Cepheid period–luminosity relation from the AKARI observations

Chow-Choong Ngeow,1⋆ Yoshifusa Ita,2 Shashi M. Kanbur,3 Hilding Neilson,4 Takashi Onaka5 and Daisuke Kato5

1Graduate Institute of Astronomy, National Central University, Jhongli City, 32001 Taïwan R.O.C.
2National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
3Department of Physics, SUNY Oswego, Oswego, NY 13126, USA
4Department of Astronomy & Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
5Department of Astronomy, Graduate School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

Accepted 2010 June 7. Received 2010 June 7; in original form 2009 September 8

ABSTRACT

In this paper, we derive the period–luminosity (P–L) relation for Large Magellanic Cloud (LMC) Cepheids based on mid-infrared AKARI observations. AKARI’s Infrared Camera sources were matched to the Optical Gravitational Lensing Experiment-III (OGLE-III) LMC Cepheid catalogue. Together with the available I-band light curves from the OGLE-III catalogue, potential false matches were removed from the sample. This procedure excluded most of the sources in the S7 and S11 bands; hence, only the P–L relation in the N3 band is derived in this paper. Random-phase corrections were included in deriving the P–L relation for the single-epoch AKARI data; even though the derived P–L relation is consistent with the P–L relation without random-phase correction, however there is an ~7 per cent improvement in the dispersion of the P–L relation. The final adopted N3-band P–L relation is N3 = −3.246 log(P) + 15.844, with a dispersion of 0.149.

Key words: stars: variables: Cepheids – distance scale.

1 INTRODUCTION

The mid-infrared (mid-IR) Cepheid period–luminosity (P–L; also known as the Leavitt law) relation will soon gain more importance in the future extra-galactic distance-scale studies (e.g. see Freedman et al. 2008a). This is mainly because the effect of extinction is negligible in the mid-IR (Freedman et al. 2008b; Ngeow et al. 2009). Other advantages of using the mid-IR P–L relation include the following (see also the discussion in Ngeow & Kanbur 2008; Freedman et al. 2008b; Madore et al. 2009; Ngeow et al. 2009; Marengo et al. 2010): (i) the dispersion of the IR P–L relation is smaller compared to the BVI P–L relations; (ii) the mid-IR light curves are expected to have smaller amplitudes than the optical counterparts; therefore, a smaller number (or even a single epoch) of observations are adequate to derive accurate mean magnitudes and P–L relations; and (iii) metallicity may not affect the luminosity of Cepheids at these wavelengths (however, metallicity may affect the observed magnitudes due to mass loss; see Neilson et al. 2009).

The Surveying the Agents of a Galaxy’s Evolution (SAGE) project (Meixner et al. 2006) has surveyed the Large Magellanic Cloud (LMC) using Spitzer’s Infrared Array Camera (IRAC) instrument at two epochs. The first data released from the SAGE team only included epoch 1 data. This has been used by Ngeow & Kanbur (2008) and Freedman et al. (2008b) to derive the LMC P–L relation in IRAC bands. The second release of the SAGE data contains both the epoch 1 and epoch 2 data and was used to improve the IRAC-band P–L relations in Ngeow et al. (2009) and Madore et al. (2009), respectively. The main difference between the Freedman/Madore group and our group is that they matched the SAGE catalogues to the LMC Cepheids from Persson et al. (2004), while we adopted the Cepheid catalogues released from the Optical Gravitational Lensing Experiment (OGLE) team (Udalski et al. 1999; Soszyński et al. 2008). The two approaches lead to a discrepancy found in the slopes of the IRAC-band P–L relations, in a sense that the slopes found by the Freedman/Madore group are steeper than the slopes found by our group (see Table 1 for a comparison of the slopes found by these two groups). Nevertheless, the SAGE catalogues used by both groups do not contain information regarding the time of observation. Hence, random-phase corrections cannot be applied to the single- or double-epoch SAGE data, in order to derive the mean magnitudes in IRAC bands.

