ON THE DISTANCE OF THE MAGELLANIC CLOUDS USING CEPHEID NIR AND OPTICAL–NIR PERIOD–WENSIHEIT RELATIONS

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ABSTRACT

We present the largest near-infrared (NIR) data sets, JHKs, ever collected for classical Cepheids in the Magellanic Clouds (MCs). We selected fundamental (FU) and first overtone (FO) pulsators, and found 4150 (2571 FU, 1579 FO) Cepheids for Small Magellanic Cloud (SMC) and 3042 (1840 FU, 1202 FO) for Large Magellanic Cloud (LMC). Current sample is 2–3 times larger than any sample used in previous investigations with NIR photometry. We also discuss optical VI photometry from OGLE-III. NIR and optical–NIR Period–Wesenheit (PW) relations are linear over the entire period range (0.0 < log P < 1.65) and their slopes are, within the intrinsic dispersions, common between the MCs. These are consistent with recent results from pulsation models and observations suggesting that the PW relations are minimally affected by the metal content. The new FU and FO PW relations were calibrated using a sample of Galactic Cepheids with distances based on trigonometric parallaxes and Cepheid pulsation models. By using FU Cepheids we found a true distance moduli of 18.45 ± 0.02 (random) ± 0.10 (systematic) mag (LMC) and 18.93 ± 0.02 (random) ± 0.10 (systematic) mag (SMC). These estimates are the weighted mean over 10 PW relations and the systematic errors account for uncertainties in the zero point and in the reddening law. We found similar distances using FO Cepheids (18.60 ± 0.03 (random) ± 0.10 (systematic) mag (LMC) and 19.12 ± 0.03 (random) ± 0.10 (systematic) mag (SMC)). These new MC distances lead to the relative distance, Δμ = 0.48 ± 0.03 mag (FU, log P = 1) and Δμ = 0.52 ± 0.03 mag (FO, log P = 0), which agrees quite well with previous estimates based on robust distance indicators.

Key words: Magellanic Clouds – stars: distances – stars: oscillations – stars: variables: Cepheids

Online-only material: color figures

1. INTRODUCTION

Recent detailed investigations indicate that 2%–3% of the systematic error affecting the Hubble constant estimate is due to the Cepheid distance to the Large Magellanic Cloud (LMC; Freedman & Madore 2010a; Rieß et al. 2011; Freedman et al. 2012). Moreover, the Magellanic Clouds (MCs) are fundamental benchmarks to constrain the accuracy and the precision of the most popular primary distance indicators (Pietrzyński et al. 2010; Matsunaga et al. 2009, 2011). The decrease of a factor two in metallicity between the LMC and the Small Magellanic Cloud (SMC) makes these galaxies also excellent laboratories to constrain the possible dependence of different standard candles on the metal content. Although, the MC Cepheids play a crucial role in many astrophysical problems, the number of homogeneous optical (B, V, R, I) and near-infrared (NIR; J, H, Ks) data sets is quite limited.

The most extensive surveys in the optical bands (VI) were performed by micro-lensing experiments (MACHO, EROS, OGLE). The MACHO project collected R, I-band data for ~1900 Cepheids in the LMC (Skrutskie et al. 2006; Alcock et al. 2000; Welch & MACHO Collaboration 1999), while EROS collected V, R-band data for ~300 and ~600 Cepheids in the LMC and in the SMC, respectively (Beaulieu & Marquette 2000). The most complete sample of MC Cepheids was collected by OGLE-III (Soszyński et al. 2008, 2010). Their catalog includes V, I-band light curves for more ~7000 Cepheids (LMC: 2000 fundamental (FU), 1000 first overtone (FO); SMC: 2500 FU, 1500 FO). Accurate distance determinations to the MCs based on optical Period–Wesenheit (PW) relations have also been provided by Udalski et al. (1999), Bono et al. (2002), Groenewegen & Salaris (2003), and Ngeow et al. (2009). More recently, Di Criscienzo et al. (2013) provided a detailed theoretical investigation concerning the PW relations in the Sloan Digital Sky Survey bands.

The NIR data bases for MC Cepheids are significantly smaller: Laney & Stobie (1986, 1994) collected NIR light curves for 44 MC Cepheids (21 LMC, 23 SMC), while Welch et al. (1987) collected light curves for 91 SMC Cepheids. More recently Persson et al. (2004, hereinafter P04) collected NIR light curves for 92 LMC Cepheids. More recently, accurate K-band photometry (12 phase points per variable) was collected by Ripepi et al. (2012, hereinafter R12) in two LMC fields located around 30 Doradus (172 FU, 152 FO) and the South Elliptical Pole (11 Cepheids). They provided, by using also literature data, accurate estimates of Period–Luminosity (PL), PW, and Period–Luminosity–Color (PLC) relations for both F and FO Cepheids. One of the key advantages in using NIR data is that the pulsation amplitude decreases for increasing wavelength and the estimate of the mean magnitude becomes
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2. DATA SETS AND DATA SELECTION

The Cepheid intrinsic parameters are taken from the OGLE-III catalog (Soszyński et al. 2008, 2010). We adopted the following Cepheid parameters: pulsation period, position (right ascension and declination), mean V- and I-band magnitude, I-band amplitude, epoch of maximum, and pulsation mode. The optical OGLE-III Cepheid catalog was cross-correlated with the NIR catalog of the IRSF/SIRIUS Near-Infrared Magellanic Clouds Survey provided by Kato et al. (2007). The single-epoch J,H,Ks magnitudes for the OGLE-III FU Cepheids were extracted by Matsunaga et al. (2011) In this investigation we also included FO Cepheids. We ended up with a sample of 3042 LMC (1840 FU, 1202 FO) and 4150 SMC (2571 FU, 1579 FO) Cepheids with three NIR (J,H,Ks) single-epoch measurements. The IRSF/SIRIUS J,H,Ks measurements were transformed into the 2MASS NIR photometric system following Kato et al. (2007).

