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# The VMC Survey – XIII. Type II Cepheids in the Large Magellanic Cloud<sup>★</sup>

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## ABSTRACT

The VISTA (Visible and Infrared Survey Telescope for Astronomy) survey of the Magellanic Clouds System (VMC) is collecting deep  $K_s$ -band time-series photometry of the pulsating variable stars hosted in the system formed by the two Magellanic Clouds and the Bridge connecting them. In this paper, we have analysed a sample of 130 Large Magellanic Cloud (LMC) Type II Cepheids (T2CEPs) found in tiles with complete or near-complete VMC observations for which identification and optical magnitudes were obtained from the OGLE III (Optical Gravitational Lensing Experiment) survey. We present  $J$  and  $K_s$  light curves for all 130 pulsators, including 41 BL Her, 62 W Vir (12 pW Vir) and 27 RV Tau variables. We complement our near-infrared photometry with the  $V$  magnitudes from the OGLE III survey, allowing us to build a variety of period–luminosity (PL), period–luminosity–colour (PLC) and period–Wesenheit (PW) relationships, including any combination of the  $V$ ,  $J$ ,  $K_s$  filters and valid for BL Her and W Vir classes. These relationships were calibrated in terms of the LMC distance modulus, while an independent absolute calibration of the PL( $K_s$ ) and the PW( $K_s$ ,  $V$ ) was derived on the basis of distances obtained from *Hubble Space Telescope* parallaxes and Baade–Wesselink technique. When applied to the LMC and to the Galactic globular clusters hosting T2CEPs, these relations seem to show that (1) the two Population II standard candles RR Lyrae and T2CEPs give results in excellent agreement with each other; (2) there is a discrepancy of  $\sim 0.1$  mag between Population II standard candles and classical Cepheids when the distances are gauged in a similar way for all the quoted pulsators. However, given the uncertainties, this discrepancy is within the formal  $1\sigma$  uncertainties.

**Key words:** surveys – stars: oscillations – stars: Population II – stars: variables: Cepheids – galaxies: distances and redshifts – Magellanic Clouds.

## 1 INTRODUCTION

The Magellanic Clouds (MCs) are fundamental benchmarks in the framework of stellar populations and galactic evolution investigations (see e.g. Harris & Zaritsky 2004, 2009; Ripepi et al. 2014b).

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The ongoing interaction with the Milky Way also allows us to study in detail the complex mechanisms that rule the interaction among galaxies (see e.g. Putman et al. 1998; Muller et al. 2004; Stanimirović, Staveley-Smith & Jones 2004; Bekki & Chiba 2007; Venzmer, Kerp & Kalberla 2012; For, Staveley-Smith & McClure-Griffiths 2013). Additionally, the MCs are more metal poor than our Galaxy and host a large population of young populous clusters; thus, they are useful to test the physical and numerical assumptions at the basis of stellar evolution codes (see e.g. Matteucci et al. 2002; Brocato et al. 2004; Neilson & Langer 2012).

The Large Magellanic Cloud (LMC) is also fundamental in the context of the extragalactic distance scale. Indeed, it represents the first critical step on which the calibration of classical Cepheid (CC) period–luminosity (PL) relations and in turn of secondary distance indicators relies (see e.g. Freedman et al. 2001; Riess et al. 2011; Walker 2012, and references therein). At the same time, the LMC hosts several thousand of RR Lyrae variables, which represent the most important Population II standard candles through the well-known  $M_V(\text{RR})$ –[Fe/H] and near-infrared (NIR) metal-dependent PL relations. Moreover, the LMC contains tens of thousands of intermediate-age red clump stars, which can profitably be used as accurate distance indicators (see e.g. Laney, Jone & Pietrzyński 2012; Subramanian & Subramanian 2013). Hence, the LMC is the ideal place to compare the distance scales derived from Population I and II indicators (see e.g. Clementini et al. 2003; Walker 2012; de Grijs, Wicker & Bono 2014, and references therein). In particular, NIR observations of pulsating stars (see e.g. Ripepi et al. 2012a, 2014a; Moretti et al. 2014, and references therein) provide stringent constraints to the calibration of their distance scale thanks to the existence of well-defined PL, period–luminosity–colour (PLC) and period–Wesenheit (PW) relations at these wavelengths (see Madore 1982; Madore & Freedman 1991, for the definition of Wesenheit functions).

The VISTA<sup>1</sup> near-infrared  $YJK_s$  survey of the Magellanic Clouds system (VMC; Cioni et al. 2011) aims at observing a wide area across the Magellanic system, including the relatively unexplored Bridge connecting the two Clouds. This European Southern Observatory (ESO) public survey relies on the VISTA InfraRed Camera (VIRCAM) (Dalton et al. 2006) of the ESO VISTA telescope (Emerson, McPherson & Sutherland 2006) to obtain deep NIR photometric data in the  $Y$ ,  $J$  and  $K_s$  filters. The main aims are (i) to reconstruct the spatially resolved star formation history and (ii) to infer an accurate 3D map of the whole Magellanic system. The properties of pulsating stars observed by VMC and adopted as tracers of three different stellar populations, namely CCs (younger than few hundred Myr), RR Lyrae stars (older than 9–10 Gyr) and anomalous Cepheids (traditionally associated with an intermediate-age population with few Gyr), have been discussed in recent papers by our team (Ripepi et al. 2012a,b, 2014a; Moretti et al. 2014). In these papers, relevant results on the calibration of the distance scales for all these important standard candles have been provided.

An additional class of Population II pulsating stars is represented by the so-called Type II Cepheids (T2CEPs; see e.g. Caputo 1998; Sandage & Tammann 2006). These objects show periods from  $\sim 1$  to  $\sim 20$  d and are observed in Galactic globular clusters (GGCs) with few RR Lyrae stars and blue horizontal branch morphology. They are brighter but less massive than RR Lyrae stars for similar metal content (see e.g. Caputo et al. 2004). T2CEPs are often separated into BL Herculis stars (BL Her; periods between 1 and 4 d)

and W Virginis stars (W Vir; periods between 4 and 20 d) and, as discussed by several authors (e.g. Wallerstein & Cox 1984; Gingold 1985; Harris 1985; Bono, Caputo & Santolamazza 1997b; Wallerstein 2002), originate from hot, low-mass stellar structures, starting their central He burning on the blue side of the RR Lyrae gap. Moreover, according to several authors (see e.g. Feast et al. 2008; Feast 2010, and references therein) RV Tauri stars, with periods from about 20 to 150 d and often irregular light curves, are considered as an additional subgroup of the T2CEP class. Their evolutionary phase corresponds to the post-asymptotic giant branch phase path towards planetary nebula status. This feature corresponds to the latest evolution of intermediate mass stellar structures and for this reason the claimed link with the low-mass W Vir stars should be considered with caution.

In addition to the three quoted groups, Soszyński et al. (2008) suggested the existence of a new sub-class of T2CEPs, the so-called peculiar W Vir (pW Vir) stars. These objects show peculiar light curves and, at constant period, are usually brighter than normal T2CEPs. It is likely that pW Vir belong to binary systems; however, the true nature of these variables remains uncertain.

Nemec, Nemec & Lutz (1994) derived metal-dependent PL relations in various optical photometric bands both in the fundamental and in the first overtone modes but subsequently Kubiak & Udalski (2003) found that all the observed T2CEPs in the OGLE II (Optical Gravitational Lensing Experiment; Udalski et al. 1992) sample, with periods in the range  $\sim 0.7$  to about 10 d, satisfy the same PL relation. This result was then confirmed by Pritzl et al. (2003) and Matsunaga et al. (2006) for GGCs, by Groenewegen, Udalski & Bono (2008) for the Galactic bulge and again by Soszyński et al. (2008) on the basis of OGLE III data.

From the theoretical point of view, Di Criscienzo et al. (2007) and Marconi & Di Criscienzo (2007) have investigated the properties of BL Her stars, by adopting an updated evolutionary and pulsational scenario for metallicities in the range of  $Z = 0.0001$ – $0.004$ . The predicted PL and PW relations derived on the basis of these models were found to be in good agreement with the slopes determined by the variables observed in GGCs. Moreover, the distances obtained from the theoretical relations for T2CEPs agree within the errors with the RR Lyrae-based values.

In the NIR bands, a tight PL for 46 T2CEPs hosted in GGCs was found by Matsunaga et al. (2006). Such relations were calibrated by Feast et al. (2008) by means of pulsation parallaxes of nearby T2CEPs and used to estimate the distances of the LMC and the Galactic Centre. Subsequent investigations (Matsunaga, Feast & Menzies 2009; Matsunaga, Feast & Soszyński 2011) confirmed the existence of such tight PL relations in the  $J$ ,  $H$ ,  $K_s$  bands for the T2CEPs belonging to the LMC and Small Magellanic Cloud found by the OGLE III collaboration (Soszyński et al. 2008). However, the NIR observations at the base of these studies consist of only two epochs for each variable light curve obtained with the Infrared Survey Facility (IRSF) 1.4 m telescope in South Africa. The average magnitudes of the T2CEPs analysed in that paper were derived by comparison with the OGLE III  $I$ -band photometry.

In the context of the VMC survey, we present here the NIR results for a significant sample of T2CEPs in the LMC, based on high precision and well-sampled  $K_s$ -band light curves.

The VMC data for the T2CEPs are presented in Section 2. The PL, PLC and PW relations involving the  $J$  and  $K_s$  bands are calculated in Section 3. Section 4 includes the absolute calibration of such relations and a comparison with the literature. In Sections 5, we discuss the results; a concise summary (Section 6) concludes the paper.

<sup>1</sup> Visible and Infrared Survey Telescope for Astronomy.

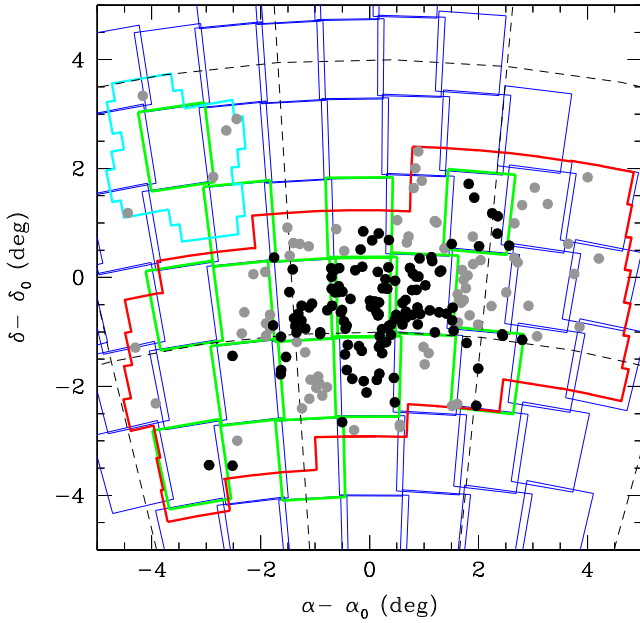


**Figure 1.** Distribution of the known T2CEPs over the LMC (projected on the sky adopting  $\alpha_0 = 81.0$  deg and  $\delta_0 = -69.0$  deg). Grey symbols show all the T2CEPs detected by the OGLE collaboration, whereas black filled circles present the T2CEPs falling in the VMC tiles and studied in this paper. Thin blue and thick green squares (distorted by the projection into the sky) show part of the VMC tiles in the LMC and the 13 tiles treated in this paper, respectively. The thick red and light blue lines show the areas covered by OGLE III and IV (released to date), respectively.

## 2 T2CEPS IN THE VMC SURVEY

T2CEPs in the LMC were identified and studied in the *V*, *I* optical bands by Soszyński et al. (2008) in the context of the OGLE III project.<sup>2</sup> We have also considered the recent early release of the OGLE IV survey (Soszyński et al. 2012), including the South Ecliptic Pole which, in turn, lies within our tile LMC 8\_8. In these surveys, a total of 207 T2CEPs were found (203 by OGLE III and 4 by OGLE IV<sup>3</sup>), of which 65 are BL Her, 98 are W Vir and 44 are RV Tau pulsators.

In this paper, we present results for the T2CEPs included on 13 ‘tiles’ (1.5 deg<sup>2</sup>) completely or nearly completely observed, processed and catalogued by the VMC survey as of 2013 March (and overlapping with the area investigated by OGLE III), namely the tiles LMC 4\_6, 4\_8, 5\_3, 5\_5, 5\_7, 6\_4, 6\_5, 6\_6, 6\_8, 7\_3, 7\_5, 7\_7 and 8\_8 (see Fig. 1 and Table 1). Tile LMC 6\_6 is centred on the well-known 30 Dor star-forming region; tiles LMC 5\_5, 6\_4 and 6\_5 are placed on the bar of the LMC. The remaining tiles lie in less crowded regions of the galaxy.