Independent of the SAGE project, the AKARI satellite (Murakami et al. 2007) has surveyed the LMC using the onboard Infrared Camera (IRC; Onaka et al. 2007) instrument. Initial results were published in Ita et al. (2008). The wavelength coverage of AKARI’s IRC instrument is similar to Spitzer’s IRAC bands. Therefore, the main purpose of this paper is to construct P–L relations based on AKARI observations and attempt to resolve the discrepancy in the slopes of the IRAC-band P–L relations calculated by our group and the Freedman/Madore group. The AKARI internal catalogue

*E-mail: cngeow@astro.ncu.edu.tw

© 2010 The Authors. Journal compilation © 2010 RAS
includes the time of observation; this allows us to obtain the phase information of the matched Cepheids:
\[ \phi = \text{mod} \left( \frac{t - t_0}{P} \right), \tag{1} \]
where \( t \) is the time of observation, \( t_0 \) is the time of maximum light (either in the \( V \) or the \( I \) band) and \( P \) is the pulsational period. Hence, \( \phi \in [0, 1] \) represents one pulsation cycle of the Cepheid. The phase information allows us to apply random-phase corrections and derive mean magnitudes; such an approach has not been applied to the SAGE data. In Sections 2 and 3, we describe the data used in this study and our adopted methodology for random-phase correction, respectively. We present the results and discussion in Section 4, followed by the conclusion in Section 5. Extinction correction is ignored in this paper since it is negligible in the mid-IR bands.

## 2 THE DATA

The AKARI catalogue provides photometric data at 3 (N3), 7 (S7), 11 (S11), 15 (L15) and 24 (L24) \( \mu \)m together with their time of observation. Photometry is on the IRC-Vega magnitude system, which is defined in Tanabé et al. (2008). Details of the data reduction and catalogue compilation processes are described in Ita et al. (2008) and will not be repeated here. The coordinates given in the AKARI catalogue are calculated by matching detected point sources with corresponding Two-Micron All-Sky Survey (2MASS) sources. If matching with the 2MASS catalogue is unsuccessful (such cases usually occur in L15 and L24 images), then we use the SAGE point source catalogue (Meixner et al. 2006) as the positional reference. The root mean squares of the residuals between the input 2MASS/SAGE catalogue coordinates and the fitted coordinates are smaller than 0.2 arcsec for N3, 0.6 arcsec for S7 and S11, and 0.9 arcsec for L15 and L24. The AKARI catalogue coordinates should be accurate to an extent that is relative to the 2MASS and SAGE catalogue coordinates.

We matched AKARI’s IRC point source catalogue given in Ita et al. (2008)\(^1\) to the OGLE-III fundamental mode Cepheid catalogue from Soszyński et al. (2008). Due to the smaller area coverage of the AKARI survey (see fig. 1 of Ita et al. 2008) as compared to the SAGE project, the number of matched sources is reduced to 537, 226 and 83 in AKARI’s N3, S7 and S11 bands, respectively. Fig. 1 shows the distribution of the separation between matched AKARI sources and the OGLE-III LMC Cepheids. The numbers of matched sources with separation greater than 1 arcsec are 100 (18.6 per cent), 124 (54.9 per cent) and 55 (63.3 per cent) in the N3, S7 and S11 bands, respectively. The corresponding \( P–L \) relations from all the matched sources are presented in Fig. 2. This figure shows that there is a well-defined sequence of the \( P–L \) relation in the N3 band. The \( P–L \) relation sequence is not obvious in the S7 band and almost disappears in the S11 band. A fraction of the matched sources deviate from the expected \( P–L \) relation sequence, with most of them having a separation greater than 1 arcsec. They are clearly the AKARI sources falsly matched to the OGLE-III Cepheid catalogue.

### 2.1 Selection of data

Since the phase information for the matched AKARI sources can be obtained from equation (1), we can construct the colour of the matched sources using the full \( I \)-band light curves from the OGLE-III catalogue given in Soszyński et al. (2008). We match the phased \( I \)-band magnitude that is closest to the phase of the AKARI magnitudes in all three bands and construct the \( I(\phi) - AKARI(\phi) \) colour at a given phase \( \phi \) for a particular matched source. The phase difference between the \( I \)-band magnitudes and the AKARI sources is always less than 0.03, with majority of them being smaller than 0.003. We have plotted the \( I(\phi) - AKARI(\phi) \) colour as a function of phases and separations in Fig. 3.