The mean magnitudes of FU Cepheids were estimated using the NIR template light curves provided by Soszyński et al. (2005). To assess the accuracy of this method, we compared our estimates of mean magnitudes with the mean magnitudes for LMC Cepheids based on finely sampled light curves (P04). The template light curves and the mean magnitude by P04 were also transformed into the 2MASS NIR photometric system following Carpenter (2001). Figure 1 shows that the intrinsic dispersion decreases by a factor of two when moving from the single-epoch measurements to the mean magnitudes based on the template (0.12 versus 0.05 mag). The total error budget of the mean magnitudes estimated using the template light curve is given by

\[ \sigma^2_{\text{cal}} = \sigma^2_{\text{ini}} + \sigma^2_{\text{ph}} + \sigma^2_{\text{cal}} + \sigma^2_{\text{ph}}, \]

where \( \sigma^2_{\text{cal}} \) is the intrinsic photometric error, with a typical value of \( \sim 0.03 \) at 16 mag in J,H,Ks; \( \sigma^2_{\text{cal}} \) is the error due to the transformation into the 2MASS photometric system, it is of the order of 0.01 mag for UKIRT, LCO, and IRSF.
systems; $\sigma_{\text{rph}}^2$ is the scatter due to the random phase sampling, it is given by the template algorithm and it is $\sim 0.05$ mag (Soszyński et al. 2005).

For the FO Cepheids the mean magnitude is based on the single-epoch measurements, since template light curves are not available for these pulsators. It is worth mentioning, that the mean magnitudes of these pulsators are less affected by their random sampling, since their luminosity amplitude is on average three times smaller than for FU Cepheids (Freedman & Madore 2010b). The errors of the FO mean magnitudes were estimated using the above relation, but the term $\sigma_{\text{rph}}^2$ gives the typical semi-amplitude of FO light curves ($\sim 0.10$ mag). We plan to address the discussion concerning the template light curve for FO Cepheids and their errors in a forthcoming paper.

3. PERIOD–WESENHEIT RELATIONS

The Wesenheit indices, introduced by Madore (1982), are pseudo-magnitudes closely related to apparent magnitudes, but minimally affected by uncertainties on reddening. On the basis of two magnitudes, $m_{\lambda_1}$ and $m_{\lambda_2}$, we can define a Wesenheit index:

$$W(\lambda_2, \lambda_1) = m_{\lambda_1} - \left[ \frac{A(\lambda_1)}{E(m_{\lambda_2} - m_{\lambda_1})} \right] \times (m_{\lambda_2} - m_{\lambda_1}),$$  \hspace{1cm} (1)

where $\lambda_1 > \lambda_2$ and $(A(\lambda_1)/E(m_{\lambda_2} - m_{\lambda_1}))$ is the total to selective extinction for the given filters—{$V, I, J, H, K_S$}—and for the adopted reddening law. The clear advantage in using the Wesenheit indices is that they are minimally affected by uncertainties affecting reddening corrections for Galactic and extragalactic Cepheids. Once we fix the reddening law (Cardelli et al. 1989) and we assume $R_V = (A(V)/(A(B) - A(V))) = 3.23$, we obtain the following selective absorption ratios, namely $A_J/A_V = 0.61$; $A_H/A_V = 0.29$; $A_K/S/A_V = 0.18$; $A_{K_S}/A_V = 0.12$ mag.

By combining the five optical–NIR ($VIJK_S$) mean magnitudes, we can compute 10 Wesenheit indices for each Cepheid in the sample, and in turn, 10 PW relations of the form $W(\lambda_2, \lambda_1) = a + b \times \log P$, where $P$ is the pulsation period in days. We decided to analyze separately FU and FO Cepheids to overcome possible systematic uncertainties that the “fundamentalization” of the FO periods might introduce in the estimate of the PL relations (Feast & Catchpole 1997; Marengo et al. 2010). Therefore, we computed independent PW relations for FU and FO Cepheids. We performed a linear fit of the data to identify possible outliers. We have included data up to $4\sigma$ from the central location by using the robust Biweight location estimator (Fabrizio et al. 2011). We ended up with a sample of $\sim 4000$ SMC ($\sim 2500$, FU; $\sim 1500$, FO) and $\sim 3000$ LMC ($\sim 1800$, FU; $\sim 1100$, FO) Cepheids. For approximately three dozen Cepheids with period $\gtrsim 20$ days, the $I$ band is saturated in the OGLE-III data set, and therefore we cannot apply the template. The NIR mean magnitudes for these Cepheids were taken from P04 and transformed into the 2MASS photometric system (see green dots in Figure 2).
We then performed a linear regression of the NIR data and the results for the three PW relations are showed in Figure 2 (see also Table 1). From top to bottom each panel shows FU (red and green dots) and FO (blue dots) LMC (left) and SMC (right) Cepheids. The PW relations are overplotted as black lines. Data plotted in Figure 2 display four relevant findings concerning the NIR PW relations. (1) The FU and the FO PW relations are linear over the entire period range. (2) The intrinsic dispersion of the SMC PW relations are approximately a factor of two larger than for the LMC PW relations. The difference is mainly caused by depth effects in the former system (van den Bergh 2000). (3) For each PW relation the difference in the slope between LMC and SMC Cepheids is small. Data listed in Tables 1 and 2 indicate that it is, on average, smaller than 0.8σtot, where σtot is the sum in quadrature of the dispersion of LMC and SMC PW relations. This indicates a minimal dependence of the NIR PW relations on the metal content. (4) The width in temperature of the FO instability strip is narrower than the instability strip for FU Cepheids (Bono et al. 2000), but the intrinsic dispersions are not significantly different. The lack of a template light curve for FO Cepheids increases the dispersion of their mean magnitudes.

