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Near-Infrared Observations of OGLE Classical and Type II Cepheid Variables in the LMC

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Abstract. This poster presented results from the Large Magellanic Cloud Near-Infrared Synoptic Survey (LMCNISS) for classical and Type II Cepheid variables that were identified in the Optical Gravitational Lensing Experiment (OGLE-III) catalogue. Multi-wavelength time-series data for classical Cepheid variables are used to study light-curve structures as a function of period and wavelength. We exploited a sample of ∼1400 classical and ∼80 Type II Cepheid variables to derive Period–Wesenheit relations that combine both optical and near-infrared data. The new Period–Luminosity and Wesenheit relations were used to estimate distances to several Local-Group galaxies (using classical Cepheids) and to Galactic globular clusters (using Type II Cepheids). By appealing to a statistical framework, we found that fundamental-mode classical Cepheid Period–Luminosity relations are non-linear around 10–18 days at optical and near-IR wavelengths. We also suggested that a non-linear relation provides a better constraint on the Cepheid Period–Luminosity relation in Type Ia Supernovæ host galaxies, though it has a negligible effect on the systematic uncertainties affecting the local measurement of the Hubble constant.

Keywords. Stars: variables: Cepheids, galaxies: Magellanic Clouds, cosmology: distance scale

1. Introduction

Cepheid variables are of vital importance for determining extragalactic distances, owing to the well-established Period–Luminosity relation (P–L), or 'Leavitt law', (Leavitt & Pickering 1912). That relationship allows one to derive an increasingly accurate and precise estimate of the Hubble constant (Freedman *et al.* 2001, Riess *et al.* 2016) independently of the cosmic microwave background by *Planck* (Ade *et al.* 2014).

The LMC has served as the first rung of the cosmic distance ladder, mainly due to its close proximity and to the fact that it hosts a number of optically-identified Cepheid variables (∼4600, Soszyński *et al.* 2015). The distance to the LMC is also known with a precision of ∼2%, when based on late-type eclipsing binary stars (Pietrzyński *et al.* 2013), thus allowing improved precision in the absolute calibration of the (P–L) relations in the LMC. Over the past decade, near-IR (NIR) observations of Cepheid variables have acquired a greater significance, because the (P–L) relations are less sensitive to extinction and metallicity at longer wavelengths. However, the time-series JHK_s observations of Cepheids in the LMC had been limited to a sample of ∼90 stars in Persson *et al.* (2004),