It can be seen from the top-left panel of Fig. 3 that colours with \( I(\phi) - N3(\phi) < 2.0 \) show a periodic behaviour. This is because most of these AKARI sources are indeed matched to the Cepheids, and hence this periodic behaviour originates from the pulsational behaviour of Cepheids. In contrast, the colours with \( I(\phi) - S7(\phi) < 2.0 \) did not show a clear periodic behaviour,\(^2\) and the periodic behaviour is totally absent for \( I(\phi) - S11(\phi) < 2.0 \) colours. The bottom panels of Fig. 3 suggest that the matched AKARI sources with \( I(\phi) - AKARI(\phi) > 2.0 \) in general have a larger separation; this further supports the conclusion that these AKARI sources are falsely matched to the OGLE-III Cepheids. Therefore, we only consider the matched AKARI sources in the N3 band in this paper with

---

1 A revision of this catalogue is currently in progress (Kato et al., in preparation) and will be published in the near future. Preliminary analysis shows that the difference of the N3-band photometry is negligible between the current and revised catalogues.

2 Even if the \( I(\phi) - S7(\phi) < 2.0 \) colours show a very weak periodic behaviour, the number of possible truly matched AKARI sources is small for a meaningful analysis of the \( P–L \) relation in the S7 band.
the following selection criteria (based on Fig. 3):

\begin{equation}
\text{Separation} < 0.7 \text{arcsec},
0.5 < I(\phi) - N3(\phi) < 1.7.
\end{equation}

These selection criteria are represented as a dashed box in the bottom-left panel of Fig. 3. Fig. 4 shows the random-phase colour–magnitude diagram (CMD) for the matched AKARI sources. Sources that satisfy the above selection criteria appear to define an instability strip occupied by Cepheids.

\subsection{The methodology}

Following Sozyński et al. (2005), we define a normalized light curve at phase $\phi$ as

\begin{equation}
T(\phi) \equiv \frac{m(\phi) - \langle m \rangle}{A}.
\end{equation}

where $\langle m \rangle$ and $A$ are the mean magnitude and amplitude of the light curve in a particular band, respectively, and $\phi$ is the phase calculated from equation (1). The function $T(\phi)$ can be modelled as an $n$-order Fourier series (Nikolaev et al. 2004; Sozyński et al. 2005):

\begin{equation}
T(\phi) = \sum_{j=1}^{n} [a_j \cos(2\pi j \phi) + b_j \sin(2\pi j \phi)].
\end{equation}

Rearrange equation (2) such that $m = \langle m \rangle + A \times T(\phi)$. If we denote the amplitude ratio of the N3 band to the I (or V) band as $A_{N3}/A_{I} = C$, then we have $m = \langle m \rangle + A_{I}C \times T(\phi)$. The amplitude ratio $C$ can be absorbed into the Fourier coefficients $a_j$ and $b_j$ in equation (3). Furthermore, the mean magnitude $\langle m \rangle$ can be replaced by the definition of the $P$–$L$ relation, $\langle m \rangle = \alpha \log(P) + \beta$. We then
obtain a linear equation which can be solved with a standard least-squares method:

$$m = \alpha \log(P) + \beta + A_1 \times \sum_{j=1}^{n} [a_j \cos(2\pi j \phi) + b_j \sin(2\pi j \phi)],$$

(4)

where $a_j' = C_a a_j$ and $b_j' = C_b b_j$. Dropping the $A_1$ and $C$ terms from equation (4), we recover the expression that is similar to the one given in Nikolaev et al. (2004):

$$m = \alpha \log(P) + \beta + \sum_{j=1}^{n} [a_j \cos(2\pi j \phi) + b_j \sin(2\pi j \phi)].$$

(5)

3.2 Test with the $K$-band data

The performance of equations (4) and (5), with the random-phase correction term, to solve for the $P$–$L$ relation can be tested with $K$-band data taken from Persson et al. (2004). We first matched 88 Cepheids (after removing HV 883, HV 2447, HV 2883 and HV 12765, as in Persson et al. 2004) with the OGLE-III Cepheid catalogue from Soszyński et al. (2008) that has both the $I$-band amplitudes and $t_0$ information. 46 Cepheids were found to be matching between these two catalogues. Each of these Cepheids has $\sim 19$–$\sim 30$ $K$-band data points per light curve.

