**The Araucaria Project: The distance to the Small Magellanic Cloud from near infrared photometry of Type II Cepheids**

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**ABSTRACT**

We have obtained deep near infrared \(J\)- and \(K\)-band observations of 14 BL Herculis and 5 W Virginis SMC stars from the OGLE III survey with the ESO New Technology Telescope equipped with the SOFI infrared camera. From these observations, period-luminosity (P-L) relations in the \(J\) and \(K\) 2MASS bands were derived. The slopes of the \(K\) and \(J\) band relations of \(-2.15 \pm 0.19\) and \(-1.95 \pm 0.24\), respectively, agree very well with the corresponding slopes derived previously for population II Cepheids in globular clusters, Galactic bulge and in the Large Magellanic Cloud. The distance modulus to the SMC obtained from our data using P-L relation derived for globular cluster Cepheids equals \(18.85 \pm 0.07\) (statistical) \(\pm 0.07\) (systematic without including potential metallicity effect), which within the uncertainties agrees well with the results obtained with other methods.

**Key words:** Stars: Variables: W Virginis, BL Herculis, Galaxies: Distances and Redshifts, Galaxies: Individual: SMC, Galaxies: Stellar Content

1. Introduction

The main goal of the long term program called the Araucaria project is to improve the calibration of the cosmic distance scale using extensive and high quality photometric and spectroscopic observations of several distance indicators in nearby galaxies (Pietrzyński and Gieren 2009, Gieren et al. 2005). Comparative analysis of high quality optical and near-infrared photometry of major distance indicators like Cepheids, RR Lyrae stars, red clump stars and tip of the red giant branch

\(^{1}\)Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile with the ESO NTT for programmes 084.D-0591(B), 084.D-0591(E) and 084.D-0640(B)
(TRGB) magnitude, in nearby galaxies possessing very different environments provide an opportunity to provide strong constraints on the population effects on these methods and construct a uniform set of accurate distances to the studied galaxies. Our results should also allow for a better calibration of other techniques of distance determinations like Type II Cepheids, blue supergiants, Anomalous Cepheids etc. Type II Cepheids are low-mass stars belonging to the disc and halo populations. They have periods and amplitudes in a similar range as classical Cepheids, but are about 1.5 - 2 mag fainter. We can divide them into four different subgroups. Three of them: BL Herculis stars, W Virginis stars and RV Tauri stars show very similar period-luminosity relations and the usual criterion of the division between them is the period. We adopted as in Soszyński et al. (2010), 4 and 20 days as the period limits to distinguish these stars. The fourth group, peculiar W Virginis stars, have light curves different from the typical light curves of W Vir stars and are a little brighter (Soszyński et al. 2008).

Recent application of Type II Cepheids for distance determination to the Galactic Center (Kubiak and Udalski, 2003; Groenewegen, Udalski and Bono, 2008), and the LMC (Matsunaga et al. 2009, hereafter M09) confirmed that these stars are very promising distance indicators. Therefore, an accurate calibration of their P-L relations, especially in the near infrared domain, where the extinction is very small, is of great importance.

In this paper we will present the $J$ and $K_s$ band period-luminosity relations based on 19 stars taken from the OGLE III catalogue of type II Cepheids in the SMC (Soszyński et al. 2010), compare it with similar relations for objects in the LMC (M09), Galactic bulge (Groenewegen, Udalski and Bono, 2008) and in globular clusters (Matsunaga et al. 2006, hereafter M06), and use it to calculate the SMC distance.

2. Observations

We chose 14 BL Her and 5 W Vir stars from the OGLE III catalogue (Soszynski et al. 2010) and observed them during three Araucaria observing runs, using the SOFI IR camera attached to the ESO New Technology Telescope (NTT) at La Silla Observatory. The wide-field mode was used to yield a $4.5 \times 4.5$ arcmin field of view and a scale of 0.288 arcsec per pixel. In order to account for frequent sky-level variations in the near IR passbands a dithering technique was employed. The detector readout time was adjusted to keep ADUs below 10000 (e.g. well within linearity regime of the detector) during the observations. The whole sequence of dithered observations (typically 15-21 different positions) for a given field resulted in a total net integration time of 21 minutes in the $K_s$-band (15 minutes for stars with period longer than 16 days) and 5.5 minutes in $J_s$, and allowed us to obtain a very good signal to noise ratio of better than 50 for our target stars.