A detailed description of the general observing strategy of the VMC survey can be found in Cioni et al. (2011). As for the variable stars, the specific procedures adopted to study these objects were discussed in Moretti et al. (2014). Here, we only briefly recall that the VMC  $K_s$ -band time-series observations were scheduled in 12 separate epochs distributed over several consecutive months. This strategy allows us to obtain well-sampled light curves for a variety

**Table 1.** Number of T2CEPs in the 13 VMC tiles analysed in this paper, according to OGLE III/IV.

| Tile<br>LMC | RA (centre)<br>J(2000) | Dec. (centre)<br>J(2000) | $n_{\text{T2CEP}}$ |
|-------------|------------------------|--------------------------|--------------------|
| LMC 4_6     | 05:38:00.41            | −72:17:20.0              | 1                  |
| LMC 4_8     | 06:06:32.95            | −72:08:31.2              | 2                  |
| LMC 5_3     | 04:58:11.66            | −70:35:28.0              | 6                  |
| LMC 5_5     | 05:24:30.34            | −70:48:34.2              | 17                 |
| LMC 5_7     | 05:51:04.87            | −70:47:31.2              | 4                  |
| LMC 6_4     | 05:12:55.80            | −69:16:39.4              | 33                 |
| LMC 6_5     | 05:25:16.27            | −69:21:08.3              | 31                 |
| LMC 6_6     | 05:37:40.01            | −69:22:18.1              | 20                 |
| LMC 6_8     | 06:02:22.00            | −69:14:42.4              | 0                  |
| LMC 7_3     | 05:02:55.20            | −67:42:14.8              | 9                  |
| LMC 7_5     | 05:25:58.44            | −67:53:42.0              | 6                  |
| LMC 7_7     | 05:49:12.19            | −67:52:45.5              | 1                  |
| LMC 8_8     | 05:59:23.14            | −66:20:28.7              | 0                  |

of variable types (including RR Lyrae variables and Cepheids of all types). Concerning the *J* and *Y* bands, the average number of epochs is 3, as a result of the observing strategy in these bands (i.e. monitoring was not planned). Hence, some epochs could occur in the same night and even one after the other. We note that in this paper, we did not consider the *Y*-band data for several reasons: (i) this filter is very rarely used in the context of distance scale; (ii) its photometric zero-point (ZP) is difficult to calibrate (no 2MASS measures); (iii) because the *Y* band is bluer than the typical NIR bands, and the PL, PLC and PW relations in this filter are expected to be more dispersed (see e.g. Madore & Freedman 2012) and of lesser utility with respect to those in *J* and  $K_s$ .

The VMC data, processed through the pipeline (Irwin et al. 2004) of the VISTA Data Flow System (VDFS; Emerson et al. 2004) are in the VISTA photometric system (Vegamag = 0). The time-series photometry used in this paper was retrieved from the VISTA Science Archive<sup>4</sup> (VSA; Cross et al. 2012). For details about the data reduction, we refer the reader to the aforementioned papers. Nevertheless, we underline two characteristics of the data reduction which we think may have importance in the subsequent discussion. First, the pipeline is able to correct the photometry of stars close to the saturation limit (Irwin 2009). This is relevant in the context of this paper because the RV Tau variables discussed here are very bright objects  $K_s \sim 12$ –13 mag, close to the saturation limits of the VMC survey. The photometry of these stars takes advantage of the VDFS ability to treat saturated images; however, as we will see below, the corrections applied are not always sufficient to fully recover the data. Secondly, the data retrieved from VSA include quality flags which are very useful to understand if the images have problems. We shall use this information later in this paper.

According to OGLE III/IV, 130 T2CEPs are expected to lie in the 13 tiles analysed in this paper. Note that no T2CEP from OGLE III or OGLE IV falls inside our tiles 6\_8 or 8\_8, respectively. Hence, in the following we only use OGLE III data. Fig. 1 and Table 1 show the distribution of such stars through the VMC tiles.

Table 2 lists the 130 T2CEPs analysed here, together with their main properties as measured by OGLE III and the information about the VMC tile they belong to, as well as the number of epochs of observations in the *J* and  $K_s$  bands. In total, our sample is composed of 41 BL Her, 62 W Vir (12 pW Vir) and 27 RV Tau variables, corresponding to 63, 63 (75 percent) and 61 percent of the

<sup>2</sup> Data available at <http://ogle.astrouw.edu.pl>

<sup>3</sup> Soszyński et al. (2012) also report the discovery of one yellow semiregular variable (SRd). Since this class of variables is not considered in this paper, we ignore this object in the present work.

<sup>4</sup> <http://horus.roe.ac.uk/vsa/>

**Table 2.** Cross-identification and main characteristics of the T2CEPs in the 13 ‘tiles’ analysed in this paper. The columns report (1) OGLE identification; (2) right ascension (OGLE); (3) declination (OGLE); (4) variability class; (5) intensity-averaged  $I$  magnitude (OGLE); (6) intensity-averaged  $V$  magnitude (OGLE); (7) period (OGLE); (8) epoch of maximum light  $-2450\,000$  d (OGLE); (9) VMC identification as in the internal VSA release VMC v1.2/v1.3(2013 August 5); (10) VMC tile; (11) number of  $J$  and  $K_s$  epochs, respectively; (12) notes on individual stars.

| ID                 | RA           | Dec.         | Type   | $\langle I \rangle$ | $\langle V \rangle$ | Period     | Epoch       | VMC-ID       | Tile | $N_{\text{Epochs}}$ | Notes                   |
|--------------------|--------------|--------------|--------|---------------------|---------------------|------------|-------------|--------------|------|---------------------|-------------------------|
| (1)                | J2000<br>(2) | J2000<br>(3) | (4)    | (mag)<br>(5)        | (mag)<br>(6)        | (d)<br>(7) | (d)<br>(8)  | (9)          | (10) | $J, K_s$<br>(11)    | (12)                    |
| OGLE-LMC-T2CEP-123 | 5:26:19.26   | -70:15:34.7  | BL Her | 18.233              | 18.723              | 1.002 626  | 454.802 33  | 558361325273 | 5_5  | 4,15                | (a); (b)                |
| OGLE-LMC-T2CEP-069 | 5:14:56.77   | -69:40:22.4  | BL Her | 18.372              | 18.919              | 1.021 254  | 457.218 15  | 558355522273 | 6_4  | 4,14                | (a); (b); (c)           |
| OGLE-LMC-T2CEP-114 | 5:23:29.75   | -68:19:07.2  | BL Her | 18.068              | 19.020              | 1.091 089  | 2167.449 39 | 558353567228 | 7_5  | 4,14                | (b)                     |
| OGLE-LMC-T2CEP-020 | 4:59:06.12   | -67:45:24.6  | BL Her | 18.036              | 18.469              | 1.108 126  | 2166.108 54 | 558351437065 | 7_3  | 4,16                | (a); (b)                |
| OGLE-LMC-T2CEP-071 | 5:15:08.63   | -68:54:53.5  | BL Her | 17.872              | 18.382              | 1.152 164  | 457.433 79  | 558354926512 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-089 | 5:18:35.72   | -69:45:45.7  | BL Her | 18.032              | 18.492              | 1.167 298  | 455.651 66  | 558355569068 | 6_4  | 11,23               |                         |
| OGLE-LMC-T2CEP-061 | 5:12:30.42   | -69:07:16.2  | BL Her | 18.018              | 18.588              | 1.181 512  | 457.305 01  | 558355098130 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-107 | 5:22:05.79   | -69:40:24.5  | BL Her | 17.684              | 18.482              | 1.209 145  | 455.573 77  | 558356704139 | 6_5  | 7,9                 | (d); (e)                |
| OGLE-LMC-T2CEP-077 | 5:16:21.44   | -69:36:59.2  | BL Her | 17.762              | 18.039              | 1.213 802  | 456.996 03  | 558355472930 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-165 | 5:38:15.29   | -69:28:57.1  | BL Her | 18.761              | 19.723              | 1.240 833  | 2187.683 39 | 558357659836 | 6_6  | 5,14                |                         |
| OGLE-LMC-T2CEP-102 | 5:21:19.67   | -69:56:56.2  | BL Her | 17.758              | 18.231              | 1.266 018  | 455.072 85  | 558356982625 | 6_5  | 7,9                 | (d); (e)                |
| OGLE-LMC-T2CEP-194 | 5:57:12.03   | -72:17:13.3  | BL Her | 17.874              | 18.447              | 1.314 467  | 2194.110 08 | 558367367174 | 4_8  | 5,10                |                         |
| OGLE-LMC-T2CEP-136 | 5:29:48.11   | -69:35:32.1  | BL Her | 17.823              | 18.095              | 1.323 038  | 454.373 19  | 558356602471 | 6_5  | 7,9                 | (b)                     |
| OGLE-LMC-T2CEP-138 | 5:30:10.87   | -68:49:17.1  | BL Her | 18.059              | 18.827              | 1.393 591  | 2167.524 91 | 558356009909 | 6_5  | 7,9                 | (b); (d)                |
| OGLE-LMC-T2CEP-109 | 5:22:12.83   | -69:41:50.6  | BL Her | 19.559              | 21.212              | 1.414 553  | 454.695 80  | 558356727002 | 6_5  | 7,9                 | (c); (d)                |
| OGLE-LMC-T2CEP-105 | 5:21:58.32   | -70:16:35.1  | BL Her | 17.645              | 18.206              | 1.489 298  | 830.773 86  | 558361351217 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-122 | 5:25:48.19   | -68:29:11.4  | BL Her | 18.241              | 19.028              | 1.538 669  | 2167.450 87 | 558353653819 | 7_5  | 4,14                |                         |
| OGLE-LMC-T2CEP-171 | 5:39:40.96   | -69:58:01.3  | BL Her | 17.824              | 18.512              | 1.554 749  | 726.828 05  | 558358012379 | 6_6  | 5,14                |                         |
| OGLE-LMC-T2CEP-068 | 5:14:27.05   | -68:58:02.0  | BL Her | 17.671              | 18.264              | 1.609 301  | 456.512 94  | 558354968904 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-124 | 5:26:55.80   | -68:51:53.9  | BL Her | 17.889              | 18.614              | 1.734 867  | 2167.638 18 | 558356040530 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-008 | 4:51:11.51   | -69:57:27.0  | BL Her | 17.842              | 18.585              | 1.746 099  | 2165.203 69 | 558358656758 | 5_3  | 4,11                | (c); (d); (f)           |
| OGLE-LMC-T2CEP-142 | 5:30:34.92   | -68:50:15.2  | BL Her | 17.580              | 18.458              | 1.760 753  | 2167.011 20 | 558353450542 | 7_5  | 4,13                | (a); (b); (g)           |
| OGLE-LMC-T2CEP-084 | 5:17:07.50   | -69:27:34.1  | BL Her | 17.512              | 17.841              | 1.770 840  | 456.088 00  | 558355348031 | 6_4  | 1,8                 | (a); (b); (g)           |
| OGLE-LMC-T2CEP-141 | 5:30:23.32   | -71:39:00.6  | BL Her | 17.975              | 18.757              | 1.822 954  | 2166.564 37 | 558367767291 | 4_6  | 6,14                |                         |
| OGLE-LMC-T2CEP-140 | 5:30:22.71   | -69:15:38.6  | BL Her | 17.760              | 18.508              | 1.841 144  | 2166.657 00 | 558356311759 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-144 | 5:31:19.82   | -68:51:54.9  | BL Her | 17.750              | 18.545              | 1.937 450  | 2166.593 87 | 558356035425 | 6_5  | 10,20               | (a); (b); (d); (f)      |
| OGLE-LMC-T2CEP-130 | 5:29:04.24   | -70:41:37.9  | BL Her | 17.527              | 18.124              | 1.944 694  | 2167.584 69 | 558361658078 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-088 | 5:18:33.57   | -70:50:19.2  | BL Her | 17.212              | 17.353              | 1.950 749  | 2161.242 95 | 558361779217 | 5_5  | 4,15                | (c); (d); (e)           |
| OGLE-LMC-T2CEP-116 | 5:23:55.90   | -69:25:30.1  | BL Her | 17.825              | 18.658              | 1.966 679  | 445.612 78  | 558356464708 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-121 | 5:25:42.79   | -70:20:46.1  | BL Her | 17.713              | 18.430              | 2.061 365  | 2166.374 79 | 558361402653 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-166 | 5:38:29.09   | -69:45:06.3  | BL Her | 16.927              | 17.696              | 2.110 599  | 2186.166 94 | 558357846207 | 6_6  | 5,14                | (h)                     |
| OGLE-LMC-T2CEP-064 | 5:13:55.87   | -68:37:52.1  | BL Her | 17.514              | 18.151              | 2.127 891  | 2167.008 43 | 558354745198 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-167 | 5:39:02.56   | -69:37:38.5  | BL Her | 17.781              | 18.597              | 2.311 824  | 2187.148 39 | 558357756388 | 6_6  | 5,14                |                         |
| OGLE-LMC-T2CEP-092 | 5:19:23.63   | -70:02:56.8  | BL Her | 17.401              | 18.433              | 2.616 768  | 2122.719 33 | 558357072491 | 6_5  | 8,24                |                         |
| OGLE-LMC-T2CEP-148 | 5:31:52.26   | -69:30:26.4  | BL Her | 17.442              | 18.194              | 2.671 734  | 453.911 38  | 558357678615 | 6_6  | 12,23               |                         |
| OGLE-LMC-T2CEP-195 | 6:02:46.27   | -72:12:47.0  | BL Her | 17.342              | 18.050              | 2.752 929  | 2186.990 00 | 558367354217 | 4_8  | 5,10                |                         |
| OGLE-LMC-T2CEP-113 | 5:23:06.33   | -69:32:20.5  | BL Her | 17.137              | 17.811              | 3.085 460  | 455.010 03  | 558356568619 | 6_5  | 7,9                 | (b); (e)                |
| OGLE-LMC-T2CEP-049 | 5:09:21.88   | -69:36:03.0  | BL Her | 17.130              | 17.703              | 3.235 275  | 723.912 43  | 558355501190 | 6_4  | 4,14                | (b)                     |
| OGLE-LMC-T2CEP-145 | 5:31:46.42   | -68:58:44.0  | BL Her | 16.726              | 17.209              | 3.337 302  | 2167.280 23 | 558357363019 | 6_6  | 12,23               |                         |
| OGLE-LMC-T2CEP-085 | 5:18:12.87   | -71:17:15.4  | BL Her | 17.142              | 17.888              | 3.405 095  | 2160.554 57 | 558362047285 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-030 | 5:03:35.82   | -68:10:16.2  | BL Her | 16.948              | 17.755              | 3.935 369  | 2166.206 73 | 558351663560 | 7_3  | 4,16                | (a); (b); (g)           |
| OGLE-LMC-T2CEP-134 | 5:29:28.49   | -69:48:00.4  | pW Vir | 16.268              | 16.851              | 4.075 726  | 454.540 80  | 558356809300 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-173 | 5:39:49.93   | -69:50:52.9  | W Vir  | 18.416              | 20.149              | 4.147 881  | 724.817 27  | 558357918488 | 6_6  | 5,14                | (a); (b)                |
| OGLE-LMC-T2CEP-120 | 5:25:29.55   | -68:48:11.8  | W Vir  | 17.002              | 17.880              | 4.559 053  | 2165.735 88 | 558356005996 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-052 | 5:09:59.34   | -69:58:28.7  | pW Vir | 16.395              | 16.861              | 4.687 925  | 2164.810 82 | 558355737497 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-098 | 5:20:25.00   | -70:11:08.7  | pW Vir | 14.374              | 14.671              | 4.973 737  | 829.464 70  | 558361278143 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-095 | 5:20:09.84   | -68:18:35.3  | W Vir  | 17.009              | 17.873              | 5.000 122  | 2121.240 28 | 558353571684 | 7_5  | 4,14                | (b); (f); (g); (h)      |
| OGLE-LMC-T2CEP-087 | 5:18:21.64   | -69:40:45.2  | W Vir  | 16.887              | 17.770              | 5.184 979  | 454.045 23  | 558355510541 | 6_4  | 11,23               |                         |
| OGLE-LMC-T2CEP-023 | 5:00:13.00   | -67:42:43.7  | pW Vir | 15.511              | 16.101              | 5.234 801  | 2163.878 39 | 558351399660 | 7_3  | 4,16                |                         |
| OGLE-LMC-T2CEP-083 | 5:16:58.99   | -69:51:19.3  | pW Vir | 16.531              | 17.320              | 5.967 650  | 2119.656 83 | 558355634988 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-062 | 5:13:19.12   | -69:38:57.6  | W Vir  | 17.338              | 18.490              | 6.046 676  | 453.313 05  | 558355513592 | 6_4  | 4,14                | (b); (e)                |
| OGLE-LMC-T2CEP-133 | 5:29:23.48   | -70:24:28.5  | W Vir  | 16.671              | 17.497              | 6.281 955  | 2162.687 87 | 558361447993 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-137 | 5:30:03.55   | -69:38:02.8  | W Vir  | 16.728              | 17.633              | 6.362 350  | 453.960 88  | 558356644891 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-183 | 5:44:32.99   | -69:48:21.8  | W Vir  | 17.293              | 18.600              | 6.509 627  | 2183.465 56 | 558357893157 | 6_6  | 5,13                |                         |
| OGLE-LMC-T2CEP-043 | 5:06:00.44   | -69:55:14.6  | W Vir  | 16.851              | 17.774              | 6.559 427  | 462.418 32  | 558355727258 | 6_4  | 4,14                | (b); (f); (e); (g); (h) |
| OGLE-LMC-T2CEP-159 | 5:36:42.13   | -69:31:11.7  | W Vir  | 16.805              | 17.769              | 6.625 570  | 2182.537 72 | 558357684253 | 6_6  | 5,14                |                         |
| OGLE-LMC-T2CEP-117 | 5:24:41.50   | -71:06:44.6  | W Vir  | 16.640              | 17.539              | 6.629 349  | 2165.529 37 | 558361934091 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-106 | 5:22:02.03   | -69:27:25.3  | W Vir  | 16.612              | 17.493              | 6.706 736  | 455.584 83  | 558356498352 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-078 | 5:16:29.09   | -69:24:09.0  | pW Vir | 16.308              | 17.206              | 6.716 294  | 455.317 68  | 558355301964 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-063 | 5:13:43.86   | -69:50:41.1  | W Vir  | 16.662              | 17.553              | 6.924 580  | 2165.500 32 | 558355642907 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-110 | 5:22:19.48   | -68:53:50.0  | W Vir  | 16.763              | 17.705              | 7.078 468  | 2151.910 51 | 558356071179 | 6_5  | 7,9                 |                         |
| OGLE-LMC-T2CEP-181 | 5:43:37.42   | -70:38:04.9  | pW Vir | 16.193              | 16.972              | 7.212 532  | 724.380 26  | 558360373616 | 5_7  | 4,8                 |                         |
| OGLE-LMC-T2CEP-047 | 5:07:46.53   | -69:37:00.3  | W Vir  | 16.616              | 17.536              | 7.286 212  | 723.500 42  | 558355524174 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-056 | 5:11:19.35   | -69:34:32.3  | W Vir  | 16.677              | 17.654              | 7.289 638  | 452.879 68  | 558355469354 | 6_4  | 4,14                |                         |
| OGLE-LMC-T2CEP-100 | 5:21:14.64   | -70:23:15.4  | W Vir  | 16.642              | 17.407              | 7.431 095  | 825.702 18  | 558361448406 | 5_5  | 4,15                |                         |
| OGLE-LMC-T2CEP-111 | 5:22:22.30   | -70:52:46.8  | W Vir  | 16.542              | 17.440              | 7.495 684  | 829.557 73  | 558361794595 | 5_5  | 4,15                |                         |