For each Cepheid, we randomly select one data point from the $K$-band light curves to represent the single-epoch observation. We then fit the randomly selected data in three cases: (i) $P$–$L$ relation without the random-phase correction (i.e. $K_{random} = \alpha \log(P) + \beta$ only), (ii) $P$–$L$ relation with the random-phase correction from equation (4) that includes an amplitude term and (iii) $P$–$L$ relation with the random-phase correction from equation (5) without the amplitude term. Note that there is no extinction correction and/or photometric transformation applied to these $K$-band magnitudes, since the purpose here is not to derive the $K$-band $P$–$L$ relations but to test the random-phase correction. We also fit the $P$–$L$ relation using the mean magnitudes from Persson et al. (2004) for these 46 Cepheids in order to compare with the $P$–$L$ relations derived from single-epoch data.

We have repeated the above test procedure 5000 times to build up the statistics for comparing the $P$–$L$ relation from randomly selected data, either with or without the random-phase correction term.
Cepheid P-L relation from AKARI

Figure 6. Comparison of the fitted $T(\phi)$ function for the data presented in Fig. 5, without (top panel) and with (bottom panel) the amplitude term. $K_{\text{rand}}$ is the randomly selected single-epoch data and $K_{\text{pleft}} = \alpha \log(P) + \beta$, where $\alpha$ and $\beta$ are fitted results from equation (4) or (5).

Table 2. Summary of the fitted Gaussian to the histograms for P-L slopes.

| n | Without Amplitude | With Amplitude |
|---|-------------------|----------------|
|   | $m_G$ | $s_G$ | $m_G$ | $s_G$ |
| 1 | -0.005 | 0.057 | -0.007 | 0.049 |
| 2 | -0.007 | 0.061 | -0.010 | 0.052 |
| 3 | -0.004 | 0.064 | -0.009 | 0.058 |
| 4 | -0.004 | 0.071 | -0.010 | 0.059 |
| 5 | -0.004 | 0.076 | -0.011 | 0.067 |
| 6 | -0.005 | 0.079 | -0.012 | 0.071 |

Table 3. Summary of the fitted Gaussian to the histograms for P-L zero-points.

| n | Without Amplitude | With Amplitude |
|---|-------------------|----------------|
|   | $m_G$ | $s_G$ | $m_G$ | $s_G$ |
| 1 | 0.013 | 0.062 | 0.015 | 0.054 |
| 2 | 0.014 | 0.066 | 0.018 | 0.059 |
| 3 | 0.011 | 0.074 | 0.017 | 0.060 |
| 4 | 0.011 | 0.080 | 0.019 | 0.069 |
| 5 | 0.011 | 0.079 | 0.021 | 0.074 |
| 6 | 0.011 | 0.091 | 0.023 | 0.079 |

corrections, to the ‘true’ P-L relation derived from mean magnitudes. Histograms were constructed for these 5000 runs when performing such comparisons, and a simple Gaussian function in the form of $A_G e^{-\Delta^2/2 \sigma_G^2}$ was fitted to these histograms (where $\Delta$ is the difference of the slopes or zero-points of fitted P-L relations). If only the randomly selected single-epoch data were used, without any random-phase correction, then $m_G = 0.017$ and $s_G = 0.093$ for the comparison of the slopes and $m_G = -0.011$ and $s_G = 0.113$ for the comparison of the zero-points of the fitted P-L relations.

We also ran our test procedure and comparisons for $n = 1–6$ in the Fourier series when applying the random-phase corrections. Tables 2 and 3 summarize the fitted values of $m_G$ and $s_G$ from the histograms with different $n$ for the P-L slopes and zero-points, respectively. Several results can be immediately seen from these tables as follows.

(i) The bias of the P-L slopes, $m_G$, has decreased from 0.017 if the random-phase correction is applied to the randomly selected single-epoch data. Random-phase correction without the amplitude term, i.e. equation (5), seems to provide a better result.

(ii) There is not much improvement for the bias in the P-L zero-points when using the random-phase corrections. Furthermore, random-phase corrections with the amplitude term (equation 4) seem to increase this bias.

(iii) The dispersion of the histogram, $s_G$, has been improved by $\sim 15–50$ per cent when the random-phase correction was included in fitting the P-L relation. Random-phase correction with the amplitude term gives a smaller dispersion than the correction without the amplitude term.

Overall, Tables 2 and 3 suggest that random-phase correction from equation (4) with $n = 1$ in the Fourier series gives the best-fitting results. Fig. 7 displays the histograms with the $n = 1$ case. The improvement of including the random-phase correction in fitting the P-L relations can be clearly seen in this figure. In the next section, we therefore include the random-phase correction with $n = 1$ when deriving the N3-band P-L relation.