The above findings support recent theoretical (Bono et al. 2010) and empirical (Majaess et al. 2011) investigations. The main advantage of the current approach is that the results rely on NIR single-epoch measurements that are 2–3 times larger than any previous investigation (Groenewegen 2000). In order to constrain the possible occurrence of systematic errors in the NIR PW relations, we also computed the optical–NIR PW relations using the \( V, \mu \) magnitude provided by OGLE-III. Figures 3 and 4 show the optical–NIR PW relations for FU (red dots) and FO (blue dots) LMC and SMC Cepheids, respectively. Once again, we found that the PW relations are linear and the slopes are minimally affected by the difference in metal content (see Table 1). Current results concerning the linearity of NIR and optical–NIR PW relations support previous findings by Ngeow et al. (2005) and Madore & Freedman (2009).

### 3.1. Linearity of PW Relations

To constrain on a more quantitative basis the linearity of NIR PW relations we estimated the distance of individual Cepheids from the least squared solution. The residuals for FU Cepheids plotted in the top panels of Figure 5 do not show any trend as a function of the pulsation period. To further constrain this evidence, we performed a linear fit to the residuals and we found that the zero points, the slopes, and the means attain vanishing values. Moreover, the dispersions are typically smaller than 0.2 mag. The same outcome applies to the FO Cepheids (see bottom panels of Figure 5). Note that the residuals of FO PW relations are larger than the residuals of the FU PW relations, since for the former ones we lack template light curves. The residuals referred to SMC are larger than the residuals of LMC due to depth effects. The anonymous referee explicitly asked a quantitative analysis concerning the linearity of the PW relations for both FU and FO SMC Cepheids. To our knowledge there is no clear physical reason why FU and FO NIR PW relations should show a break, therefore, we decided to constrain the possible occurrence using different breaks in period. We split the entire Cepheid sample by adopting a break in period at \( \log P = 0.45 \). This means that we assume as short-period Cepheids those with \( \log P \leq 0.45 \), while the long-period ones are those with \( 0.45 < \log P \leq 1.65 \) (FU) and with \( 0.45 < \log P \leq 0.65 \) (FO). The zero points and the slopes for FU NIR PW relations listed in Table 3 show that their errors are a factor of 3–4 larger than the errors of the linear regressions based on the entire sample. This trend is expected, since the number of Cepheids included in the two new linear regressions decreases from a factor of three (long period) to 50\% (short period). On the other hand, the dispersions of the new PW relations are either similar (short period) or on average smaller (long period). The new FO PW relations show similar trends concerning the intrinsic errors on the zero points, on the slopes and on the dispersions.

The break in period is defined somewhat arbitrarily, therefore, we decided to perform the same test, but using a break at \( \log P = 0.40 \) and \( \log P = 0.35 \). Current empirical evidence suggests that optical PL relations of SMC Cepheids show a break in period at \( \log P \approx 0.4 \) (Sandage et al. 2009), while for LMC Cepheids the break seems to be at \( \log P \approx 1 \) (Sandage et al. 2004). The results concerning the new NIR PW relations are listed in Table 3 and indicate that the short-period PW relations are quite similar to the global PW relations, i.e., the PW relations covering the entire period range. This trend is—once again—expected, since more than 2/3 of the Cepheid sample is in the short-period range. The evidence that linear regressions with an arbitrary break in period, give PW relations with either similar or marginally smaller dispersion is also expected. This is the consequence of the increase in the degrees of freedom of the linear regressions. However, this does not mean that the PW relations with a break in period are a better representation of observations. To address this issue on a more quantitative basis, we devised a new empirical test based on the relative distance between SMC and LMC. The MC relative distance is quite solid, since different standard candles provide similar estimates.