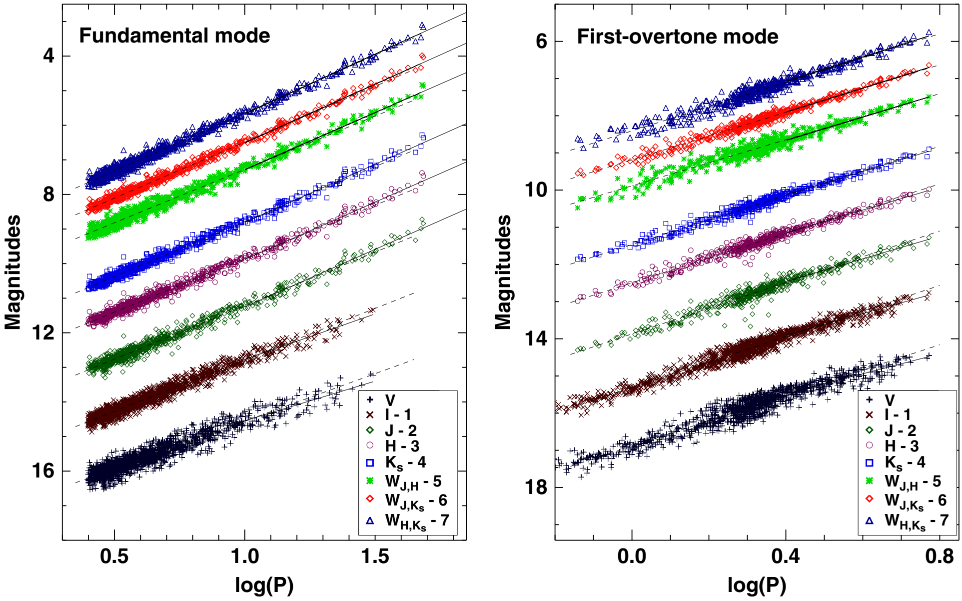

Figure 1. Multi-band (P–L) relations and NIR (P–W) relations for classical Cepheids in the LMC. The dashed and solid lines are best-fit regression lines for the entire, or the long-period, range respectively.

and most of the (P–L) relations were based on single-epoch measurements, for example, Matsunaga, Feast & Soszyński (2011), Inno *et al.* (2013).

Macri *et al.* (2015) carried out a NIR synoptic survey (LMCNISS) of the central $18^{\circ 2}$ of the LMC and cross-matched the output with the OGLE-III survey. They identified ∼1500 Cepheid variables with JHK_s light-curves that had accurate periods and VI-band photometry from OGLE-III. Details regarding the data reduction, photometric accuracy, calibration into 2MASS photometric system, crowding and extinction corrections, etc., can be found in Macri *et al.* (2015). In the following sections we summarise results based on the LMCNISS data, including a calibration of Period–Wesenheit (P–W) relations and their application to the distance scale (Bhardwaj *et al.* 2016a), a statistical study of non-linearity in the Leavitt law (Bhardwaj *et al.* 2016b), and NIR (P–L) relations for Type II Cepheids in the LMC (Bhardwaj *et al.* 2017a).

2. Classical Cepheids

Bhardwaj *et al.* (2015) used multi-band time-series data, from OGLE-III and LMCNISS, for classical Cepheid variables in the LMC, to perform a Fourier analysis of their light-curves (see Simon & Lee 1981), and presented a variation of the light-curve parameters as a function of period and wavelength. Macri *et al.* (2015) provided absolute calibration of the (P–L) relations for ∼800 fundamental-mode and ∼500 first-overtone mode classical Cepheids in the LMCNISS. The fundamental-mode Cepheid (P–L) relations provided 10 times better constraints on the slopes and zero-points than previous work based on time-series JHK_s data. Bhardwaj *et al.* (2016a) then extended that work in order to derive optical and NIR (P–W) relations using LMCNISS and OGLE data. Figure 1 displays multi-band (P–L) relations and NIR (P–W) relations for classical Cepheids based on the OGLE–LMCNISS data. It is evident from Figure 1 that W_{J,K_s} (Wesenheit) exhibits the least scatter for both fundamental-mode and

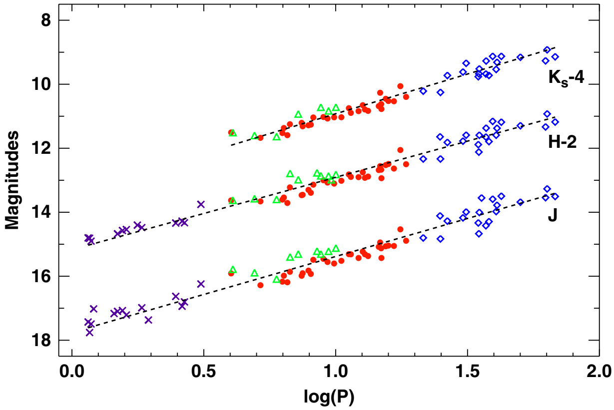

Figure 2. NIR (P–L) relations for Type II Cepheids in the LMC. The crosses, dots, triangles and diamonds represent BL Her, W Vir, peculiar W Vir, and RV Tau stars, respectively. The dashed line represents the best-fit linear regression over the entire period range.