Table 2 – *continued*

| ID                 | RA         | Dec.        | Type   | (I)    | (V)     | Period     | Epoch       | VMC-ID       | Tile | $N_{\text{Epochs}}$ | Notes              |
|--------------------|------------|-------------|--------|--------|---------|------------|-------------|--------------|------|---------------------|--------------------|
| (1)                | (2)        | (3)         | (4)    | (mag)  | (mag)   | (d)        | (d)         | (9)          | (10) | (11)                | (12)               |
| OGLE-LMC-T2CEP-170 | 5:39:38.12 | -68:48:24.9 | W Vir  | 16.703 | -99.990 | 7.682 906  | 2181.190 87 | 558357268116 | 6_6  | 5,14                | (i)                |
| OGLE-LMC-T2CEP-151 | 5:34:35.73 | -69:59:14.9 | W Vir  | 16.479 | 17.384  | 7.887 246  | 455.117 56  | 558358035015 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-179 | 5:43:04.02 | -70:01:33.6 | W Vir  | 16.744 | 17.805  | 8.050 065  | 2185.448 13 | 558358064065 | 6_6  | 4,14                |                    |
| OGLE-LMC-T2CEP-182 | 5:43:46.89 | -70:42:36.5 | W Vir  | 16.312 | 17.265  | 8.226 419  | 2188.390 82 | 558360430553 | 5_7  | 4,8                 |                    |
| OGLE-LMC-T2CEP-094 | 5:19:53.20 | -69:53:09.9 | W Vir  | 16.588 | 17.529  | 8.468 490  | 2120.738 41 | 558356923555 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-019 | 4:58:49.42 | -68:04:27.8 | pW Vir | 15.989 | 16.853  | 8.674 863  | 2162.749 38 | 558351644677 | 7_3  | 4,16                |                    |
| OGLE-LMC-T2CEP-039 | 5:05:11.31 | -67:12:45.3 | W Vir  | 16.322 | 17.192  | 8.715 837  | 2166.319 77 | 558351083913 | 7_3  | 4,16                |                    |
| OGLE-LMC-T2CEP-028 | 5:03:00.85 | -70:07:33.7 | pW Vir | 15.543 | 16.045  | 8.784 807  | 2168.948 00 | 558358668771 | 5_3  | 4,9                 |                    |
| OGLE-LMC-T2CEP-074 | 5:15:48.75 | -68:48:48.1 | W Vir  | 16.070 | 16.892  | 8.988 344  | 2123.389 75 | 558354851839 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-152 | 5:34:37.58 | -70:01:08.5 | W Vir  | 16.453 | 17.323  | 9.314 921  | 453.026 63  | 558358053632 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-021 | 4:59:34.97 | -71:15:31.2 | pW Vir | 15.884 | 16.580  | 9.759 502  | 2161.102 77 | 558359420632 | 5_3  | 4,11                |                    |
| OGLE-LMC-T2CEP-132 | 5:29:08.23 | -69:56:04.3 | pW Vir | 15.818 | 16.548  | 10.017 829 | 448.218 17  | 558356939981 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-146 | 5:31:48.01 | -68:49:12.1 | W Vir  | 16.392 | 17.347  | 10.079 593 | 2161.817 03 | 558357277233 | 6_6  | 12,23               |                    |
| OGLE-LMC-T2CEP-097 | 5:20:20.58 | -69:12:20.9 | W Vir  | 16.177 | 17.064  | 10.510 167 | 446.108 16  | 558356294442 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-022 | 4:59:58.56 | -70:34:27.8 | W Vir  | 16.271 | 17.179  | 10.716 780 | 2157.787 14 | 558359020369 | 5_3  | 4,11                |                    |
| OGLE-LMC-T2CEP-201 | 5:15:12.67 | -69:23:08.0 | pW Vir | 14.611 | 15.152  | 11.007 243 | 456.113 01  | 558355159487 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-101 | 5:21:18.87 | -69:11:47.3 | W Vir  | 16.035 | 16.838  | 11.418 560 | 444.882 81  | 558356283672 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-013 | 4:55:24.41 | -69:55:43.4 | W Vir  | 16.184 | 17.119  | 11.544 611 | 2157.451 85 | 558358587418 | 5_3  | 4,11                |                    |
| OGLE-LMC-T2CEP-178 | 5:42:19.01 | -70:24:08.1 | W Vir  | 16.326 | 17.406  | 12.212 367 | 726.431 60  | 558360198448 | 5_7  | 4,8                 |                    |
| OGLE-LMC-T2CEP-127 | 5:27:59.80 | -69:23:27.5 | W Vir  | 16.120 | 17.092  | 12.669 118 | 454.171 11  | 558356420696 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-118 | 5:25:15.05 | -68:09:11.7 | W Vir  | 16.103 | 17.037  | 12.698 580 | 2163.344 77 | 558353477576 | 7_5  | 4,14                |                    |
| OGLE-LMC-T2CEP-103 | 5:21:35.27 | -70:13:25.7 | W Vir  | 16.039 | 16.995  | 12.908 278 | 824.386 16  | 558361309970 | 5_5  | 4,15                |                    |
| OGLE-LMC-T2CEP-044 | 5:06:28.86 | -69:43:58.8 | W Vir  | 16.099 | 17.108  | 13.270 100 | 464.577 26  | 558355611443 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-026 | 5:02:11.56 | -68:20:16.0 | W Vir  | 16.091 | 17.026  | 13.577 869 | 2156.872 52 | 558351786614 | 7_3  | 4,16                |                    |
| OGLE-LMC-T2CEP-096 | 5:20:10.42 | -68:48:39.2 | W Vir  | 15.918 | 16.832  | 13.925 722 | 2129.223 74 | 558356025075 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-157 | 5:36:02.60 | -69:27:16.1 | W Vir  | 16.045 | 17.050  | 14.334 647 | 2181.193 12 | 558357639701 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-017 | 4:56:16.02 | -68:16:16.4 | W Vir  | 15.986 | 16.968  | 14.454 754 | 2157.707 44 | 558351791598 | 7_3  | 4,16                |                    |
| OGLE-LMC-T2CEP-143 | 5:31:09.75 | -69:15:48.9 | W Vir  | 15.806 | 16.701  | 14.570 185 | 2166.573 16 | 558356313034 | 6_5  | 12,23               |                    |
| OGLE-LMC-T2CEP-046 | 5:07:38.94 | -68:20:05.9 | W Vir  | 15.547 | 16.415  | 14.743 796 | 2162.697 05 | 558351740940 | 7_3  | 4,16                | (b); (c); (d); (f) |
| OGLE-LMC-T2CEP-139 | 5:30:22.56 | -69:09:12.1 | W Vir  | 15.968 | 17.003  | 14.780 410 | 2156.199 00 | 558356235708 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-177 | 5:40:36.54 | -69:13:04.3 | W Vir  | 16.132 | 17.240  | 15.035 903 | 2178.318 37 | 558357492207 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-099 | 5:20:44.48 | -69:01:48.4 | W Vir  | 15.932 | 16.999  | 15.486 788 | 2111.721 12 | 558356167163 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-086 | 5:18:17.80 | -69:43:27.7 | W Vir  | 15.629 | 16.486  | 15.845 500 | 452.844 78  | 558355544575 | 6_4  | 11,23               |                    |
| OGLE-LMC-T2CEP-126 | 5:27:53.42 | -70:51:30.9 | W Vir  | 16.210 | 17.436  | 16.326 778 | 2167.506 61 | 558361770086 | 5_5  | 4,15                |                    |
| OGLE-LMC-T2CEP-057 | 5:11:21.13 | -68:40:13.3 | W Vir  | 15.749 | 16.707  | 16.632 041 | 2159.167 41 | 558354781673 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-093 | 5:19:26.45 | -69:51:51.0 | W Vir  | 15.130 | 15.861  | 17.593 049 | 446.066 33  | 558356904142 | 6_5  | 7,9                 | (j)                |
| OGLE-LMC-T2CEP-128 | 5:28:43.81 | -70:14:02.3 | W Vir  | 15.517 | 16.460  | 18.492 694 | 453.208 28  | 558361300181 | 5_5  | 4,15                |                    |
| OGLE-LMC-T2CEP-058 | 5:11:33.52 | -68:35:53.7 | RV Tau | 15.511 | 16.594  | 21.482 951 | 2167.453 98 | 558354737426 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-104 | 5:21:49.10 | -70:04:34.3 | RV Tau | 14.937 | 15.830  | 24.879 948 | 447.757 45  | 558361170450 | 5_5  | 11,24               |                    |
| OGLE-LMC-T2CEP-115 | 5:23:43.53 | -69:32:06.8 | RV Tau | 15.593 | 16.651  | 24.966 913 | 2145.848 89 | 558356566155 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-192 | 5:53:55.69 | -70:17:11.4 | RV Tau | 15.233 | 16.148  | 26.194 001 | 2181.449 82 | 558360150098 | 5_7  | 4,8                 |                    |
| OGLE-LMC-T2CEP-135 | 5:29:38.50 | -69:15:12.2 | RV Tau | 15.194 | 16.162  | 26.522 364 | 2144.300 37 | 558356308540 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-108 | 5:22:11.27 | -68:11:31.3 | RV Tau | 14.746 | 15.477  | 30.010 843 | 2113.813 36 | 558353504910 | 7_5  | 4,14                | (k)                |
| OGLE-LMC-T2CEP-162 | 5:37:44.95 | -69:54:16.5 | RV Tau | 15.112 | 16.200  | 30.394 148 | 706.209 90  | 558357961649 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-180 | 5:43:12.87 | -68:33:57.1 | RV Tau | 14.502 | 15.303  | 30.996 315 | 2178.207 91 | 558352877374 | 7_7  | 4,8                 |                    |
| OGLE-LMC-T2CEP-119 | 5:25:19.48 | -70:54:10.0 | RV Tau | 14.391 | 15.225  | 33.825 094 | 2158.593 49 | 558361803554 | 5_5  | 4,15                |                    |
| OGLE-LMC-T2CEP-050 | 5:09:26.15 | -68:50:05.0 | RV Tau | 14.964 | 15.661  | 34.748 344 | 713.647 55  | 558354903269 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-200 | 5:13:56.43 | -69:31:58.3 | RV Tau | 15.092 | 16.124  | 34.916 555 | 423.706 70  | 558355423319 | 6_4  | 4,14                | (k)                |
| OGLE-LMC-T2CEP-065 | 5:14:00.75 | -68:57:56.8 | RV Tau | 14.699 | 15.611  | 35.054 940 | 455.175 14  | 558354970692 | 6_4  | 4,14                | (k)                |
| OGLE-LMC-T2CEP-091 | 5:18:45.48 | -69:03:21.6 | RV Tau | 14.203 | 14.899  | 35.749 346 | 425.386 22  | 558355015602 | 6_4  | 11,23               |                    |
| OGLE-LMC-T2CEP-203 | 5:22:33.79 | -69:38:08.5 | RV Tau | 15.395 | 16.723  | 37.126 746 | 448.749 61  | 558356665485 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-202 | 5:21:49.09 | -70:46:01.4 | RV Tau | 15.167 | 16.359  | 38.135 567 | 812.559 23  | 558361722614 | 5_5  | 4,15                |                    |
| OGLE-LMC-T2CEP-112 | 5:22:58.36 | -69:26:20.9 | RV Tau | 14.065 | 14.749  | 39.397 704 | 421.634 29  | 558356478674 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-051 | 5:09:41.93 | -68:51:25.0 | RV Tau | 14.569 | 15.440  | 40.606 400 | 720.056 75  | 558354917278 | 6_4  | 4,14                | (k)                |
| OGLE-LMC-T2CEP-080 | 5:16:47.43 | -69:44:15.1 | RV Tau | 14.341 | 15.175  | 40.916 413 | 436.421 11  | 558355560379 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-149 | 5:32:54.46 | -69:35:13.2 | RV Tau | 14.151 | 14.868  | 42.480 613 | 2149.996 73 | 558357730269 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-032 | 5:03:56.31 | -67:27:24.6 | RV Tau | 14.011 | 14.992  | 44.561 195 | 2152.876 23 | 558351226498 | 7_3  | 4,16                |                    |
| OGLE-LMC-T2CEP-147 | 5:31:51.00 | -69:11:46.3 | RV Tau | 13.678 | 14.391  | 46.795 842 | 2135.147 58 | 558357481187 | 6_6  | 9,23                |                    |
| OGLE-LMC-T2CEP-174 | 5:40:00.50 | -69:42:14.7 | RV Tau | 13.693 | 14.457  | 46.818 956 | 2166.799 27 | 558357814883 | 6_6  | 5,14                |                    |
| OGLE-LMC-T2CEP-067 | 5:14:18.11 | -69:12:35.0 | RV Tau | 13.825 | 14.627  | 48.231 705 | 442.942 73  | 558355160313 | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-075 | 5:16:16.06 | -69:43:36.9 | RV Tau | 14.568 | 15.728  | 50.186 569 | 430.990 79  | 55835554309  | 6_4  | 4,14                |                    |
| OGLE-LMC-T2CEP-014 | 4:55:35.40 | -69:54:04.2 | RV Tau | 14.312 | 15.103  | 61.875 713 | 2161.688 72 | 558358564467 | 5_3  | 4,11                | (k)                |
| OGLE-LMC-T2CEP-129 | 5:28:54.60 | -69:52:41.1 | RV Tau | 14.096 | 14.813  | 62.508 947 | 397.727 80  | 558356885794 | 6_5  | 7,9                 |                    |
| OGLE-LMC-T2CEP-045 | 5:06:34.06 | -69:30:03.7 | RV Tau | 13.729 | 14.787  | 63.386 339 | 2148.644 83 | 558355447114 | 6_4  | 4,14                |                    |