By adopting both NIR and optical–NIR PW relations, we found that the relative distance modulus based on FU Cepheids and at \( \log P = 1 \) is \( \Delta \mu = 0.48 \pm 0.03 \) mag. This evaluation agrees quite well with similar estimates available in the literature (see Section 4). To further constrain the intrinsic accuracy of the NIR PW relations with a break in period, we computed three new PW(J, Ks) relations for LMC Cepheids. Following Sandage et al. (2004), we adopted a break in period at \( \log P = 1 \). The zero points and the slopes of the new NIR PW relations are listed in Table 4. We estimated the MC relative distances by using the short-period and the long-period PW relations. The relative distances based on the former ones were estimated at \( \log P = 0.3 \), while those based on the latter ones were estimated at \( \log P = 1.0 \). The results listed in Table 5 indicate—as expected—that the MC relative distances based on short-period PW relations agree quite well with the MC relative distances based on global PW relations. The main difference is that the relative distance based on short-period PW relations have intrinsic errors, estimated by propagating the errors on both the coefficients and the dispersion of the individual PW relations, that are on average a factor of two larger than those ones based on the global PW relations. The same outcome applies to the MC relative distances based on the long-period PW relations. However, their intrinsic errors are larger and they also show a larger spread among the three different NIR PW relations. Note that the MC relative distance based on the long-period PW(J, H) relations are systematically smaller than the others, because the zero point of the long-period PW relation for LMC Cepheids is larger than the zero point of the global PW relation (15.949 versus 15.876).

We repeated the same test by using two different pivot periods, namely \( \log P = 0.2 \) for the short-period and \( \log P = 1.2 \) for the long-period PW relations and the results are quite similar. We


**Table 1**

NIR and Optical–NIR PW Relations for LMC and SMC Cepheids

| W(i2, λ1)α | Mode  | a      | b      | σb   | μa   | μtheo  |
|------------|-------|--------|--------|------|------|--------|
|            |       |        |        |      |      |        |
| LMC        |       |        |        |      |      |        |
| W(J, Ks)   | FU    | 15.876 | -3.365 | 0.008 | 18.44 | 18.53  |
| W(J, H)    | FU    | 15.630 | -3.373 | 0.008 | 18.30 | 18.65  |
| W(H, Ks)   | FU    | 16.058 | -3.360 | 0.010 | 18.54 | 18.46  |
| W(V, Ks)   | FU    | 15.901 | -3.326 | 0.008 | 18.46 | 18.51  |
| W(V, H)    | FU    | 15.816 | -3.315 | 0.008 | 18.40 | 18.56  |
| W(V, J)    | FU    | 15.978 | -3.272 | 0.009 | 18.49 | 18.47  |
| W(I, Ks)   | FU    | 15.902 | -3.325 | 0.008 | 18.46 | 18.52  |
| W(I, H)    | FU    | 15.801 | -3.317 | 0.008 | 18.39 | 18.55  |
| W(I, J)    | FU    | 16.002 | -3.243 | 0.011 | 18.50 | 18.46  |
| W(V, I)    | FU    | 15.899 | -3.327 | 0.008 | 18.47 | 18.53  |
| Mean (FU)  |       | 15.927 | -3.341 | 0.010 | 18.50 | 18.57  |
| W(J, Ks)   | FO    | 15.370 | -3.471 | 0.013 | 0.08 | 18.60  |
| W(J, H)    | FO    | 15.207 | -3.507 | 0.015 | 0.09 | 18.60  |
| W(H, Ks)   | FO    | 15.483 | -3.425 | 0.017 | 0.10 | 18.59  |
| W(V, Ks)   | FO    | 15.410 | -3.456 | 0.013 | 0.07 | 18.61  |
| W(V, H)    | FO    | 15.357 | -3.485 | 0.011 | 0.08 | 18.61  |
| W(V, J)    | FO    | 15.475 | -3.435 | 0.014 | 0.10 | 18.62  |
| W(I, Ks)   | FO    | 15.402 | -3.448 | 0.013 | 0.08 | 18.61  |
| W(I, H)    | FO    | 15.351 | -3.489 | 0.012 | 0.08 | 18.62  |
| W(I, J)    | FO    | 15.499 | -3.423 | 0.020 | 0.13 | 18.66  |
| W(V, I)    | FO    | 15.399 | -3.460 | 0.009 | 0.07 | 18.52  |
| Mean (FO)  |       | 15.467 | -3.451 | 0.014 | 0.16 | 18.76  |
| SMC        |       |        |        |      |      |        |
| W(J, Ks)   | FU    | 16.457 | -3.480 | 0.011 | 0.16 | 18.92  |
| W(J, H)    | FU    | 16.217 | -3.542 | 0.011 | 0.17 | 18.74  |
| W(H, Ks)   | FU    | 16.638 | -3.445 | 0.011 | 0.19 | 18.95  |
| W(V, Ks)   | FU    | 16.507 | -3.461 | 0.011 | 0.15 | 18.95  |
| W(V, H)    | FU    | 16.426 | -3.475 | 0.010 | 0.15 | 18.88  |
| W(V, J)    | FU    | 16.614 | -3.427 | 0.011 | 0.16 | 19.00  |
| W(I, Ks)   | FU    | 16.511 | -3.464 | 0.011 | 0.16 | 18.95  |
| W(I, H)    | FU    | 16.417 | -3.480 | 0.011 | 0.15 | 18.87  |
| W(I, J)    | FU    | 16.662 | -3.424 | 0.013 | 0.18 | 19.01  |
| W(V, I)    | FU    | 16.482 | -3.449 | 0.010 | 0.13 | 18.95  |
| Mean (FU)  |       | 16.493 | -3.458 | 0.014 | 0.19 | 18.99  |
| W(J, Ks)   | FO    | 15.947 | -3.651 | 0.022 | 0.16 | 19.06  |
| W(J, H)    | FO    | 15.778 | -3.722 | 0.023 | 0.17 | 19.17  |
| W(H, Ks)   | FO    | 16.069 | -3.579 | 0.027 | 0.19 | 19.00  |
| W(V, Ks)   | FO    | 15.992 | -3.624 | 0.021 | 0.16 | 19.09  |
| W(V, H)    | FO    | 15.937 | -3.660 | 0.020 | 0.15 | 19.16  |
| W(V, J)    | FO    | 16.074 | -3.578 | 0.023 | 0.18 | 19.17  |
| W(I, Ks)   | FO    | 15.990 | -3.630 | 0.020 | 0.16 | 19.09  |
| W(I, H)    | FO    | 15.932 | -3.667 | 0.020 | 0.16 | 19.17  |
| W(I, J)    | FO    | 16.113 | -3.595 | 0.027 | 0.20 | 19.17  |
| W(V, I)    | FO    | 15.958 | -3.599 | 0.019 | 0.14 | 19.12  |
| Mean (FO)  |       | 15.923 | -3.603 | 0.021 | 0.19 | 19.02  |