Detailed information about each observed field and observation conditions dur-
ing the exposures is given in Table 1. (Note that name of each field is the name of the OGLE star, on which this field is centered).

| Field name           | R.A. 2000   | Decl. 2000   | Date of observation | HJD-2450000 of $J_s$ exposure | HJD-2450000 of $K_s$ exposure | Conditions | Extinction $E(B-V)$ |
|----------------------|-------------|--------------|---------------------|------------------------------|-------------------------------|------------|---------------------|
| OGLE-SMC-T2CEP-02    | 00:34:53.51 | -72:58:45.9  | 2010 Dec 02         | 5168.707950                  | 5168.719090                   | STD        | 0.087               |
| OGLE-SMC-T2CEP-03    | 00:37:08.35 | -73:43:04.9  | 2010 Dec 02         | 5168.730445                  | 5168.741590                   | STD        | 0.070               |
| OGLE-SMC-T2CEP-04    | 00:38:20.36 | -73:17:16.4  | 2010 Dec 04         | 5170.618600                  | 5170.689680                   | STD        | 0.070               |
| OGLE-SMC-T2CEP-05    | 00:42:03.81 | -74:01:24.6  | 2010 Dec 02         | 5168.666730                  | 5168.677870                   | STD        | 0.087               |
| OGLE-SMC-T2CEP-06    | 00:42:16.01 | -73:39:13.5  | 2010 Dec 03         | 5169.554910                  | 5169.566020                   | STD        | 0.078               |
| OGLE-SMC-T2CEP-08    | 00:44:00.77 | -73:22:54.4  | 2010 Dec 04         | 5170.592745                  | 5170.603870                   | STD        | 0.089               |
| OGLE-SMC-T2CEP-09    | 00:44:12.37 | -72:59:28.5  | 2010 Dec 27         | 5193.702160                  | 5193.690865                   | CLR        | 0.089               |
| OGLE-SMC-T2CEP-15    | 00:49:36.92 | -73:10:01.4  | 2010 Nov 05         | 5141.677870                  | 5141.666550                   | STD        | 0.101               |
| OGLE-SMC-T2CEP-16    | 00:50:12.58 | -72:43:12.4  | 2010 Dec 28         | 5194.648940                  | 5194.637630                   | CLR        | 0.101               |
| OGLE-SMC-T2CEP-17    | 00:50:42.03 | -71:39:18.4  | 2010 Dec 03         | 5169.676400                  | 5169.685200                   | STD        | 0.087               |
| OGLE-SMC-T2CEP-22    | 00:54:46.72 | -73:48:32.6  | 2010 Dec 03         | 5169.740075                  | 5169.751170                   | STD        | 0.087               |
| OGLE-SMC-T2CEP-27    | 00:57:28.64 | -73:31:26.9  | 2010 Dec 03         | 5169.700485                  | 5169.711610                   | STD        | 0.087               |
| OGLE-SMC-T2CEP-30    | 00:57:40.76 | -73:03:04.9  | 2010 Nov 06         | 5142.690225                  | 5142.678905                   | CLR        | 0.100               |
| OGLE-SMC-T2CEP-33    | 00:59:03.09 | -72:28:32.2  | 2010 Nov 06         | 5142.655995                  | 5142.644685                   | CLR        | 0.100               |
| OGLE-SMC-T2CEP-35    | 01:00:35.01 | -73:46:57.9  | 2010 Nov 07         | 5143.576060                  | 5143.567220                   | CLR        | 0.087               |
| OGLE-SMC-T2CEP-37    | 01:03:46.50 | -74:07:28.8  | 2010 Nov 07         | 5143.682545                  | 5143.671235                   | CLR        | 0.087               |
|                     |             |              | 2010 Dec 26         | 5192.683115                  | 5192.671810                   | STD        | 0.084               |
| OGLE-SMC-T2CEP-39    | 01:06:40.91 | -73:07:05.0  | 2010 Nov 07         | 5143.606935                  | 5143.596055                   | CLR        | 0.084               |
| OGLE-SMC-T2CEP-40    | 01:08:46.85 | -71:51:09.4  | 2010 Nov 07         | 5143.754020                  | 5143.745155                   | CLR        | 0.087               |
|                     |             |              | 2010 Dec 27         | 5193.654555                  | 5193.645705                   | CLR        | 0.087               |
| OGLE-SMC-T2CEP-42    | 01:23:26.69 | -72:00:24.3  | 2010 Dec 27         | 5193.677110                  | 5193.665815                   | CLR        | 0.087               |