- (a) Large separation ( $> 0.5$  arcsec) between VMC and OGLE III star centroids likely due to crowding; (b) blended object; (c) faint object; (d) poor light curve; (e) very low amplitude in the optical; (f) source lies within a strip of the tile that has half the exposure of most of the tile (see Cross et al. 2012); (g) poorly sampled or heavily dispersed light curve (due to e.g. blending, saturation); (h) source image comes partly from detector 16 (on the top half of detector 16, the quantum efficiency varies on short time-scales making flat-fields inaccurate; Cross et al. 2012); (i) missing OGLE V magnitude; (j) light curve showing pulsation plus eclipse according to OGLE III; (k) correction for saturation not effective.

known LMC populations of the three different variable classes, respectively.

The OGLE III catalogues of T2CEP variables were cross-correlated against the VMC catalogue to obtain the  $J$  and  $K_s$  light curves for these variables. All the 130 T2CEPs were found to have a counterpart in the VMC catalogue within 2 arcsec from the OGLE III positions. The great majority of the objects showed separation in position with respect to OGLE III less than 0.1 arcsec. However, eight stars (OGLE-LMC-T2CEP-020, 030, 069, 084, 123, 142, 144, 173) present separations significantly larger than average ( $> 0.5$  arcsec). Fig. 2 shows the OGLE III and VMC finding charts of 29 stars with some kind of identification or data problem, within which we included the eight objects quoted above. It can be seen that all the stars lie in crowded regions or are clearly blended by other stars or diffuse objects (e.g. OGLE-LMC-T2CEP-142). We will discuss these objects further in the following sections.

## 2.1 T2CEP light curves

The VMC time-series  $J$  and  $K_s$  photometry for the 130 objects is provided in Table 3, which is published in its entirety in the online version of the paper.

Periods and epochs of maximum light available from the OGLE III catalogue were used to fold the  $J$ - and  $K_s$ -band light curves produced by the VMC observations. Given the larger number of epochs in  $K_s$  with respect to  $J$ , we discuss first the  $K_s$ -band data.

The  $K_s$ -band light curves for a sample of 120 T2CEPs with useful light curves are shown in Fig. A1. Apart from a few cases, these light curves are generally well sampled and nicely shaped. Some clearly discrepant data points (open circles in Fig. A1) in the light curves were excluded from the fit but were plotted in the figure for completeness. Note that most of these ‘bad’ data points belong to observations collected during nights that did not strictly meet the VMC observing constraints (see table 2 in Cioni et al. 2011). The final spline fit to the data is shown by a solid line in Fig. A1. Intensity-averaged  $\langle K_s \rangle$  magnitudes were derived from the light curves using custom software written in c, which performs a spline interpolation to the data with no need of using templates. The numerical model of the light curve is thus obtained and then integrated in intensity to obtain the mean intensity which is eventually transformed to mean magnitude.

10 objects in our sample showed unusable light curves, namely OGLE-LMC-T2CEP-014, 030, 043, 051, 065, 084, 095, 108, 142 and 200. Their light curves are displayed in Fig. A2, whereas their finding charts are shown in Fig. 2. A quick analysis of the finding charts reveals that all these stars have significant problems of crowding/blending. Three of the aforementioned objects (OGLE-LMC-T2CEP-030, 084 and 142) have centroids significantly shifted with respect to OGLE’s, thus confirming the presence of strong blending.

As for the  $J$ -band data, Fig. A3 shows the light curves for the 34 stars that have sufficiently good data to allow an independent spline fit (solid line in the figure). Figs A4 and A5 show the light curves for the remaining 86 and 10 objects with small number of epochs ( $\sim 4$ –5 on average) and dispersed light curves, respectively. The latter variables show the same problems reported for the  $K_s$  band. To estimate the intensity-averaged  $J$  magnitude for the 86 stars possessing only few epochs of observation, we decided to use the spline-fit curves in the  $K_s$  band as templates.<sup>5</sup> To this aim,

for each star we performed the following steps: (1) subtracted the average  $\langle K_s \rangle$  magnitude from the  $K_s$  spline-fit curve; (2) adjusted by eye the data obtained in this way to fit the  $J$  light curve by (i) adding a ZP, (ii) multiplying the amplitude by a proper factor and (iii) shifting the light curve in phase. The factor needed for point (ii) is the ratio  $\text{Amp}(J)/\text{Amp}(K_s)$ . To estimate this number, we used the 34 stars with independent  $J$ -band spline fit, obtaining a value of  $1.1 \pm 0.2$ . The uncertainty of  $\sim 20$  per cent may appear large, but it does not actually represent a problem since its contribution to the error on the intensity-averaged  $J$  is of the order of 0.5 per cent. In some favourable cases, the few data points covered both maximum and minimum of the light curve and it was then possible to constrain directly the amplitude ratio. The shift in phase (point iii above) varied from case to case, but was on average close to 0.05–0.06. The final error on the intensity-averaged  $J$  magnitude was calculated by summing in quadrature the error on the  $K_s$  magnitude, the uncertainty on the  $J$  magnitude caused by the error on the amplitude ratio and an additional 1 per cent to take into account the uncertainty on the phase shift. The goodness of this procedure can be appreciated in Fig. 3, where we show in different colours the PL and PW relations (see the next section for a detailed description of these relations) for the stars with intensity-averaged  $J$  photometry obtained directly from spline fits (black points) and with the template fits (grey points). The figure clearly shows that the results obtained on the basis of the  $K_s$  templates are usable for scientific purposes. The final  $\langle J \rangle, \langle K_s \rangle$  magnitudes with relative uncertainties, as well as pulsational amplitudes and adopted reddening values (see Section 3), are provided in Table 4.

We recall that the  $J$  and  $K_s$  photometry presented in this paper is set in the VISTA system. A consistent comparison between our results and those in the widely used 2MASS system (Two Micron All Sky Survey; Skrutskie et al. 1996) can be performed after applying proper system transformations as for instance those provided by the Cambridge Astronomy Survey Unit (CASU):<sup>6</sup> ( $J - K_s$ )(2MASS) = 1.081( $J - K_s$ )(VISTA),  $J$ (2MASS) =  $J$ (VISTA) + 0.07( $J - K_s$ )(VISTA) and  $K_s$ (2MASS) =  $K_s$ (VISTA) – 0.011( $J - K_s$ )(VISTA).

Since the  $\langle J \rangle - \langle K_s \rangle$  colour of our T2CEP sample typically ranges from 0.1 to 0.6 mag, the VISTA and 2MASS  $K_s$  can be considered equivalent for T2CEPs (see Fig. 4) and for CCs (see Ripepi et al. 2012b), to a very good approximation (better than  $\sim 5$  mmag).

## 3 $J$ -, $K_s$ -BAND PL, PLC AND PW RELATIONS

The data reported in Table 4 allow us to calculate different useful relationships adopting various combinations of magnitudes and colours. In particular, we derived PL relations in  $J$  and  $K_s$  as well as PW and PLC relations for the following combinations: ( $J$ ,  $V - J$ ), ( $K_s$ ,  $V - K_s$ ) and ( $K_s$ ,  $J - K_s$ ).

We first corrected magnitudes and colours for reddening using the recent extinction maps by Haschke, Grebel & Duffau (2011). Individual  $E(V - I)$  reddening values for the 120 T2CEPs with useful VMC data are reported in column 10 of Table 4. The reliability of this reddening correction can be questioned by observing that it has been derived from the analysis of the red clump stars, which trace the intermediate-age population (2–9 Gyr)

<sup>5</sup> A comparison of Fig. A1 ( $K_s$  light curves) and A3 ( $J$  light curves) for stars possessing sufficient data points to be analysed independently from the  $K_s$

band) shows that at present level of precision, the light curves in  $J$  and  $K_s$  are sufficiently similar to allow us using the  $K_s$  spline fits as templates.