We also compared the estimated mean magnitudes from the random-phase correction ($m - T(\phi)$) to the ‘true’ mean magnitudes from Persson et al. (2004). A Gaussian fit to the histograms for the difference in mean magnitudes reveals that there is no bias introduced from the random-phase correction. The error of the estimated mean magnitudes is about 0.06 mag, for both the random-phase corrections that either do or do not include the amplitude term.

4 THE N3-BAND P-L RELATION

There are 338 matched AKARI sources in the N3 band left after the selection criteria described in Section 2.1. We further remove one Cepheid with log($P$) = 0.066 to avoid contamination from overtone Cepheids. To remove any possible outliers presented in the data, we employed an iterative 2.5σ-clipping procedure to fit equations (4) and (5) that include the random-phase corrections, when deriving the P-L relation. The resulting P-L relations (for 327 Cepheids) are as follows.

No random-phase correction:

$$N3 = -3.198(\pm0.046) \log(P) + 15.816(\pm0.031), \quad \sigma = 0.161.$$  From equation (5):

$$N3 = -3.189(\pm0.042) \log(P) + 15.811(\pm0.029), \quad \sigma = 0.148.$$  From equation (4):

$$N3 = -3.193(\pm0.043) \log(P) + 15.813(\pm0.029), \quad \sigma = 0.149.$$  

The derived P-L relation without the random-phase correction agrees well to the P-L relations that include the random-phase corrections. This further supports the suggestion that random-phase corrections may not be required for deriving the mid-IR P-L relations, due to the expected small amplitudes in those bands (Ngeow & Kanbur 2008). However, the dispersion of the P-L relation ($\sigma$) decreases by $\sim 7$ per cent if the random-phase correction is included.

The P-L relations derived from either using equation (4) or (5) are

3 The N3 photometry of these Cepheids will be available at the SIMBAD CDS data base (http://simbad.u-strasbg.fr/simbad/) once the revised catalogue (Kato et al. in preparation) is published.
almost identical, suggesting that the amplitude term may not need to be included in the random-phase correction.

Since the N3 band is closely matched to Spitzer’s 3.6-μm band, the slope of the N3 P–L relation is expected to be close to the 3.6-μm P–L relations. The slopes from the latest determined 3.6-μm P–L relations are $-3.253(\pm0.010)$ from Ngeow et al. (2009) and $-3.40(\pm0.02)$ from Madore et al. (2009). The N3 P–L relation seems to be shallower than the 3.6-μm P–L relations. Plotting out the N3 P–L relation reveals that the six Cepheids with log($P$) > 1.2 appear to be (systematically) fainter than what is expected from a ridge line of the P–L relation (see also the top panel in Fig. 2). This can cause the P–L relation to appear shallower. Note that the saturation limit at the N3 band is 7.8 mag (Ita et al. 2008), which cannot account for the appearing zero-point offset of the photometry for these six long-period Cepheids. If we exclude these long-period Cepheids, then the fitted P–L relations (for 321 Cepheids) are as follows.

No random-phase correction:

\[
N3 = -3.254(\pm0.051) \log(P) + 15.850(\pm0.034), \quad \sigma = 0.160.
\]

From equation (5):

\[
N3 = -3.241(\pm0.047) \log(P) + 15.842(\pm0.031), \quad \sigma = 0.147.
\]

From equation (4):

\[
N3 = -3.246(\pm0.047) \log(P) + 15.844(\pm0.031), \quad \sigma = 0.149.
\]

Fig. 8 presents the final N3 P–L relations and Fig. 9 shows the corresponding $T(\phi)$ as a function of phase for the final adopted Cepheids. Note that the slope of the N3 P–L relation without the random-phase correction is identical to Spitzer’s 3.6-μm-band P–L relation from Ngeow et al. (2009), whose random-phase corrections were not applied to the SAGE data. We took the P–L relation derived from equation (4) as our final adopted N3 P–L relation:

\[
N3 = -3.246 \log(P) + 15.844.
\]
The final P–L relations in the $N_3$ band, for using the single-epoch random-phase data only (top panel) and with the inclusion of the random-phase correction (bottom panel). The P–L relations derived from equations (4) and (5) are identical; hence, only one of them is plotted here. Open circles are the excluded Cepheids (see the text for details). Error bars are omitted for clarity.