Note: Extinction values are taken from the reddening maps of Udalski et al. (1999). For objects located outside the OGLE II fields we adopted mean value of $E(B-V)$ from all OGLE II fields (0.087 mag). The entries STD and CLR mean photometric and clear observing conditions, respectively.

3. Data reductions and calibrations

For all reductions and calibrations the pipeline developed in the course of Araucaria Project was used. First, we applied a two-step sky level subtraction process, including masking of stars with the IRAF\textsuperscript{2} \texttt{xdimsum} package (Pietrzyński and Gieren 2002). Next, each single image was flat-fielded and stacked into the final deep field. Then point-spread function (PSF) photometry, including aper-

\textsuperscript{2}IRAFl is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.
ture corrections, was performed in the same way as described in Pietrzyński et al. (2002).

The data collected under photometric conditions were calibrated onto the standard UKIRT system using observations of 16 standard stars from the list published by Hawarden et al. (2001). The standard stars were observed at different air masses and hour angles spread in between the regular target fields acquisition. The accuracy of the zero points for both K and J band were estimated to be better than 0.02 mag. Next, the calibrated photometry was transformed onto the 2MASS photometric system using relations (37) and (39) given by Carpenter (2001). In order to perform an external check on the accuracy of the zero point of our photometry in each field we identified stars common to the 2MASS Point Source Catalog (Wachter et al. 2003). In each case the zero point offset in both J and K bands was always smaller than 0.02 mag. The photometry of fields observed under non-photometric conditions, were tied directly onto the 2MASS system comparing our instrumental $j_s, k_s$ magnitudes with the 2MASS data.

Since most of our stars have just single epoch measurements we derived their mean magnitudes applying a simple method, following M09. Shortly, assuming that Type II Cepheids have similar light curve shapes in $I$ and near infrared $K$ and $J$ bands, and using $I$-band light curves from (Soszyński et al. 2010) a correction between the observed random-phase K band magnitude and the mean magnitude can be derived. Mean magnitudes obtained in this way will be called phase-corrected data.

The calibrated data for all stars are presented in Table 2. In the columns are star name (from OGLE III catalogue), star type, period, $K_s$ magnitude and $J − K_s$ color (at the phase of measurement), and mean $K_s$ magnitude and $J − K_s$ color. All errors are uncertainties as returned by DAOPHOT.

4. Period-luminosity relations

A fundamental issue while applying P-L relations of pulsating stars for distance measurement is to reassure the use of the correct fiducial period-luminosity relation. M06 calibrated such a relation for Type II Cepheids using 46 stars (3 with periods longer than 20 days and only 7 with shorter than 4 days) from 26 globular clusters and in the $K_s$ and $J$ bands obtained

\[ M_{K_s} = -2.41(\pm 0.05) \log P - 1.108(\pm 0.02) \]  
\[ M_J = -2.23(\pm 0.05) \log P - 0.864(\pm 0.03) \]

with standard deviations of 0.14 and 0.16 mag, respectively. In this paragraph we will check whether the P-L relations of Matsunaga can be applied to the SMC Type II Cepheids by computing the free least square fits for different subsamples of the observed target stars for both filters and comparing the resulting slopes with the slope from equations (1) and (2).
In order to produce reddening corrected P-L relations for the SMC Type II Cepheids we adopted the E(B-V) values for all observed fields from the OGLE reddening maps (Udalski et al. 1999) as listed in Table 1, and assume the reddening law of Cardelli et al. (1989) (e.g. $R_V = 3.1$, $A_K = 0.365 \times E(B-V)$, $A_J = 0.866 \times E(B-V)$). In the case of stars with two measurements we took mean value of them. Figures 1, 2, 3 and 4 show the results for a mixed sample of BL Her and W Vir stars, and BL Her stars solely, respectively (unfortunately, we have not enough data to obtain a credible relation for W Vir stars alone). In all figures circled points and solid line represent the phase-corrected data, whereas crosses and dashed lines are for uncorrected observations.