<sup>6</sup> <http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/photometric-properties>

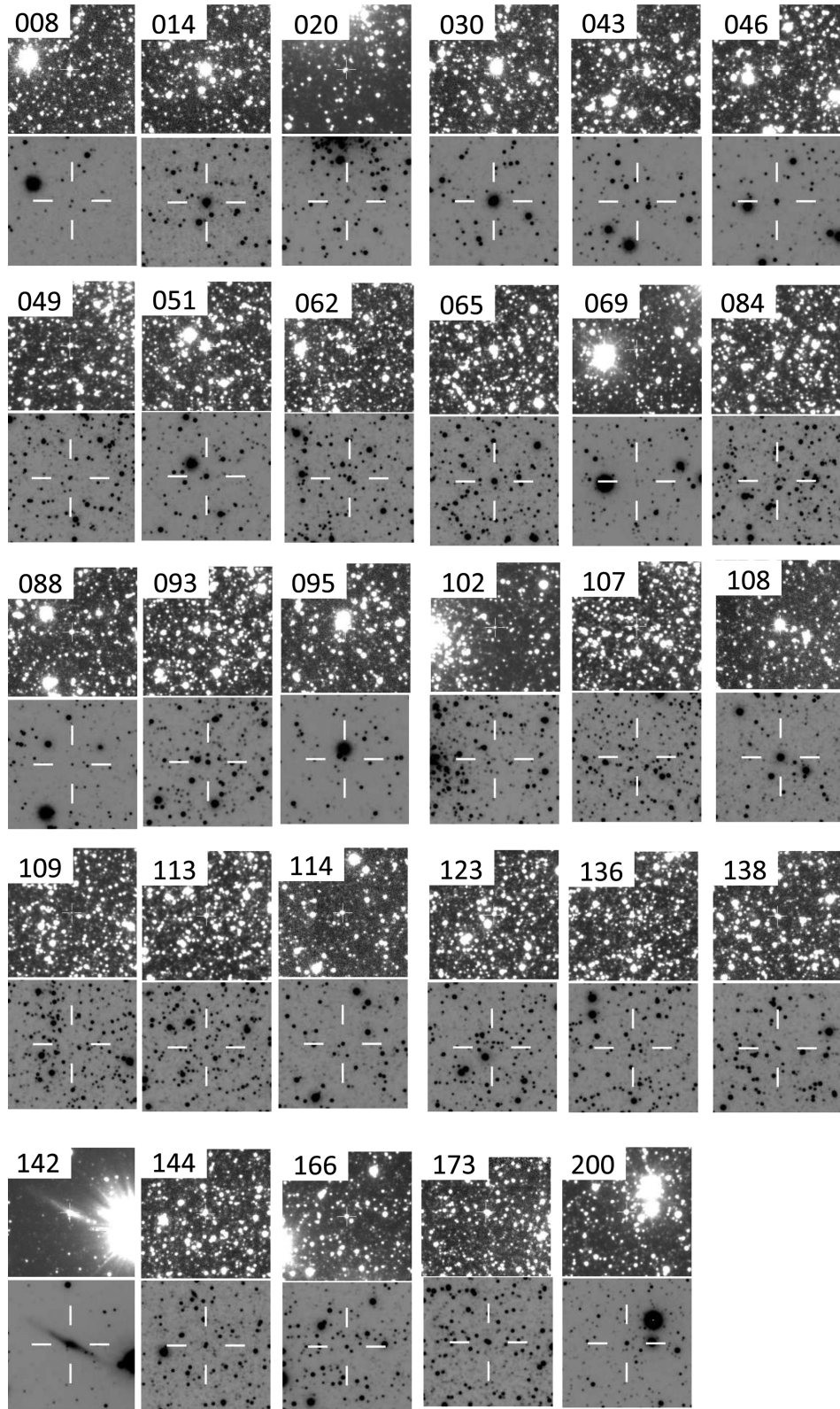


**Figure 2.** Sky pictures for 29 problematic stars extracted from the VMC (bottom panels) and the OGLE III (top panels) archives. The target is identified with the last three digits of the OGLE III identification (i.e. without the prefix ‘OGLE-LMC-T2CEP-’).

instead of the old one to whom BL Her and W Vir belong. However, we recall that in the NIR bands the interstellar absorption is very low:  $A_J \sim 0.25A_V$  and  $A_{K_s} \sim 0.1A_V$ , where  $A_V$  is the absorption in the visible. Hence, even in the unlikely case of a 10 percent

large error in our  $A_V$  estimates, this would introduce an amount of uncertainties of only  $\sim 2.5$  percent and  $\sim 1$  percent in  $J$  and  $K_s$ , respectively. An a posteriori indication about the global correctness of the adopted reddening correction is represented by the

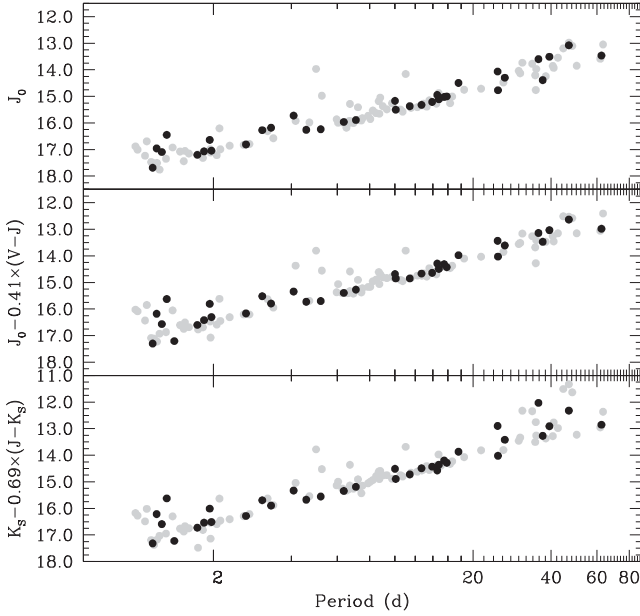


**Figure 3.** From top to bottom: PL in the  $J$  band, PW in  $(J, V - J)$  and PW in  $(K_s, J - K_s)$  for T2CEPs whose intensity-averaged  $\langle J \rangle$  magnitude was obtained on the basis of direct spline fit (black filled circles) or template fit (grey filled circles). See the text for details.

**Table 3.**  $J$  and  $K_s$  time-series photometry for the T2CEPs investigated in this paper. The data below refer to the variable OGLE-LMC-T2CEP-123.

| HJD-2400000 | $J$    | $\sigma_J$     |
|-------------|--------|----------------|
| 55487.77111 | 16.963 | 0.014          |
| 55487.80976 | 16.959 | 0.014          |
| 55497.79317 | 16.989 | 0.014          |
| 55497.86048 | 16.950 | 0.013          |
| HJD-2400000 | $K_s$  | $\sigma_{K_s}$ |
| 55495.82644 | 16.520 | 0.020          |
| 55497.75937 | 16.520 | 0.020          |
| 55497.81507 | 16.513 | 0.024          |
| 55499.82170 | 16.517 | 0.023          |
| 55511.74774 | 16.507 | 0.020          |
| 55516.77236 | 16.496 | 0.023          |
| 55526.78868 | 16.498 | 0.021          |
| 55539.82483 | 16.488 | 0.022          |
| 55557.73937 | 16.482 | 0.023          |
| 55563.71325 | 16.465 | 0.021          |
| 55587.65755 | 16.470 | 0.023          |
| 55844.79771 | 16.526 | 0.020          |
| 55865.82753 | 16.483 | 0.021          |
| 55887.74744 | 16.477 | 0.022          |
| 55937.67877 | 16.454 | 0.021          |

Table 3 is published in its entirety only in the electronic edition of the journal. A portion is shown here for guidance regarding its form and content.

concordance of results provided by the PL (reddening-dependent) and PW (reddening-independent) relations (see Sections 4 and 5). The reddening values were converted using the following equations:  $E(V - J) = 1.80E(V - I)$ ,  $E(V - K_s) = 2.24E(V - I)$  and

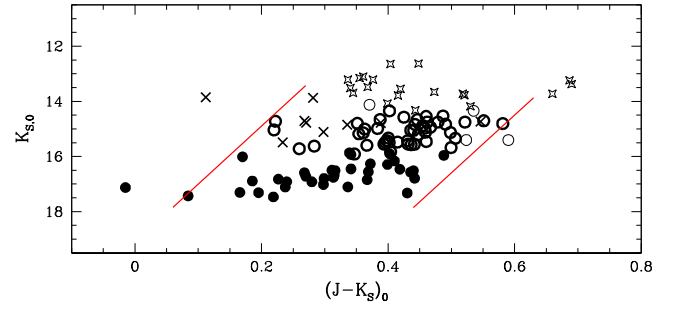


**Figure 4.** Observed instability strip in the plane  $K_{s,0}$  versus  $(J - K_s)_0$ . Filled circles, open circles, crosses and stars show BL Her, W Vir, pW Vir and RV Tau variables, respectively. The solid lines show the approximate borders of the BL Her/W Vir instability strip. Blue and red edges are described by the following equations:  $K_{s,0} = 19.1 - 21(J - K_s)_0$  ( $0.06 < (J - K_s)_0 < 0.27$  mag) and  $K_{s,0} = 27.1 - 21(J - K_s)_0$  ( $0.44 < (J - K_s)_0 < 0.63$  mag), respectively.

$E(J - K_s) = 0.43E(V - I)$  (Cardelli, Clayton & Mathis 1989; Gao et al. 2013).<sup>7</sup> The coefficients of the PW relations were calculated in a similar way.

In principle, an additional preliminary step would be required, i.e. the correction for the inclination of the LMC disc-like structure by de-projecting each T2CEP with respect to the LMC centre. To do this, we followed the procedure suggested in van der Marel & Cioni (2001) and adopted their values of the LMC centre, inclination and position angle of the line of nodes. However, we have a posteriori verified that the introduction of this correction leads to worse results, i.e. larger dispersion in the various relationships mentioned above. To verify if different choices about the inclined disc parameters could improve the results, we have carried out the de-projection using several results present in the literature (see Haschke et al. 2012; Rubele et al. 2012; Subramanian & Subramanian 2013, and references therein). Under no circumstances, the dispersion of the PWs decreased (we used PWs as reference because they are reddening-free). To explain this occurrence, we can reasonably hypothesize that the T2CEPs (actually BL Her and W Vir), being old (age  $> 10$  Gyr) objects, are not preferentially distributed along the main disc-like structure of the LMC. Alternatively, the adopted parameters for the de-projection are not accurate enough, although this conclusion may be influenced by the relatively small number of objects. Subsequent studies using a larger number of objects observed in the VMC context sampling different populations (CCs, T2CEPs and RR Lyrae stars) will clarify the issue. In any case, in the following analysis we did not apply any magnitude correction accounting for the LMC disc structure.

Figs 5–8 show all the relationships investigated here. An inspection of these figures confirms the findings by Matsunaga et al. (2009) that BL Her and W Vir star follow a common PL relation, whereas RV Tau show a different and more dispersed relation (the dispersion is less severe in the  $J$  than in the  $K_s$  band). In our case, the dispersion among RV Tau stars can in part be due to the proximity of several bright variables to the saturation limit. As a consequence, we decided to exclude these stars from the calculation of the PL, PW and PLC relations. To check if BL Her and W Vir stars can actually be fitted with a unique relation, we performed an independent test by fitting separately the PL( $K_s, J$ ) and PW( $K_s, V$ ) relations for each class of variables. The result of this exercise is shown in Fig. 9: for

<sup>7</sup> The coefficients we used are suited for the 2MASS system, to which the VISTA system is tied (see Section 2.1).

**Table 4.** Results for the 120 T2CEPs with useful NIR light curves analysed in this paper. The columns report (1) OGLE identification; (2) variability class; (3) period (OGLE); (4) intensity-averaged  $J$  magnitude; (5) uncertainty on the  $\langle J \rangle$  (6) intensity-averaged  $K_s$  magnitude; (7) uncertainty on the  $\langle K_s \rangle$ ; (8) peak-to-peak amplitude in  $J$ ; (9) peak-to-peak amplitude in  $K_s$ ; (10) adopted reddening; (11) T = results in  $J$  obtained on the basis of the  $K_s$  template, S = results in  $J$  obtained on the basis of direct spline fitting to the data.