first-overtone-mode Cepheids. The absolute calibration based on the distance to the LMC derived from eclipsing binaries ($\mu = 18.493 \pm 0.047$) results in the following relation:

$$W_{J,K_s} = -3.276 \pm 0.010 - 6.019 \pm 0.049 \quad (\sigma = 0.077) \text{ (Fundamental)}$$
$$W_{J,K_s} = -3.216 \pm 0.024 - 6.518 \pm 0.049 \quad (\sigma = 0.082) \text{ (First overtone)},$$

where the zero-points of the (P–L) relations are at 10 days. We used the calibration of LMC W_{J,K_s} (Wesenheit) to estimate Cepheid-based distances to several Local Group galaxies covering a wide range of metallicity ($7.7 < 12 + \log[O/H] < 8.6$ dex). We derived a global slope for W_{J,K_s} (Wesenheit) of -3.244 ± 0.016 mag dex^{-1}, and we did not find any significant metallicity dependence on (P–W) relations. The Cepheid-based distance estimates are consistent with other estimates that utilise the tip of the red-giant branch.

We also developed a statistical framework that included the F-test, random-walk, testimator, segmented lines and the Davis test, to find possible statistically significant non-linearities in Cepheid (P–L) relations. Details of the statistics of the tests can be found in Bhardwaj *et al.* (2016b). We found that fundamental-mode Cepheid (P–L) relations in the LMC exhibit a break at 10 days in optical bands and around 18 days in NIR bands. The first-overtone-mode Cepheid (P–L) relations were found to be non-linear at 2.5 days. These observed non-linearities can be attributed to sharp changes in the Fourier parameters at similar periods (Bhardwaj *et al.* 2015). The use of LMCNISS data together with Cepheids in the Type Ia supernovae host galaxies from Riess *et al.* (2011) suggested that a non-linear version provides a twice tighter constraint on the slope and metallicity coefficients of the (P–L) relations. The two-slope model was also adopted in the Cepheid (P–L) relations for the most precise estimate (to 2.4%) of the local value of the Hubble constant by Riess *et al.* (2016).

3. Type II Cepheids

Bhardwaj *et al.* (2017a) used the JHK_s observations of 81 Type II Cepheid variables (16 BL Her, 31 W Vir, 12 peculiar W Vir and 22 RV Tau types) from OGLE-III and LMCNISS to derive (P–L) and (P–W) relations. Our NIR (P–L) relations, shown in Figure 2, are based on template-fitted mean magnitudes, where the templates are derived from IK_s-band data. We found that (P–L) and (P–W) relations are consistent with published results based on single-epoch data if long-period RV Tau stars were excluded.

We used *HST* trigonometric parallaxes for k Pav, and *Gaia DR1* ones for VY Pyx, to estimate the distance to the LMC. In addition, the calibrated LMC (P–L) relations anchored to the distance derived from eclipsing-binary data yielded robust distances to 26 Galactic globular clusters given in Matsunaga *et al.* (2006). Those Type II Cepheid-based distances are consistent with estimates using the $M_V - [Fe/H]$ relation for horizontal-branch stars. Bhardwaj *et al.* (2017b) also used the absolute calibration of Type II Cepheid (P–L) relations in the LMC to estimate the distance to the Galactic centre, employing data from the VISTA Variables in the Vía Láctea survey (Minniti *et al.* 2010).

4. Conclusions

The time-series data derived from our analyses of LMCNISS observations of classical and Type II Cepheid variables enabled us to derive new (P–L) and Wesenheit relations for those variables with a greater sample size and a better precision compared to results in the literature. Furthermore, the LMCNISS data for Cepheids were used as calibrators in the recent (and most precise) estimate of the Hubble constant based on Cepheid variables (Riess *et al.* 2016). The ongoing VISTA survey of the Magellanic Clouds (Cioni *et al.* 2011) is also providing NIR data for Cepheid variables in the LMC (for example, Ripepi *et al.* 2012, 2015), but the time-series photometry is limited to the K_s-band, in contrast to full-phased light-curves with LMCNISS.

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