Last square solutions for BL Her and W Vir data yield:

\[
K_v = -2.15(\pm0.19) \log P + 17.59(\pm0.11), \quad (\sigma = 0.29)
\]

\[
J = -2.05(\pm0.23) \log P + 17.87(\pm0.13), \quad (\sigma = 0.34)
\]

### Table 2

Calibrated magnitudes and colors for SMC population-II Cepheids

| Star ID          | Type | Period (days) | $K_v$   | $J - K_v$ | $< K_v > $ | $< J - K_v > $ |
|------------------|------|---------------|---------|-----------|------------|----------------|
| OGLE-SMC-T2CEP-02| BL Her | 1.3721870     | 17.54 ± 0.05 | 0.41 ± 0.06 | 17.39 ± 0.06 | 0.40 ± 0.08 |
| OGLE-SMC-T2CEP-03| W Vir  | 4.3598789     | 16.75 ± 0.03 | 0.50 ± 0.04 | 16.50 ± 0.04 | 0.54 ± 0.05 |
| OGLE-SMC-T2CEP-04| W Vir  | 6.5333997     | 15.54 ± 0.03 | 0.19 ± 0.04 | 15.58 ± 0.03 | 0.16 ± 0.04 |
| OGLE-SMC-T2CEP-05| W Vir  | 8.2058890     | 15.92 ± 0.02 | 0.55 ± 0.03 | 15.83 ± 0.02 | 0.57 ± 0.03 |
| OGLE-SMC-T2CEP-06| BL Her | 1.2356136     | 17.71 ± 0.06 | 0.42 ± 0.07 | 17.67 ± 0.07 | 0.41 ± 0.09 |
| OGLE-SMC-T2CEP-08| BL Her | 1.4897859     | 16.97 ± 0.04 | 0.26 ± 0.04 | 16.90 ± 0.04 | 0.27 ± 0.05 |
| OGLE-SMC-T2CEP-09| BL Her | 2.9710719     | 16.83 ± 0.04 | 0.44 ± 0.04 | 16.85 ± 0.04 | 0.47 ± 0.04 |
| OGLE-SMC-T2CEP-15| BL Her | 2.5695964     | 16.25 ± 0.02 | 0.11 ± 0.03 | 16.32 ± 0.02 | 0.11 ± 0.03 |
| OGLE-SMC-T2CEP-16| BL Her | 2.1131980     | 16.91 ± 0.04 | 0.37 ± 0.04 | 17.01 ± 0.04 | 0.39 ± 0.05 |
| OGLE-SMC-T2CEP-17| BL Her | 1.2993097     | 17.29 ± 0.05 | 0.29 ± 0.06 | 17.16 ± 0.06 | 0.31 ± 0.07 |
| OGLE-SMC-T2CEP-22| BL Her | 1.4705261     | 17.69 ± 0.06 | 0.29 ± 0.07 | 17.75 ± 0.07 | 0.29 ± 0.09 |
| OGLE-SMC-T2CEP-27| BL Her | 1.5417249     | 17.60 ± 0.06 | 0.27 ± 0.07 | 17.66 ± 0.06 | 0.21 ± 0.08 |
| OGLE-SMC-T2CEP-30| BL Her | 3.3889388     | 16.12 ± 0.04 | 0.52 ± 0.05 | 16.00 ± 0.04 | 0.52 ± 0.05 |
| OGLE-SMC-T2CEP-33| BL Her | 1.8776865     | 16.63 ± 0.03 | 0.38 ± 0.03 | 16.72 ± 0.03 | 0.31 ± 0.04 |
| OGLE-SMC-T2CEP-35| W Vir  | 17.1814841    | 15.07 ± 0.01 | 0.36 ± 0.01 | 15.21 ± 0.01 | 0.36 ± 0.02 |
| OGLE-SMC-T2CEP-37| BL Her | 1.5590709     | 17.29 ± 0.03$^1$ | 0.25 ± 0.04$^1$ | 17.18 ± 0.03 | 0.35 ± 0.04 |
| OGLE-SMC-T2CEP-39| BL Her | 1.8875529     | 16.95 ± 0.03$^1$ | 0.29 ± 0.04$^1$ | 16.90 ± 0.03 | 0.33 ± 0.04 |
| OGLE-SMC-T2CEP-40| W Vir  | 16.1110373    | 15.27 ± 0.01$^1$ | 0.53 ± 0.01$^1$ | 14.93 ± 0.01 | 0.50 ± 0.01 |
| OGLE-SMC-T2CEP-42| BL Her | 1.4874289     | 17.29 ± 0.04 | 0.46 ± 0.04 | 17.31 ± 0.04 | 0.50 ± 0.06 |