| ID                 | Var. class | Period     | $\langle J \rangle$ | $\sigma_J$ | $\langle K_s \rangle$ | $\sigma_{K_s}$ | Amp( $J$ ) | Amp( $K_s$ ) | $E(V - I)$ | Note |
|--------------------|------------|------------|---------------------|------------|-----------------------|----------------|------------|--------------|------------|------|
| (1)                | (2)        | (d)        | (mag)               | (mag)      | (mag)                 | (mag)          | (mag)      | (mag)        | (mag)      | (11) |
| OGLE-LMC-T2CEP-123 | BL Her     | 1.002 6263 | 16.939              | 0.021      | 16.486                | 0.013          | 0.05       | 0.05         | 0.080      | T    |
| OGLE-LMC-T2CEP-069 | BL Her     | 1.021 2542 | 17.042              | 0.033      | 16.585                | 0.021          | 0.10       | 0.10         | 0.050      | T    |
| OGLE-LMC-T2CEP-114 | BL Her     | 1.091 0886 | 17.329              | 0.069      | 16.831                | 0.019          | 0.17       | 0.16         | 0.130      | T    |
| OGLE-LMC-T2CEP-020 | BL Her     | 1.108 1258 | 16.735              | 0.043      | 16.310                | 0.022          | 0.09       | 0.07         | 0.060      | T    |
| OGLE-LMC-T2CEP-071 | BL Her     | 1.152 1638 | 17.522              | 0.022      | 17.326                | 0.026          | 0.40       | 0.38         | 0.070      | T    |
| OGLE-LMC-T2CEP-089 | BL Her     | 1.167 2977 | 17.715              | 0.018      | 17.479                | 0.043          | 0.40       | 0.32         | 0.040      | S    |
| OGLE-LMC-T2CEP-061 | BL Her     | 1.181 5124 | 17.581              | 0.037      | 17.458                | 0.031          | 0.38       | 0.19         | 0.090      | T    |
| OGLE-LMC-T2CEP-107 | BL Her     | 1.209 1451 | 16.979              | 0.005      | 16.526                | 0.016          | 0.19       | 0.13         | 0.030      | S    |
| OGLE-LMC-T2CEP-077 | BL Her     | 1.213 8023 | 17.521              | 0.045      | 17.317                | 0.025          | 0.18       | 0.17         | 0.020      | T    |
| OGLE-LMC-T2CEP-165 | BL Her     | 1.240 8330 | 17.889              | 0.049      | 17.381                | 0.024          | 0.34       | 0.32         | 0.180      | T    |
| OGLE-LMC-T2CEP-102 | BL Her     | 1.266 0176 | 17.146              | 0.010      | 16.817                | 0.020          | 0.20       | 0.13         | 0.070      | S    |
| OGLE-LMC-T2CEP-194 | BL Her     | 1.314 4675 | 17.406              | 0.017      | 17.134                | 0.018          | 0.38       | 0.24         | 0.080      | T    |
| OGLE-LMC-T2CEP-136 | BL Her     | 1.323 0384 | 16.492              | 0.011      | 15.978                | 0.006          | 0.31       | 0.08         | 0.060      | S    |
| OGLE-LMC-T2CEP-138 | BL Her     | 1.393 5906 | 16.975              | 0.043      | 16.576                | 0.017          | 0.07       | 0.07         | 0.070      | T    |
| OGLE-LMC-T2CEP-109 | BL Her     | 1.414 5528 | 18.610              | 0.056      | 17.790                | 0.038          | 0.43       | 0.38         | 0.030      | S    |
| OGLE-LMC-T2CEP-105 | BL Her     | 1.489 2979 | 17.134              | 0.012      | 16.914                | 0.021          | 0.41       | 0.27         | 0.080      | T    |
| OGLE-LMC-T2CEP-122 | BL Her     | 1.538 6690 | 17.520              | 0.034      | 17.136                | 0.018          | 0.24       | 0.23         | 0.110      | T    |
| OGLE-LMC-T2CEP-171 | BL Her     | 1.554 7492 | 17.175              | 0.017      | 16.875                | 0.017          | 0.18       | 0.17         | 0.170      | T    |
| OGLE-LMC-T2CEP-068 | BL Her     | 1.609 3007 | 17.225              | 0.028      | 16.942                | 0.018          | 0.27       | 0.26         | 0.100      | T    |
| OGLE-LMC-T2CEP-124 | BL Her     | 1.734 8666 | 17.280              | 0.009      | 16.953                | 0.030          | 0.30       | 0.30         | 0.110      | S    |
| OGLE-LMC-T2CEP-008 | BL Her     | 1.746 0989 | 17.257              | 0.023      | 17.389                | 0.028          | 0.08       | 0.08         | 0.100      | T    |
| OGLE-LMC-T2CEP-141 | BL Her     | 1.822 9539 | 17.389              | 0.023      | 17.048                | 0.021          | 0.36       | 0.40         | 0.100      | T    |
| OGLE-LMC-T2CEP-140 | BL Her     | 1.841 1435 | 17.127              | 0.012      | 16.779                | 0.014          | 0.21       | 0.27         | 0.080      | S    |
| OGLE-LMC-T2CEP-144 | BL Her     | 1.937 4502 | 16.726              | 0.017      | 16.302                | 0.011          | 0.22       | 0.20         | 0.120      | S    |
| OGLE-LMC-T2CEP-130 | BL Her     | 1.944 6935 | 17.036              | 0.016      | 16.740                | 0.021          | 0.36       | 0.34         | 0.060      | T    |
| OGLE-LMC-T2CEP-088 | BL Her     | 1.950 7490 | 17.158              | 0.012      | 17.147                | 0.028          | 0.09       | 0.09         | 0.060      | T    |
| OGLE-LMC-T2CEP-116 | BL Her     | 1.966 6793 | 17.086              | 0.038      | 16.746                | 0.007          | 0.23       | 0.32         | 0.060      | S    |
| OGLE-LMC-T2CEP-121 | BL Her     | 2.061 3655 | 17.234              | 0.033      | 16.854                | 0.014          | 0.45       | 0.43         | 0.030      | T    |
| OGLE-LMC-T2CEP-166 | BL Her     | 2.110 5987 | 16.343              | 0.015      | 15.922                | 0.006          | 0.23       | 0.22         | 0.190      | T    |
| OGLE-LMC-T2CEP-064 | BL Her     | 2.127 8906 | 17.043              | 0.019      | 16.698                | 0.025          | 0.47       | 0.45         | 0.070      | T    |
| OGLE-LMC-T2CEP-167 | BL Her     | 2.311 8238 | 17.091              | 0.045      | 16.685                | 0.010          | 0.50       | 0.48         | 0.320      | T    |
| OGLE-LMC-T2CEP-092 | BL Her     | 2.616 7684 | 16.864              | 0.097      | 16.526                | 0.066          | 0.69       | 0.66         | 0.050      | T    |
| OGLE-LMC-T2CEP-148 | BL Her     | 2.671 7338 | 16.853              | 0.011      | 16.516                | 0.015          | 0.43       | 0.56         | 0.060      | S    |
| OGLE-LMC-T2CEP-195 | BL Her     | 2.752 9292 | 16.850              | 0.021      | 16.474                | 0.008          | 0.55       | 0.46         | 0.080      | T    |
| OGLE-LMC-T2CEP-113 | BL Her     | 3.085 4602 | 16.285              | 0.002      | 15.935                | 0.008          | 0.10       | 0.06         | 0.020      | S    |
| OGLE-LMC-T2CEP-049 | BL Her     | 3.235 2751 | 16.359              | 0.015      | 15.926                | 0.010          | 0.25       | 0.24         | 0.070      | T    |
| OGLE-LMC-T2CEP-145 | BL Her     | 3.337 3019 | 16.269              | 0.008      | 16.047                | 0.015          | 0.11       | 0.08         | 0.120      | S    |
| OGLE-LMC-T2CEP-085 | BL Her     | 3.405 0955 | 16.640              | 0.017      | 16.191                | 0.011          | 0.47       | 0.45         | 0.090      | T    |
| OGLE-LMC-T2CEP-134 | pW Vir     | 4.075 7258 | 15.782              | 0.009      | 15.514                | 0.007          | 0.31       | 0.36         | 0.080      | S    |
| OGLE-LMC-T2CEP-173 | W Vir      | 4.147 8811 | 16.049              | 0.018      | 15.452                | 0.005          | 0.12       | 0.11         | 0.170      | T    |
| OGLE-LMC-T2CEP-120 | W Vir      | 4.559 0530 | 16.354              | 0.007      | 15.951                | 0.009          | 0.38       | 0.38         | 0.130      | S    |
| OGLE-LMC-T2CEP-052 | pW Vir     | 4.687 9253 | 16.031              | 0.018      | 15.741                | 0.022          | 0.14       | 0.13         | 0.070      | T    |
| OGLE-LMC-T2CEP-098 | pW Vir     | 4.973 7372 | 14.056              | 0.014      | 13.892                | 0.005          | 0.15       | 0.14         | 0.120      | T    |
| OGLE-LMC-T2CEP-087 | W Vir      | 5.184 9790 | 16.302              | 0.013      | 15.859                | 0.015          | 0.30       | 0.31         | 0.090      | S    |
| OGLE-LMC-T2CEP-023 | pW Vir     | 5.234 8007 | 15.005              | 0.043      | 14.720                | 0.013          | 0.36       | 0.34         | 0.040      | T    |
| OGLE-LMC-T2CEP-083 | pW Vir     | 5.967 6496 | 15.936              | 0.054      | 15.462                | 0.011          | 0.48       | 0.46         | 0.100      | T    |
| OGLE-LMC-T2CEP-062 | W Vir      | 6.046 6764 | 16.060              | 0.019      | 15.431                | 0.003          | 0.05       | 0.05         | 0.090      | T    |
| OGLE-LMC-T2CEP-133 | W Vir      | 6.281 9551 | 16.013              | 0.010      | 15.564                | 0.013          | 0.09       | 0.09         | 0.040      | T    |
| OGLE-LMC-T2CEP-137 | W Vir      | 6.362 3499 | 16.044              | 0.004      | 15.630                | 0.010          | 0.11       | 0.11         | 0.110      | S    |
| OGLE-LMC-T2CEP-183 | W Vir      | 6.509 6275 | 16.325              | 0.016      | 15.739                | 0.016          | 0.15       | 0.14         | 0.200      | T    |
| OGLE-LMC-T2CEP-159 | W Vir      | 6.625 5696 | 16.089              | 0.015      | 15.605                | 0.010          | 0.09       | 0.09         | 0.110      | T    |
| OGLE-LMC-T2CEP-117 | W Vir      | 6.629 3487 | 16.007              | 0.012      | 15.579                | 0.005          | 0.12       | 0.11         | 0.080      | T    |
| OGLE-LMC-T2CEP-106 | W Vir      | 6.706 7363 | 15.956              | 0.055      | 15.474                | 0.010          | 0.16       | 0.15         | 0.050      | T    |
| OGLE-LMC-T2CEP-078 | pW Vir     | 6.716 2943 | 15.349              | 0.016      | 14.764                | 0.011          | 0.15       | 0.14         | 0.090      | T    |
| OGLE-LMC-T2CEP-063 | W Vir      | 6.924 5800 | 16.040              | 0.023      | 15.577                | 0.016          | 0.14       | 0.13         | 0.050      | T    |
| OGLE-LMC-T2CEP-110 | W Vir      | 7.078 4684 | 15.978              | 0.008      | 15.511                | 0.017          | 0.16       | 0.15         | 0.120      | S    |
| OGLE-LMC-T2CEP-181 | pW Vir     | 7.212 5323 | 15.505              | 0.013      | 15.151                | 0.005          | 0.07       | 0.07         | 0.130      | T    |
| OGLE-LMC-T2CEP-047 | W Vir      | 7.286 2123 | 15.943              | 0.018      | 15.511                | 0.011          | 0.14       | 0.13         | 0.070      | T    |
| OGLE-LMC-T2CEP-056 | W Vir      | 7.289 6382 | 15.965              | 0.017      | 15.522                | 0.004          | 0.16       | 0.15         | 0.110      | T    |