Notes.

α The color coefficients of the adopted PW relations are the following: (A_k / E(J − Ks)) = 0.69; (A_h / E(J − H)) = 1.63; (A_k / E(H − Ks)) = 1.92; (A_k / E(V − Ks)) = 0.13; (A_h / E(V − H)) = 0.22; (A_j / E(V − J)) = 0.41; (A_k / E(I − Ks)) = 0.24; (A_h / E(I − H)) = 0.42; (A_j / E(I − J)) = 0.92; (A_j / E(I − V)) = 1.55.

β Distance modulus based on the zero-point calibration from Benedict et al. (2007).

μ Distance modulus based on the zero-point calibration obtained by the predicted FU PW relations for Magellanic Cepheids provided by Marconi et al. (2005). The associated error is the dispersion of the theoretical PW relation.

δ Weighted distance modulus estimated using the distance moduli of individual PW relations.

ε Distance modulus obtained using Polaris for the zero-point calibration (van Leeuwen et al. 2007).

f Distance modulus based on the zero-point calibration obtained by the predicted FO PW relations for Magellanic Cepheids provided by Marconi et al. (2005). The associated error is the dispersion of the theoretical PW relation.
also performed the same test using NIR FO PW relations and the outcome is—once again—quite similar. Note that the intrinsic errors on the coefficients of the long-period FO PW relations are larger than the errors of the short-period ones, since the Cepheid sample in the former period interval is from a factor of five to a factor of 10 smaller than in the latter one.

The above findings indicate that the PW relations with arbitrary breaks in period when compared with global PW relations have larger intrinsic errors on the coefficients of the linear regressions and roughly equivalent dispersions.

However, the MC relative distances based on the former ones are characterized by intrinsic errors that are, on average, a factor of two larger than the latter ones. Thus further supporting the use of global NIR PW relations.

This provides an independent support to the results concerning the linearity of both optical and NIR PW relations for FU Cepheids by Persson et al. (2004), Bono et al. (2010), and Ngeow (2012, and references therein). We found that optical and NIR PW relations for FO Cepheids are also linear over the entire period range, supporting previous findings by Ngeow et al. (2005) and Madore & Freedman (2009). We are thus facing the empirical evidence that optical and NIR PL relations for FU Cepheids do show a change in the slope for log P ≈ 0.4 (Sasselov et al. 1997; Bono et al. 1999; Ngeow et al. 2005; Koen et al. 2007; Matsunaga et al. 2011). The difference between the PL and the PW relations is mainly due to the fact that the latter is mimicking, as originally suggested by Bono & Marconi (1999), a PLC relation.

### 3.2. Metallicity Dependence of the PW Relations

To further constrain the metallicity dependence of the NIR PW relations, we performed a detailed comparison with similar estimates available in the literature. The middle panel of Figure 6 shows the difference between the slope of the PW(J,K₅) relations we estimated for LMC (black line) and SMC (green line) Cepheids with similar PW relations for Galactic Cepheids (see Table 6) derived by Storm et al. (2011a, hereinafter S11a; red line) and Ngeow (2012, hereinafter N12; purple line). The standard deviations plotted in the same figure clearly indicate that current Magellanic and Galactic NIR PW relations do agree within 1σ. The difference in the slope between our SMC and Galactic PW(J,K₅) relations is, on average, smaller than 0.3σ (N12) and 0.4σ (S11a).

The anonymous referee suggested that we perform the same comparison for the optical PW(V,I) relation. The top panel of Figure 6 shows the difference between the slope of the PW(V,I) relations we estimated for LMC (black line) and SMC (green line) Cepheids with similar PW relations for Galactic Cepheids (see Table 6) derived by Bono & Marconi (1999) and Vink et al. (2011). The difference in the slope of the PW(V,I) relation between our metal-poor stellar system (SMC, [Fe/H] = −0.75) and our metal-rich stellar system (Galaxy, [Fe/H] = −0.18 to 0.25) is on average, smaller than ~0.1σ (B07) and ~0.02σ (S11a).

The bottom panel of Figure 6 shows the difference between the slope of the PW(V,K₅) relations we estimated for LMC (black line) and SMC (green line) Cepheids with the PW relation for LMC Cepheids (see Table 6) derived by R12 (gray line). Data plotted in this figure clearly indicate the good agreement between the two independent LMC slopes. Moreover, current SMC and LMC PW relations do agree within 1σ. The other NIR and optical–NIR PW relations provide similar results. The quoted numbers indicate that the PW relations are, in the metallicity range covered by Magellanic Cepheids, independent of metal abundance. The extension into the more metal-rich regime does require more accurate measurements for Galactic Cepheids.