* night 07-12-2009, * night 26-12-2009, * night 27-12-2009
Fig. 1. Reddening free $K_s$ band P-L relation of type II Cepheids in the SMC. Filled circles and solid line represent phase-corrected data, while crosses and dashed line stand for uncorrected observations.

in the case of phase-corrected data and

$$K_s = -2.05 (\pm 0.20) \log P + 17.58 (\pm 0.11), (\sigma = 0.30)$$
$$J = -1.95 (\pm 0.24) \log P + 17.86 (\pm 0.13), (\sigma = 0.36)$$  \( (3) \)

for uncorrected data.

For BL Her data solely we obtained:

$$K_s = -3.04 (\pm 0.61) \log P + 17.79 (\pm 0.17), (\sigma = 0.28)$$
$$J = -2.91 (\pm 0.69) \log P + 18.06 (\pm 0.19), (\sigma = 0.33)$$

in the case of phase-corrected data and

$$K_s = -3.14 (\pm 0.56) \log P + 17.82 (\pm 0.16), (\sigma = 0.26)$$
$$J = -3.02 (\pm 0.66) \log P + 18.09 (\pm 0.19), (\sigma = 0.31)$$
As is clearly visible, the phase-correction method did not allow to reduce the scatter on the observed $J$ and $K$-band P-L relations. A method for correction of mean magnitudes should take into account different shapes of the Type II Cepheids light curves and the phase shift between the maximum in the optical and near infrared bands. Such a technique has been developed for Classical Cepheids by Soszynski et al. (2005). Unfortunately, template light curves in the near infrared bands are still lacking for Type II Cepheids, so in the following we decided to use the uncorrected, random-phase data.

The scatter on the relations is significantly larger in comparison with the results obtained for Type II Cepheids in the LMC, the Galactic bulge and Galactic globular clusters (M09, M06, Groenewegen, Udalski and Bono, 2009). This fact is mostly related to the geometrical extension of the SMC in the line of sight, and also to using single-phase data to construct the P-L relation. This, together with the relatively

Fig. 2. Reddening free $K_s$ band P-L relation of BL Her stars in SMC. Filled circles and solid line represent phase-corrected data, crosses and dashed line stand for uncorrected observations.
Fig. 3. Reddening free $J$ band P-L relation of type II Cepheids in the SMC. Filled circles and solid line represent phase-corrected data, while crosses and dashed line stand for uncorrected observations.

small range of periods of BL Her stars and the small number of W Virginis stars in our sample, prevented us from providing a strong test wether the $J$ and $K$-band P-L relations of these stars and W Vir are co-linear in the SMC. Since within the uncertainties ($2\sigma$) there is no evidence for a difference in the slopes derived for the combined set of Type II Cepheids and BL Her stars alone, and M09 have shown that the relations for BL Her and W Vir stars are co-linear in the LMC, we decided to use the combined sample for the distance determination to the SMC.

