the faint end in these two bands. We also test the nonlinearity of the P-L relations in the IRAC band using the $F$-statistical test. As expected, the $F$-test
Fig. 11.—CMD from the matched sources in the SAGE archive after the removal of the outliers.
results show that the P-L relations are linear in the 3.6, 4.5, and 5.8 μm bands, but the 8.0 μm P-L relation is found to be nonlinear. However, the nature of the nonlinear 8.0 μm P-L relation is still inconclusive. For the P-C relations, it was found that the slopes of the P-C relation are relatively flat in the IRAC bands. Even though there may be some associated issues regarding the SAGE database. We also thank Lucas Macri and Nancy Evans for useful discussion. C. N. acknowledges support from NSF award OPP-0130612 and a University of Illinois seed funding award to the Dark Energy Survey. S. M. K. acknowledges support from the Chretien International Research Award from the American Astronomical Society. This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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**TABLE 6**

| Band          | Slope_L | Zero Point_L | σ_L  | N_L  |
|---------------|---------|--------------|------|------|
| m_{3.6} - m_{4.5} | −0.017 ± 0.019 | 0.001 ± 0.012 | 0.061 | 521 |
| m_{3.6} - m_{5.8} | −0.117 ± 0.050 | 0.093 ± 0.034 | 0.146 | 429 |
| m_{4.5} - m_{6.0} | −0.370 ± 0.097 | 0.376 ± 0.072 | 0.189 | 213 |
| m_{4.5} - m_{6.0} | −0.118 ± 0.051 | 0.107 ± 0.034 | 0.149 | 438 |
| m_{5.8} - m_{6.0} | −0.335 ± 0.094 | 0.364 ± 0.070 | 0.185 | 217 |
| m_{5.8} - m_{6.0} | −0.377 ± 0.106 | 0.381 ± 0.078 | 0.204 | 215 |

Note.—The parameter σ is the dispersion of the P-C relation.