Table 4 – continued

| ID                 | Var. class | Period      | $\langle J \rangle$ | $\sigma_J$ | $\langle K_s \rangle$ | $\sigma_{K_s}$ | Amp(J) | Amp( $K_s$ ) | $E(V - J)$ | Note |
|--------------------|------------|-------------|---------------------|------------|-----------------------|----------------|--------|--------------|------------|------|
| (1)                | (2)        | (3)         | (4)                 | (5)        | (6)                   | (7)            | (8)    | (9)          | (10)       | (11) |
| OGLE-LMC-T2CEP-100 | W Vir      | 7.431 0950  | 15.965              | 0.012      | 15.647                | 0.020          | 0.29   | 0.28         | 0.080      | T    |
| OGLE-LMC-T2CEP-111 | W Vir      | 7.495 6838  | 15.865              | 0.011      | 15.441                | 0.006          | 0.19   | 0.18         | 0.060      | T    |
| OGLE-LMC-T2CEP-170 | W Vir      | 7.682 9062  | 15.926              | 0.018      | 15.423                | 0.004          | 0.16   | 0.15         | 0.180      | T    |
| OGLE-LMC-T2CEP-151 | W Vir      | 7.887 2458  | 15.814              | 0.016      | 15.366                | 0.009          | 0.14   | 0.13         | 0.110      | T    |
| OGLE-LMC-T2CEP-179 | W Vir      | 8.050 0650  | 15.932              | 0.014      | 15.378                | 0.005          | 0.14   | 0.13         | 0.110      | T    |
| OGLE-LMC-T2CEP-182 | W Vir      | 8.226 4194  | 15.628              | 0.035      | 15.218                | 0.007          | 0.37   | 0.35         | 0.130      | T    |
| OGLE-LMC-T2CEP-094 | W Vir      | 8.468 4897  | 15.659              | 0.048      | 15.143                | 0.006          | 0.10   | 0.10         | 0.040      | T    |
| OGLE-LMC-T2CEP-019 | pW Vir     | 8.674 8634  | 15.263              | 0.024      | 14.880                | 0.015          | 0.33   | 0.31         | 0.110      | T    |
| OGLE-LMC-T2CEP-039 | W Vir      | 8.715 8373  | 15.682              | 0.018      | 15.217                | 0.009          | 0.19   | 0.18         | 0.040      | T    |
| OGLE-LMC-T2CEP-028 | pW Vir     | 8.784 8073  | 15.083              | 0.016      | 14.791                | 0.006          | 0.32   | 0.30         | 0.050      | T    |
| OGLE-LMC-T2CEP-074 | W Vir      | 8.988 3439  | 15.414              | 0.019      | 15.025                | 0.025          | 0.22   | 0.21         | 0.060      | T    |
| OGLE-LMC-T2CEP-152 | W Vir      | 9.314 9211  | 15.559              | 0.013      | 15.080                | 0.004          | 0.39   | 0.37         | 0.100      | T    |
| OGLE-LMC-T2CEP-021 | pW Vir     | 9.759 5024  | 15.309              | 0.046      | 15.059                | 0.018          | 0.16   | 0.15         | 0.070      | T    |
| OGLE-LMC-T2CEP-132 | pW Vir     | 10.017 8287 | 15.227              | 0.015      | 14.804                | 0.005          | 0.22   | 0.09         | 0.080      | S    |
| OGLE-LMC-T2CEP-146 | W Vir      | 10.079 5925 | 15.576              | 0.026      | 15.172                | 0.021          | 0.37   | 0.29         | 0.100      | S    |
| OGLE-LMC-T2CEP-097 | W Vir      | 10.510 1666 | 15.530              | 0.062      | 15.068                | 0.006          | 0.28   | 0.27         | 0.050      | T    |
| OGLE-LMC-T2CEP-022 | W Vir      | 10.716 7800 | 15.598              | 0.011      | 15.126                | 0.015          | 0.35   | 0.33         | 0.030      | T    |
| OGLE-LMC-T2CEP-201 | pW Vir     | 11.007 2431 | 14.195              | 0.018      | 13.892                | 0.007          | 0.06   | 0.06         | 0.050      | T    |
| OGLE-LMC-T2CEP-101 | W Vir      | 11.418 5596 | 15.427              | 0.009      | 15.009                | 0.007          | 0.45   | 0.40         | 0.080      | S    |
| OGLE-LMC-T2CEP-013 | W Vir      | 11.544 6113 | 15.498              | 0.014      | 15.001                | 0.013          | 0.22   | 0.21         | 0.090      | T    |
| OGLE-LMC-T2CEP-178 | W Vir      | 12.212 3667 | 15.517              | 0.020      | 14.985                | 0.008          | 0.33   | 0.31         | 0.150      | T    |
| OGLE-LMC-T2CEP-127 | W Vir      | 12.669 1185 | 15.372              | 0.022      | 14.851                | 0.011          | 0.48   | 0.37         | 0.070      | S    |
| OGLE-LMC-T2CEP-118 | W Vir      | 12.698 5804 | 15.412              | 0.038      | 14.914                | 0.007          | 0.72   | 0.69         | 0.100      | T    |
| OGLE-LMC-T2CEP-103 | W Vir      | 12.908 2775 | 15.336              | 0.011      | 14.859                | 0.019          | 0.40   | 0.38         | 0.080      | T    |
| OGLE-LMC-T2CEP-044 | W Vir      | 13.270 1004 | 15.455              | 0.030      | 14.835                | 0.013          | 0.30   | 0.29         | 0.090      | T    |
| OGLE-LMC-T2CEP-026 | W Vir      | 13.577 8689 | 15.209              | 0.089      | 14.823                | 0.012          | 0.39   | 0.37         | 0.080      | T    |
| OGLE-LMC-T2CEP-096 | W Vir      | 13.925 7224 | 15.277              | 0.056      | 14.776                | 0.006          | 0.81   | 0.75         | 0.090      | S    |
| OGLE-LMC-T2CEP-157 | W Vir      | 14.334 6466 | 15.304              | 0.045      | 14.782                | 0.043          | 0.66   | 0.63         | 0.100      | T    |
| OGLE-LMC-T2CEP-017 | W Vir      | 14.454 7544 | 15.354              | 0.056      | 14.785                | 0.021          | 0.81   | 0.77         | 0.110      | T    |
| OGLE-LMC-T2CEP-143 | W Vir      | 14.570 1846 | 14.991              | 0.075      | 14.743                | 0.068          | 1.05   | 0.72         | 0.060      | S    |
| OGLE-LMC-T2CEP-046 | W Vir      | 14.743 7956 | 14.921              | 0.058      | 14.360                | 0.021          | 0.62   | 0.59         | 0.060      | T    |
| OGLE-LMC-T2CEP-139 | W Vir      | 14.780 4104 | 15.220              | 0.014      | 14.709                | 0.005          | 0.50   | 0.51         | 0.150      | S    |
| OGLE-LMC-T2CEP-177 | W Vir      | 15.035 9027 | 15.245              | 0.024      | 14.741                | 0.007          | 0.69   | 0.66         | 0.270      | T    |
| OGLE-LMC-T2CEP-099 | W Vir      | 15.486 7877 | 15.094              | 0.003      | 14.564                | 0.005          | 0.51   | 0.52         | 0.100      | S    |
| OGLE-LMC-T2CEP-086 | W Vir      | 15.845 5000 | 15.024              | 0.011      | 14.586                | 0.017          | 0.79   | 0.80         | 0.030      | S    |
| OGLE-LMC-T2CEP-126 | W Vir      | 16.326 7785 | 15.323              | 0.023      | 14.733                | 0.013          | 0.77   | 0.73         | 0.090      | T    |
| OGLE-LMC-T2CEP-057 | W Vir      | 16.632 0415 | 15.052              | 0.021      | 14.566                | 0.013          | 0.82   | 0.78         | 0.060      | T    |
| OGLE-LMC-T2CEP-093 | W Vir      | 17.593 0492 | 14.524              | 0.021      | 14.136                | 0.019          | 0.61   | 0.47         | 0.040      | S    |
| OGLE-LMC-T2CEP-128 | W Vir      | 18.492 6938 | 14.787              | 0.023      | 14.363                | 0.054          | 0.71   | 0.68         | 0.050      | T    |
| OGLE-LMC-T2CEP-058 | RV Tau     | 21.482 9509 | 14.777              | 0.017      | 14.208                | 0.014          | 0.75   | 0.71         | 0.090      | T    |
| OGLE-LMC-T2CEP-104 | RV Tau     | 24.879 9480 | 14.131              | 0.020      | 13.402                | 0.043          | 0.32   | 0.61         | 0.090      | S    |
| OGLE-LMC-T2CEP-115 | RV Tau     | 24.966 9126 | 14.790              | 0.002      | 14.334                | 0.013          | 0.66   | 0.63         | 0.030      | S    |
| OGLE-LMC-T2CEP-192 | RV Tau     | 26.194 0011 | 14.521              | 0.033      | 14.096                | 0.008          | 1.09   | 1.04         | 0.060      | T    |
| OGLE-LMC-T2CEP-135 | RV Tau     | 26.522 3638 | 14.350              | 0.016      | 13.799                | 0.015          | 1.09   | 0.76         | 0.070      | S    |
| OGLE-LMC-T2CEP-162 | RV Tau     | 30.394 1483 | 14.294              | 0.043      | 13.726                | 0.043          | 0.57   | 0.41         | 0.220      | T    |
| OGLE-LMC-T2CEP-180 | RV Tau     | 30.996 3145 | 13.785              | 0.068      | 12.921                | 0.033          | 0.42   | 0.40         | 0.070      | T    |
| OGLE-LMC-T2CEP-119 | RV Tau     | 33.825 0938 | 13.832              | 0.021      | 12.951                | 0.064          | 0.89   | 0.85         | 0.080      | T    |
| OGLE-LMC-T2CEP-050 | RV Tau     | 34.748 3438 | 14.257              | 0.030      | 13.811                | 0.014          | 0.19   | 0.18         | 0.070      | T    |
| OGLE-LMC-T2CEP-091 | RV Tau     | 35.749 3456 | 13.652              | 0.045      | 12.693                | 0.055          | 0.62   | 0.64         | 0.070      | S    |
| OGLE-LMC-T2CEP-203 | RV Tau     | 37.126 7463 | 14.416              | 0.007      | 13.739                | 0.004          | 0.61   | 0.39         | 0.040      | S    |
| OGLE-LMC-T2CEP-202 | RV Tau     | 38.135 5674 | 14.310              | 0.013      | 13.753                | 0.015          | 0.07   | 0.07         | 0.090      | T    |
| OGLE-LMC-T2CEP-112 | RV Tau     | 39.397 7037 | 13.531              | 0.021      | 13.163                | 0.009          | 0.27   | 0.24         | 0.030      | S    |
| OGLE-LMC-T2CEP-080 | RV Tau     | 40.916 4131 | 13.957              | 0.027      | 13.253                | 0.047          | 0.44   | 0.42         | 0.040      | T    |
| OGLE-LMC-T2CEP-149 | RV Tau     | 42.480 6129 | 13.649              | 0.039      | 13.252                | 0.007          | 0.13   | 0.12         | 0.140      | T    |
| OGLE-LMC-T2CEP-032 | RV Tau     | 44.561 1948 | 13.232              | 0.030      | 12.212                | 0.090          | 0.36   | 0.34         | 0.050      | T    |
| OGLE-LMC-T2CEP-147 | RV Tau     | 46.795 8419 | 13.145              | 0.017      | 12.658                | 0.013          | 0.06   | 0.06         | 0.090      | T    |
| OGLE-LMC-T2CEP-174 | RV Tau     | 46.818 9562 | 13.089              | 0.016      | 12.048                | 0.030          | 0.46   | 0.44         | 0.150      | T    |
| OGLE-LMC-T2CEP-067 | RV Tau     | 48.231 7051 | 13.176              | 0.022      | 12.263                | 0.052          | 0.20   | 0.19         | 0.100      | T    |
| OGLE-LMC-T2CEP-075 | RV Tau     | 50.186 5686 | 13.900              | 0.110      | 13.502                | 0.033          | 0.78   | 0.74         | 0.070      | T    |
| OGLE-LMC-T2CEP-129 | RV Tau     | 62.508 9466 | 13.514              | 0.035      | 13.123                | 0.013          | 0.16   | 0.14         | 0.070      | S    |
| OGLE-LMC-T2CEP-045 | RV Tau     | 63.386 3391 | 13.098              | 0.024      | 12.664                | 0.021          | 0.16   | 0.15         | 0.070      | T    |

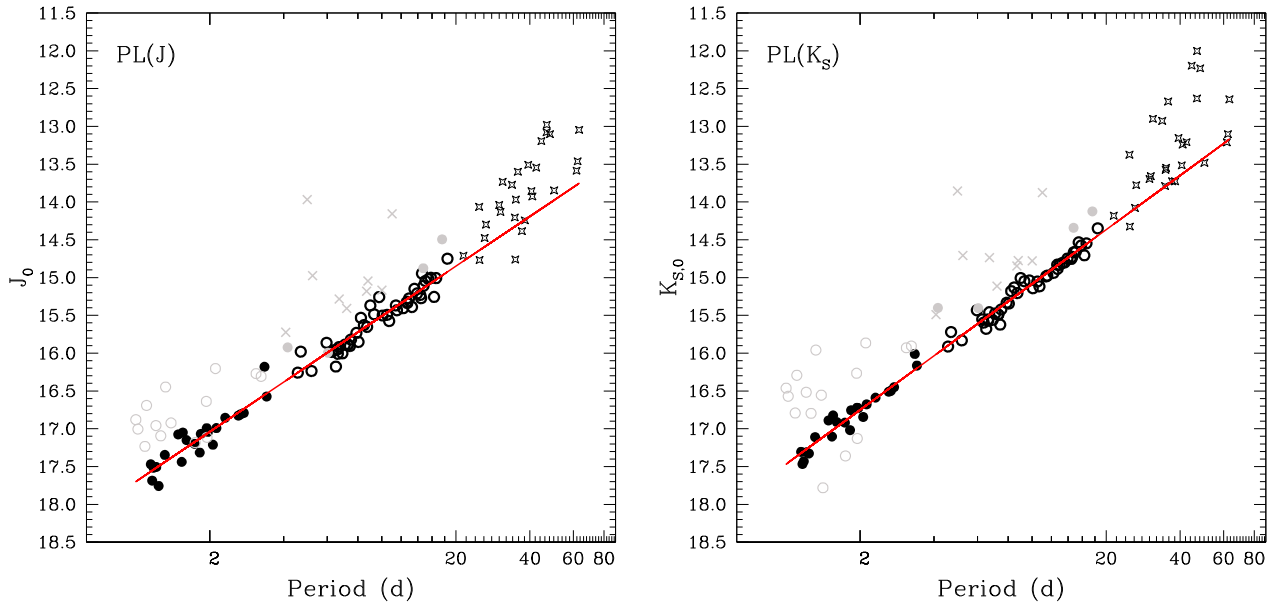


**Figure 5.**  $PL(J)$  and  $PL(K_s)$  relations for the T2CEPs investigated in this paper. The meaning of the symbols is the following: black filled and open circles are the BL Her and W Vir variables used in the derivation of the PL, PW and PLC relationships, respectively. Grey open and filled circles are the BL Her and W Vir variables discarded because of problems in the photometry (see the text). Grey crosses are the peculiar W Vir stars. The starred symbols represent the RV Tau variables. The size of the symbols is generally representative of the measurement errors. The solid lines represent the least-squares fit to the data shown in Table 5. We recall that RV Tau stars were not used in the calculation of the least-squares fits (see the text).