### 3.3. Absolute Calibration of the PW Relations

To estimate the distances to the MCs, we combined our new comprehensive sets of PW relations with recent findings concerning absolute magnitudes of Galactic Cepheids. We followed the same approach suggested by Bono et al. (1999) to calibrate the LMC PW relations and adopted the 10 FU Galactic Cepheids with Hubble Space Telescope (HST) trigonometric parallaxes (Benedict et al. 2007). To calibrate the FO PW relations, we adopted the Hipparcos trigonometric parallaxes for Polaris provided by van Leeuwen et al. (2007). The mean J,H,K₅ magnitudes for the calibrating Galactic Cepheids are from Laney & Stobie (1992). We estimated the true distance modulus, μ, of both LMC and SMC by using the quoted calibrators and by imposing the slope of individual PW relations for FU and FO Cepheids (see the Column 6 of Table 1).

Note that the true distance moduli for FU Cepheids were estimated as the weighted mean of the μᵢ of individual calibrating Cepheids. The associated error on μ is the sum in quadrature of the weighted error on the distance and of the intrinsic dispersion associated with the linear regression (see Column 5 of Table 1). The weighted means based on the FU PW relations give μ(LMC) = 18.45 ± 0.02 and μ(SMC) = 18.93 ± 0.02 mag, while the weighted means based on FO PW relations give μ(LMC) = 18.60 ± 0.03 and μ(SMC) = 19.12 ± 0.03 mag.

To constrain the possible occurrence of deceptive errors in the absolute zero point, we performed an independent zero-
Figure 3. Optical–NIR Period–Wesenheit relations for LMC Cepheids. Symbols and lines are the same as Figure 2. (A color version of this figure is available in the online journal.)

The two independent empirical calibrations for FU and FO Cepheids provide weighted true distance moduli to the MCs that differ from 0.15 (LMC) to 0.19 (SMC) mag. On the other hand, the weighted true distance moduli based on the theoretical calibrations differ at the level of a few hundredths of mag. The difference between the two empirical calibrations is due to the fact that the empirical calibrations for FO PW relations rely on a single object (see Section 4).

However, data listed in Table 1 indicate that the PW(J, H) and the PW(I, H) relations for FU and FO Cepheids, calibrated using the Galactic Cepheids with trigonometric distances, provide true distance moduli that differ at the 2σ–3σ level from the weighted mean. The evidence that distances based on PW relations, calibrated using theoretical predictions for MC Cepheids (L. Inno et al. 2013, in preparation), show smaller differences indicates that the main culprit seems to be the precision of the H-band zero-point calibration. However, the difference in the weighted mean distances, provided by the two independent zero-point calibrations for FO Cepheids, is smaller than 5% (LMC: 49.0 ± 1.2 versus 51.5 ± 1.2 kpc; SMC: 61.1 ± 2.2 versus 68.8 ± 2.3 kpc). Moreover, the total uncertainty of current LMC and SMC distances is at the ∼2% and at the ∼4% level, respectively. Note that we obtain very similar distances if we neglect the distances based on the PW(J, H) and PW(I, H) relations, namely 18.47 ± 0.02 (trigonometric parallaxes) and 18.57 ± 0.03 (theory) mag.

To further constrain the possible sources of systematic errors in current distance estimates, we also constrained the impact of
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SMC

FU 2268
FO 1465

FU 2269
FO 1465

FU 2286
FO 1495

FU 2285
FO 1476

FU 2295
FO 1470

FU 2294
FO 1467

12
15
18 W(I, V)

12
15
18 W(J, H)

12
15
18 W(V, J)

12
15
18 W(V, K)

12
15
18 W(I, K)

−0.5 0.0 0.5 1.0 1.5 log P [days]

Figure 4. Same as Figure 3, but for SMC Cepheids.

(A color version of this figure is available in the online journal.)

the adopted reddening law. In a recent investigation (Kudritzki & Urbaneja 2012) suggested that distance determinations based on the PW relations may be affected by changes in the reddening law either in the Galaxy or in external stellar systems. To constrain this effect we computed a new set of PW relations by adopting the reddening law by McCall (2004). We found that the difference in the true distance moduli, based on the two different reddening laws, is on average ∼0.01 mag. The mild dependence of current distance determinations on the reddening law might also be due to the fact that the selective absorption ratios of optical–NIR PW relations are less sensitive to the fine structure of the reddening law. The selective absorption ratios given in Section 3 indicate that the coefficient of the color term of the PW(V, K) relation is at least one order of magnitude smaller than the coefficients of PW(J, H) and PW(H, K) relations (0.13 versus 1.63 and 1.92 mag). This evidence indicates that the difference in the true distance moduli based on PW(J, H) and PW(H, K) relations might also be caused either by photometric error in the mean magnitudes or by changes in the reddening law along the line of sight of the HST Galactic calibrating Cepheids.