The locations of the Cepheids from our final adopted sample are shown in Fig. 11, where the dashed box represents the LMC bar region. We divided our sample into two sub-samples: one within the bar region and one outside the bar region. In Table 5, the P–L slopes derived from these two sub-samples were compared, together with their mean period and the number of Cepheids separated at

The effect of period cuts on the $N_3$ P–L slope.

| log($P_{cut}$) | Slope     | N  | (log($P$)) |
|---------------|-----------|----|------------|
| 0.50          | $-3.203 \pm 0.056$ | 261 | 0.688      |
| 0.55          | $-3.156 \pm 0.065$ | 207 | 0.731      |
| 0.60          | $-3.205 \pm 0.074$ | 163 | 0.774      |
| 0.65          | $-3.231 \pm 0.085$ | 131 | 0.810      |
| 0.70          | $-3.293 \pm 0.113$ |  91 | 0.869      |
| 0.75          | $-3.399 \pm 0.135$ |  75 | 0.902      |
| 0.80          | $-3.524 \pm 0.151$ |  60 | 0.934      |
| 0.85          | $-3.468 \pm 0.209$ |  43 | 0.978      |

Comparison of $N_3$ P–L slopes from two regions.

| P–L slope | log($P$) | In the LMC bar | Outside the LMC bar |
|-----------|---------|----------------|---------------------|
| $-3.275 \pm 0.079$ | 0.627 | 135 | 111 |
| $-3.240 \pm 0.056$ | 0.658 | 31  | 44  |

Due to the influence of the crowding on the photometry, especially for the short-period Cepheids, the P–L slope for the sub-sample from the bar region is expected to be shallower. However, this is not seen from the results given in Table 5, which suggest that crowding within the bar region does not affect AKARI’s photometry. Furthermore, the slopes from the two regions are consistent with each other. We have shifted, expanded or contracted the bar region as shown in Fig. 11; the results still hold with similar slopes presented in Table 5.

The structure of the mid-IR P–L relation has been found to be modified by the presence of circumstellar envelopes (Neilson et al. 2009, 2010), like those discovered by Kervella et al. (2006). It is argued that the envelopes are formed by a Cepheid wind where dust forms at a large distance from the star and causes an IR excess (Neilson & Lester 2008). This IR excess changes the structure of the mid-IR P–L relation, by increasing the observed mid-IR brightness of Cepheids. The IR excess is found to be important in two regimes: for Cepheids with log($P$) $< 0.7$ and for long-period Cepheids. The IR excess of short-period Cepheids is significant and makes the slope of the P–L relation appear more shallow than it actually is. For long-period Cepheids, the IR excess causes the slope to become steeper. The observed 3.6-$\mu$m P–L relation for log($P$) $> 1.0$ is $-3.23$ (Ngeow et al. 2009), and when the IR excess is removed the slope is predicted to be $-3.19$. For increased period cuts, the predicted P–L relations tend to have a shallower slope. It was also noted that the observed P–L relation tends to steepen with an increased period cut and shown that the samples in Ngeow et al. (2009) and Madore et al. (2009) are consistent. This suggests that a fraction of the Cepheids in the Madore et al. (2009) sample could be affected by IR excess due to mass loss.

Freedman et al. (2008b) suggested that the slopes of the mid-IR P–L relation should reach an asymptotic value that can be predicted from the slope of the period–radius (P–R) relation. If the temperature term at the mid-IR is ignored, then the predicted luminosity will be $L \propto R^2$, and hence $m = -2.5 \log(L) \propto -5 \log(R)$. Adopting the observed P–R slope of 0.68 from Gieren, Moffett & Barnes (1999), the predicted P–L slopes in the mid-IR is $-3.40$. This value is closer to the slopes found in Freedman et al. (2008b) and Madore

© 2010 The Authors. Journal compilation © 2010 RAS, MNRAS 408, 983–991
et al. (2009). However, Neilson et al. (2010) argue that the temperature term cannot be ignored, since the mid-IR luminosity is at the Rayleigh–Jeans tail of the blackbody function ($L \propto R^2 T_{\text{eff}}$). If the temperature term is included, then the predicted $P-L$ slopes at the mid-IR will be $\sim -3.23$ (for more details, see Neilson et al. 2010), which is closer to the slopes found in the $N_3$ band from this paper and in Ngeow et al. (2009).