5. Distance determination

The slopes of our $J$ and $K_s$-band P-L relations obtained for the SMC Population II Cepheids ($K_s: -2.05 \pm 0.20$, $J: -1.95 \pm 0.24$) agree within their uncertainties with the corresponding slopes obtained for these stars in the LMC (M09: $K_s: -2.278 \pm 0.047$, $J: -2.163 \pm 0.044$), Galactic bulge (Groenewegen, Udalski and Bono, 2009; $K_s: -2.24 \pm 0.14$), globular clusters (M06; $K_s: -2.41 \pm 0.05$, $J: 2.23$)


Fig. 4. Reddening free $J$ band P-L relation of BL Her stars in SMC. Filled circles and solid line represent phase-corrected data, crosses and dashed line stand for uncorrected observations.

\[ (m - M)_0 = 18.85 \pm 0.07 \text{ (statistical)} \text{ (}K_s\text{ band)} \] (4)

\[ (m - M)_0 = 18.85 \pm 0.09 \text{ (statistical)} \text{ (}J\text{ band)} \] (5)

These results are (by coincidence) identical to each other and to the distance modulus of 18.85 ± 0.11 derived from OGLE optical photometry of Type II Cepheids (Majaess et al. 2009). Within its uncertainties they also agree with the SMC distance moduli obtained from near-infrared photometry of RR Lyr variables (Szewczyk et al. 2009) and red clump stars (Pietrzyński al. 2003). Moreover the differential distances Galactic bulge - LMC - SMC calculated from the $K$ band photometry of
Type II Cepheids agree very well with the corresponding data obtained for other distance indicators (Cepheids, TRGB, RR Lyrae, etc; e.g. Udalski 2000, Groenewegen, Udalski, Bono 2009). Our results suggest that any population dependence of the slope and zero point of the \( K_s \) and \( J \) band P-L relations for Type II Cepheids should be small. In line with this conclusion, M06 found also no evidence for significant population effects on JHK band P-L relations of Type II Cepheids from the globular cluster data they used. These conclusions are further supported by theoretical models (Bono, Caputo & Santolamazza, 1997, Di Criscienzo et al. 2007), which suggest that the properties of Type II Cepheids should be only minimally affected by metallicity.

In order to estimate the systematic error on the SMC distance determined in this paper we took into account the errors associated with photometric zero points (0.02 for both filters), transformation onto the 2MASS system (0.01), reddening (0.01 for \( K_s \) and 0.02 for \( J \) band) and the adopted fiducial P-L relation of M06. M06 combined the sample of Type II Cepheids observed in different clusters using distance moduli calculated based on the magnitudes of the horizontal branches of the clusters. They adopted the relation of Gratton (2003) \( (M_V=0.22[Fe/H]+0.89) \), calibrated based on the main sequence distances. Therefore it is rather difficult to estimate a realistic systematic error of the zero point of the M06 calibration. Independently, the zero point of the P-L relation for Type II Cepheids may be calibrated using two Galactic stars with pulsational parallaxes (Feast et al. 2008) with a precision of 0.06 mag. If we adopt both zero point calibrations and calculate a distance to the LMC the difference in the corresponding distance moduli is 0.04 mag only. Therefore it is reasonable to assume 0.06 as a realistic error of the zero point of the current calibrations of the P-L relation of Type II Cepheids. Combining all errors quadratically we obtain 0.07 mag as the total systematic error of the SMC distance. This error does not contain the possible effect of a metallicity dependence on the slope and zero point of the Type II Cepheids P-L relation. However, as has been discussed above such an effect is supposed to be small.

6. Summary and conclusions

We presented precision \( J \)- and \( K_s \)-band photometry of 19 Type II Cepheids in the SMC. The slope of the resulting \( J \) and \( K_s \) band P-L relations were found to be, within the errors, in good agreement with the corresponding slopes obtained for Type II Cepheids in the LMC (M09), Galactic bulge (Groenewegen, Udalski and Bono) and globular clusters (M06).

Assuming the fiducial P-L relation of M06 the following SMC distance modulus was derived from our data:

\[
(m-M)_0 = 18.85 \pm 0.07(\text{statistical}) \pm 0.07(\text{systematic})
\]  

(6)

This result agrees very well with recent distance determinations to the SMC.
based on other techniques. Moreover, the differential distances between the LMC, SMC and Galactic Bulge derived from Type II Cepheids are very similar to those obtained from Cepheids, TRGB, RR Lyrae stars and red clump stars, which suggests that the population effects on the slope and/or zero point of the Type II Cepheid P-L relation must be small. Our results confirm that Type II Cepheids (W Vir and BL Her) are very good standard candles.

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