4. SUMMARY AND DISCUSSION

We present new true distance modulus determinations of the MCs using NIR and optical–NIR PW relations. The NIR PW relations were estimated by adopting the largest data set of J, H, K_S single-epoch measurements ever collected for MC Cepheids. The optical V, I measurements come from the OGLE-III data set. We ended up with a sample of 4150 (2571, FU; 1579, FO; SMC) and 3042 (1840, FU; 1202, FO; LMC) Cepheids. We estimated independent PW relations for both FU and FO Cepheids. The slopes of the current FU PW relations agree quite well with similar estimates available in the literature. We found that they agree at 1.2σ level with the slopes of the NIR PW relations for LMC Cepheids derived by P04. The agreement is even better if we compare our slopes for the PW(J, K) relations with the slopes recently provided by Storm et al. (2011b, hereinafter S11b) for the LMC (LMC: −3.31 ± 0.09 versus −3.365 ± 0.008). The above findings are even more relevant if we take into account that current slopes are based on data samples that are from 80 (S11b), 30 (P04), and ∼3 (Groenewegen 2000) times larger than the quoted samples. We cannot perform a similar comparison concerning the slopes of the FO PW relations, since to our knowledge they are not available in the literature.

Moreover, we found that both FU and FO PW relations are linear over the entire period range and their slopes attain, within the intrinsic dispersions, similar values in the MCs. The difference is, on average, smaller than 0.8σ. The difference between the slope of our SMC and Galac-
Figure 5. Top: difference between individual NIR Wesenheit mean magnitudes of LMC (left) and SMC (right) Cepheids and the PW relations. The linear fit of the residuals is also overplotted (dashed green line). The weighted means and the intrinsic dispersions are also labeled. Bottom: same as the top but for FO Cepheids. (A color version of this figure is available in the online journal.)

tic PW(J,K$_S$) relations available in the literature is, on average, smaller than 0.5σ (0.3σ, N12; 0.4σ, S11b). The same outcome applies to optical bands, and indeed the difference in the slope between our SMC and Galactic PW(V, I) relations available in the literature is, on average, smaller than $\sim$0.1σ (B07) and $\sim$0.9σ (S11a). This supports the evidence for a marginal dependence of NIR and PW(V, I) relations on the metal content, as suggested by pulsation predictions and recent empirical investigations.

The new PW relations were calibrated using two independent sets of Galactic Cepheids with individual distances based either on trigonometric parallaxes or on theoretical models. By using FU Cepheids we found a true distance modulus to the LMC of 18.45 ± 0.02 (random) ± 0.10 (systematic) mag and to the SMC of 18.93 ± 0.02 (random) ± 0.10 (systematic) mag. These estimates are the weighted mean over the entire set of distance determinations. The random error was estimated by taking into account the intrinsic dispersion of individual PW relations. The systematic error is the sum in quadrature of the difference in $\mu$ introduced by the change in reddening law and the zero-point calibration.

We found similar distances using FO Cepheids 18.60 ± 0.03 (random) ± 0.10 (systematic) mag, LMC and 19.12 ± 0.03 (random) ± 0.10 (systematic) mag, SMC. Once again the random errors were estimated by taking into account the intrinsic dispersion of individual PW relations, while the systematic ones are the sum in quadrature of the difference in $\mu$ introduced by the change in reddening law and the zero-point calibration.
The two independent empirical calibrations for FU and FO Cepheids provide weighted true distance moduli to the MCs that differ for 0.15 (LMC) and 0.19 (SMC) mag. On the other hand, the weighted true distance moduli based on the theoretical calibrations differ at the level of a few hundredths of mag. The difference between the empirical and theoretical calibrations is due to the fact that the empirical calibrations for FO PW relations rely on a single object (see Section 3.2).
The relative distance of the MCs, for distance indicators minimally affected by the metal content, is independent of uncertainties affecting the zero-point calibration. We found that the weighted mean relative distance between SMC and LMC using FU Cepheids and the PW relation listed in Table 1 ($\log P = 1$) is $\Delta \mu = 0.48 \pm 0.03$ mag. We applied the same approach by using FO Cepheids and we found $\Delta \mu = 0.52 \pm 0.03$ mag ($\log P = 0.5$). The errors on the weighted mean relative distances were estimated by using the dispersions of individual PW relations. The quoted determinations agree quite well with each other and with the recent estimate $\Delta \mu = 0.47 \pm 0.15$ mag provided by S11b by using the IRSB method (see also Groenewegen 2000; Bono et al. 2010; Matsunaga et al. 2011).

The distance modulus we obtained for the LMC agrees quite well with the recent estimate provided by S11b ($18.45 \pm 0.04$ mag) and P04 ($18.50 \pm 0.05$ mag) by using the NIR PL, PLC, and PW relations. The difference is also minimal with the “classical” value—$18.50 \pm 0.10$ mag—Freedman et al. (2001). The same conclusion can be reached if we compare the current estimate with recent distance moduli provided by Benedict et al. (2007; $18.50 \pm 0.03$; HST trigonometric parallaxes for Galactic Cepheids and the LMC slope of the optical PW relation), Ngeow & Kanbur (2008; $18.49 \pm 0.04$; optical PL and PLC relations), Freedman & Madore (2010a; $18.44 \pm 0.03$ (random) $\pm 0.06$ (systematic); PW($V, I$) relation for Galactic and LMC Cepheids), and Ngeow (2012; $18.531 \pm 0.043$ mag; NIR and optical–NIR PW relations). Moreover, our result also agrees with the most recent distance modulus—$18.477 \pm 0.033$—provided by Scowcroft et al. (2011) and by Freedman et al. (2012), using the Spitzer mid-IR band PL relations.