5 CONCLUSION

In this paper, we matched AKARI’s IRC catalogue with the OGLE-III LMC Cepheid catalogue. This allows us to derive the $P-L$ relation in mid-IR bands. We have applied a conservative cut to the matched sources based on the colour information (at random phase) and the separation between the matched sources in the two catalogues. Only the matched sources in the $N_3$ band have a sufficient number of Cepheids for deriving the $P-L$ relation after applying these selection criteria.

We have employed a modified random-phase correction based on the methodology adopted from Nikolaev et al. (2004) and Soszyński et al. (2005). The correction function was modelled with a lower order Fourier series which either include or does not include the amplitude term. The $K$-band light-curve data from Persson et al. (2004) were used to test the fitting procedure including the random-phase correction. It was found that random-phase correction with $n = 1$ in the Fourier series provides the best-fitting results.

The derived $N_3$-band $P-L$ relation with the random-phase correction is consistent with the $P-L$ relation without the random-phase correction. However, the dispersion of the $P-L$ relation was improved by $\sim 7$ per cent when the random-phase correction was applied to the single-epoch $N_3$-band data. The slope of the $N_3$ $P-L$ relation, which is independent of the SAGE data, is in good agreement with the 3.6-µm $P-L$ relation found in Ngeow et al. (2009).

ACKNOWLEDGMENTS

This research is based on observations with AKARI, a JAXA project with the participation of ESA. We thank the AKARI IRC LMC.
survey team for early access to the data and Nancy Evans for constructive discussion. We would also like to thank the referee, Barry F. Madore, for useful comments. This work is partly supported by a Grant-in-Aid for Scientific Research (A) no. 18204014 from Japan Society for the Promotion of Science. C-CN thanks the funding from National Science Council (of Taiwan) under the contract NSC 98-2112-M-008-013-MY3.

REFERENCES

Bono G., Caputo F., Marconi M., 1998, ApJ, 497, L43
Freedman W., Madore B., Mager V., Persson E., Rigby J., Sturch L., 2008a, Spitzer Proposal ID 60010
Freedman W., Madore B., Rigby J., Persson S. E., Sturch L., 2008b, ApJ, 679, 71
Gieren W. P., Moffett T. J., Barnes T. G. III, 1999, ApJ, 512, 553
Ita Y. et al., 2008, PASJ, 60, 435
Kervella P., Mérand A., Perrin G., Coudé Du Foresto V., 2006, A&A, 448, 623
Madore B. F., Freedman W. L., Rigby J., Persson S. E., Sturch L., Major V., 2009, ApJ, 695, 988
Majaess D. J., Turner D. G., Lane D. J., 2008, MNRAS, 390, 1539
Marengo M., Evans N. R., Barmby P., Bono G., Welch D. L., Romaniello M., 2010, ApJ, 709, 120
Meixner M. et al., 2006, AJ, 132, 2268
Murakami H. et al., 2007, PASJ, 59, 369
Neilson H. R., Lester J. B., 2008, ApJ, 684, 569
Neilson H. R., Ngeow C.-C., Kanbur S. M., Lester J. B., 2009, ApJ, 692, 81
Neilson H. R., Ngeow C.-C., Kanbur S., Lester J. B., 2010, ApJ, 716, 1136
Ngeow C.-C., Kanbur S., 2008, ApJ, 679, 76
Ngeow C.-C., Kanbur S. M., Neilson H. R., Nanthakumar A., Buonaccorsi J., 2009, ApJ, 693, 691
Nikolaev S., Drake A. J., Keller S. C., Cook K. H., Dalal N., Griest K., Welch D. L., Kanbur S. M., 2004, ApJ, 601, 260
Onaka T. et al., 2007, PASJ, 59, 401
Persson S., Madore B., Krzemiński W., Freedman W., Roth M., Murphy D. C., 2004, AJ, 128, 2239
Soszyński I., Gieren W., Pietrzyński G., 2005, PASP, 117, 823
Soszyński I. et al., 2008, Acta Astron., 58, 163
Tanabè T. et al., 2008, PASJ, 60, 375
Udalski A., Soszynski I., Szymanski M., Kubiak M., Pietrzynski G., Wozniak P., Zebrun K., 1999, Acta Astron., 49, 223

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.