The distance modulus we obtained for the SMC is, once again, in very good agreement with the independent estimates provided by Groenewegen (2000; $19.11 \pm 0.11$ mag; Hipparcos trigonometric parallaxes and PW($V, I$) relation) and S11b ($18.92 \pm 0.14$ mag).

Note that in the comparison of LMC distance moduli, we adopted the estimates that neglect the metallicity dependence.
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5. FINAL REMARKS

The key feature of current findings is that the random errors associated to our distance determinations are very small, due to the fact that we adopt an homogeneous and accurate NIR data set and also because we are fully exploiting the use of NIR and optical–NIR PW relations. Moreover, the use of two independent zero-point calibrations and two different reddening laws indicate that the global uncertainty on the MC distances seems to be of the order of 1% by using either the 10

Table 5

\[
\begin{array}{cccc}
W(J, \lambda_1) & \text{Mode} & \Delta \mu_{\text{short}} & \Delta \mu_{\text{long}} & \text{Break} \\
W(J, K_S) & \text{FU} & 0.55 \pm 0.06 & 0.47 \pm 0.06 & \ldots & 0.3 & 1.0 \\
& \text{``} & 0.54 \pm 0.11 & 0.48 \pm 0.13 & 0.35 & 0.3 & 1.0 \\
& \text{``} & 0.54 \pm 0.10 & 0.44 \pm 0.13 & 0.40 & 0.3 & 1.0 \\
& \text{``} & 0.54 \pm 0.09 & 0.48 \pm 0.13 & 0.45 & 0.3 & 1.0 \\
W(J, H) & \text{FU} & 0.55 \pm 0.05 & 0.42 \pm 0.06 & \ldots & 0.3 & 1.0 \\
& \text{``} & 0.51 \pm 0.11 & 0.31 \pm 0.16 & 0.35 & 0.3 & 1.0 \\
& \text{``} & 0.51 \pm 0.10 & 0.31 \pm 0.16 & 0.40 & 0.3 & 1.0 \\
& \text{``} & 0.50 \pm 0.10 & 0.31 \pm 0.16 & 0.45 & 0.3 & 1.0 \\
W(H, K_S) & \text{FU} & 0.56 \pm 0.07 & 0.50 \pm 0.08 & \ldots & 0.3 & 1.0 \\
& \text{``} & 0.56 \pm 0.12 & 0.52 \pm 0.16 & 0.35 & 0.3 & 1.0 \\
& \text{``} & 0.56 \pm 0.14 & 0.51 \pm 0.15 & 0.40 & 0.3 & 1.0 \\
& \text{``} & 0.56 \pm 0.13 & 0.52 \pm 0.17 & 0.45 & 0.3 & 1.0 \\
\end{array}
\]

Notes. The errors on the relative distances were estimated by accounting for the uncertainties both in the coefficients and in the dispersion of the individual PW relations. Relative distance moduli estimated using the PW relations on the entire range of periods. \(\Delta \mu_{\text{short}}\) here is the relative distance moduli obtained at \(\log P = x_1\), while \(\Delta \mu_{\text{long}}\) is obtained at \(\log P = x_2\).

5.1. Exact distances moduli obtained at log P = x_1, while Δμ_long is obtained at log P = x_2.

Table 6

| \(W(J, \lambda_1)\) | Mode | \(a\) | \(b\) | \(\sigma\) | Galaxy | Reference |
|------------------|-----|-----|-----|-----|-------|---------|
| \(W(J, K_S)\) | FU (229) | \(-2.65 \pm 0.02\) | \(-3.34 \pm 0.03\) | 0.10 | MW | N12 |
| \(W(J, K_S)\) | FU (70) | \(-2.52 \pm 0.12\) | \(-3.44 \pm 0.09\) | 0.23 | MW | S11a |
| \(W(V, I)\) | FU (70) | \(-2.70 \pm 0.15\) | \(-3.26 \pm 0.11\) | 0.26 | MW | S11a |
| \(W(V, I)\) | FU (10) | \(-2.48 \pm 0.15\) | \(-3.37 \pm 0.12\) | 0.11 | MW | B07 |
| \(W(V, K_S)\) | FU (10) | \(-2.60 \pm 0.07\) | \(-3.325 \pm 0.014\) | 0.08 | LMC | R12 |

5.2. Accurate spectroscopic iron abundances are only available for roughly the 50% of Galactic Cepheids (Romaniello et al. 2008; Pedicelli et al. 2009; Luck & Lambert 2011, and references therein) and for a few dozen of MC Cepheids. However, the empirical scenario will have a relevant jump thanks to the ongoing massive ground-based spectroscopic surveys at the 8 m class telescopes (Gaia ESO Survey; Gilmore et al. 2012; Tolstoy et al. 2009)

5.3. Plain physical arguments indicate that FO Cepheids have the potential to be robust distance indicators (Bono et al. 2000). However, we still lack for these variables NIR template light curves. Moreover, current FO absolute calibrations are also hampered by the lack of precise distance determinations based on trigonometric parallaxes for a good sample of Galactic calibrators. These circumstantial evidence limits the precision of MC distance determinations based on FO Cepheids.

5.5. Absolute distances based on PW relations including the \(H\) band are characterized by a large spread. The reasons for this behavior are not clear. There is no doubt that new high-resolution, high signal-to-noise NIR spectra of Galactic Cepheids (Bono et al. 2012) can shed new lights on this open problem.

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