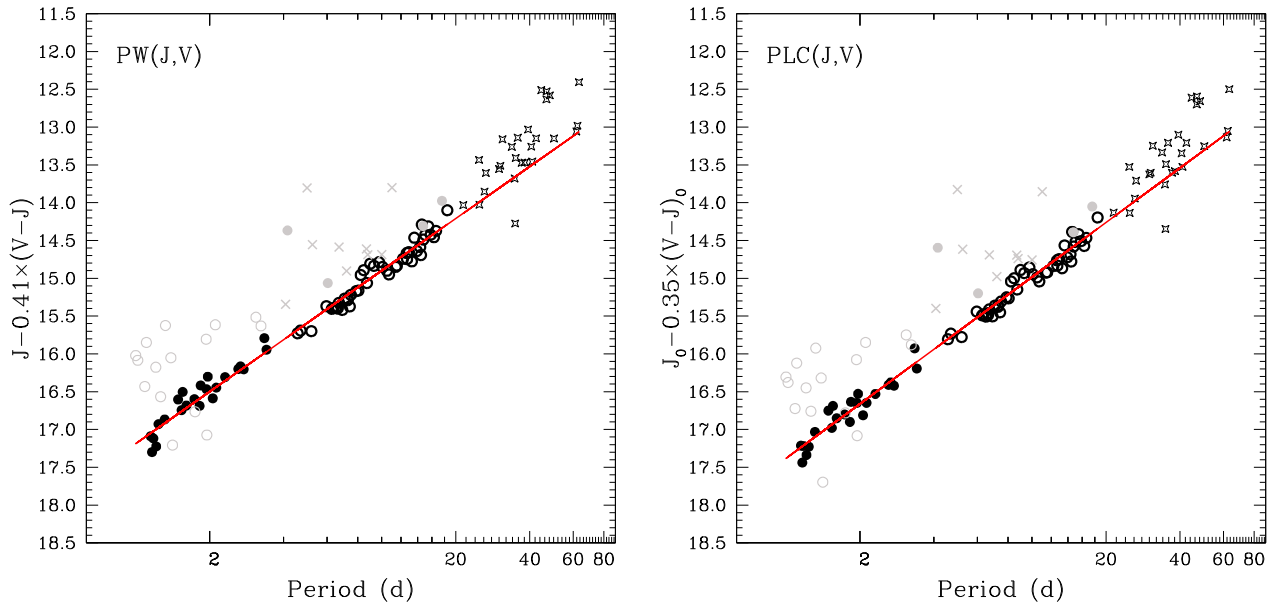


**Figure 6.**  $PW(J, V)$  and  $PLC(J, V)$  for the T2CEPs investigated in this paper. Symbols are as in Fig. 5.

both relations, the two variable classes seem to show results that agree with each other well within  $1\sigma$ , thus confirming that we can use BL Her and W Vir variables together.

For each combination of periods, magnitudes and colours, we performed independent least-squares fits to the data, adopting equations of the form reported in Table 5. The results of the fitting procedure are shown in the same table as well as in Figs 5–8 with a solid line. Note that the equations listed in Table 5 are given in terms of absolute magnitudes since we subtracted the dereddened distance modulus ( $DM_{0, LMC}$ ) of the LMC from each equation. Thus, the absolute ZP of the relations in Table 5 can

be simply obtained by using the preferred value for the  $DM_{0, LMC}$  value.

In deriving the equations of Table 5, we have implicitly neglected any dependence of both PL and PW relations on the metallicity of the pulsators. This is in agreement with Matsunaga et al. (2006), who found a hardly significant dependence of the PL relations on metallicity ( $0.1 \pm 0.06 \text{ mag dex}^{-1}$ ), whereas the theoretical models by Di Criscienzo et al. (2007) predict a very mild metallicity dependence  $\Delta \text{Mag}/\Delta [\text{Fe}/\text{H}] \sim 0.04\text{--}0.06 \text{ mag dex}^{-1}$  for both the PL and PW relations in the magnitudes and colours of interest. In any case, the very low dispersions of our PL and PW relations listed

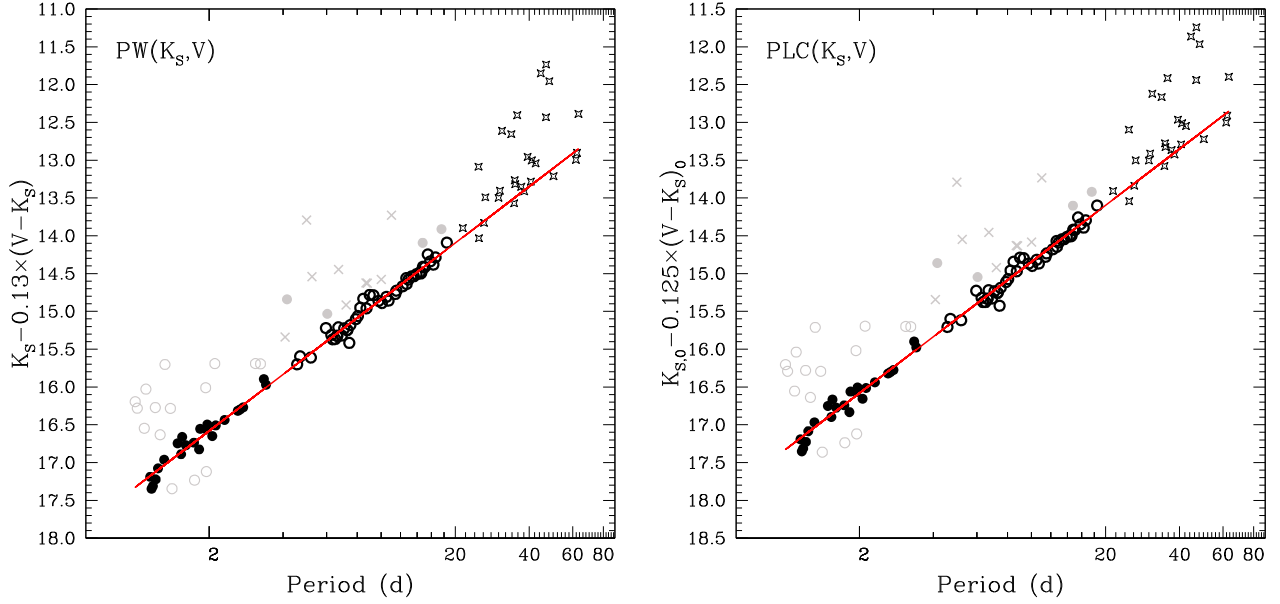


**Figure 7.**  $PW(K_s, V)$  and  $PLC(K_s, V)$  for the T2CEPs investigated in this paper. Symbols are as in Fig. 5.

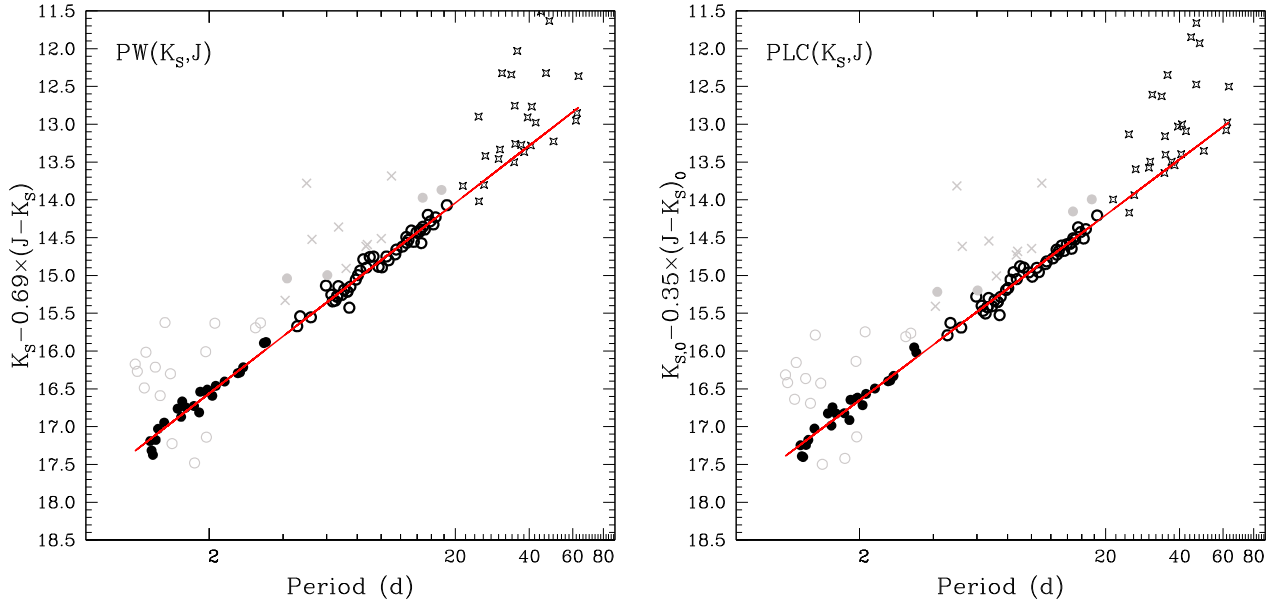


**Figure 8.**  $PW(K_s, J)$  and  $PLC(K_s, J)$  for the T2CEPs investigated in this paper. Symbols are as in Fig. 5.

in Table 5 seem to suggest that the metallicity dependence, if any, should be very small. Alternatively, a small dispersion in metallicity among our sample could explain the results as well. However, since the low-metallicity dependence found by Matsunaga et al. (2006) is based on T2CEPs spanning a wide range of  $[Fe/H]$ , the latter explanation is less likely.

In each figure, a number of stars are shown with grey symbols. They significantly deviate from almost all relationships discussed above. The crosses represent the stars classified by Soszyński et al. (2008) as peculiar W Vir (see column 4 in Table 2), i.e. suspected binaries that do not follow the optical PL and PW relations. We note that three of these peculiar W Vir stars, namely OGLE-LMC-T2CEP-021, 052 and 083, do not show any difference with respect to the normal W Vir stars in our PL, PW and PLC planes, and were hence included in the calculations. As for BL Her and W Vir, 15

and 4 stars of the two classes were not used in the least-squares fits because, with few exceptions, they show large scattering in almost all the relationships calculated here, and, in particular in the most reliable ones, namely the PWs and PLCs based on the  $K_s$ -band photometry. The finding charts for all these stars are displayed in Fig. 2, whereas the notes in Table 2 explain in detail the causes that led us to exclude these objects, with blending by close companions being the most common cause.

Table 5 deserves some discussion: (i) the dispersion of the  $PL(J)$  relation is, as expected, larger than for the  $PL(K_s)$ ; (ii) for any combination of magnitude and colour, the dispersions of PW and PLC are equal (this reflects the correctness of the reddening correction applied in this paper); (iii) the  $PW(J, V)$  and  $PLC(J, V)$  are significantly more dispersed than the  $PW(K_s, V)$ – $PLC(K_s, V)$  and  $PW(K_s, J)$ – $PLC(K_s, J)$  couples; (iv) the best combination of

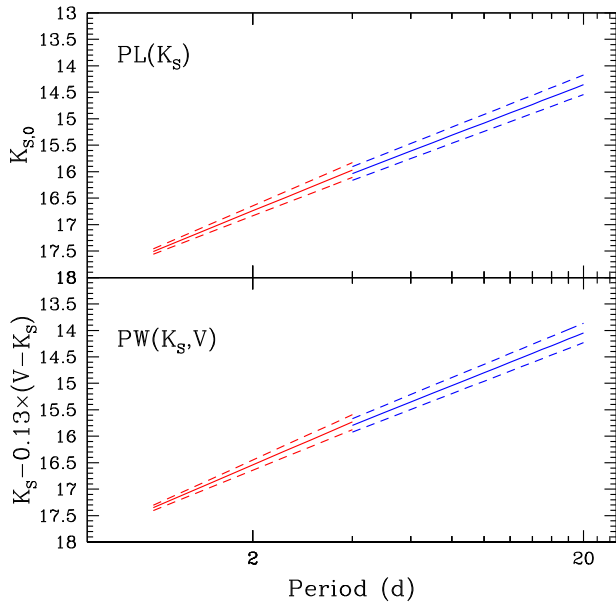


**Figure 9.** Top panel:  $PL(K_s)$  relation calculated separately for BL Her (red) and W Vir (blue) variables. The solid and dashed lines show the best-fits  $\pm 1\sigma$  error (both for slope and ZP), respectively. Bottom panel: as above but for the  $PW(K_s, J - K_s)$  relation.

magnitude and colour (lower dispersion) appears to be the  $K_s, V$ ; (v) the colour coefficients of the  $PW(K_s, V)$  and  $PLC(K_s, V)$  relations are very similar and the two relations are coincident. Similarly, for  $PW(J, V)$  and  $PLC(J, V)$ , the colour coefficients are the same within the errors, whereas this is not true for the couple  $PW(K_s, J) - PLC(K_s, J)$ .

#### 4 ABSOLUTE CALIBRATION OF PL, PLC AND PW RELATIONS

In Table 5, we provided the absolute ZP for the relevant PL, PLC and PW relations as a function of the  $DM_{0, LMC}$ . However, it is of considerable astrophysical interest to obtain an independent absolute calibration for at least some of these relations. Indeed, this would allow us to obtain an independent measure of the distance to the LMC and to the GGCs hosting T2CEP variables. To this aim, we can only rely on calibrators located close enough to the Sun to have a measurable parallax or whose distances have been estimated by Baade–Wesselink (BW) techniques (see Gaitschy 1987, for a review on this method). There are only two T2CEPs whose parallaxes were measured with reasonable accuracy with the *Hubble Space Telescope* (*HST*; Benedict et al. 2011), namely  $\kappa$  Pav (W Vir) and VY Pyx (BL Her). For two additional BL Her variables, SW

Tau and V533 Cen, as well as for  $\kappa$  Pav, a BW-based distance is also available (Feast et al. 2008). However, VY Pyx turned out to be a peculiar star, unusable as calibrator (see discussion in Benedict et al. 2011). As for  $\kappa$  Pav, the pulsational parallax estimated by Feast et al. (2008) through BW analysis is about  $2\sigma$  smaller than the trigonometric parallax measured by *HST* and adopted here ( $\Delta\pi = 0.67 \pm 0.33$  mas). Feast et al. (2008) investigated the possible causes of the discrepancy with respect to the *Hipparcos* parallax (van Leeuwen 2007), which was even larger than the *HST* one, but did not find any definitive explanation. A well-known potential problem related with the application of the BW technique is the uncertainty on the projection factor  $p$  (see e.g. Molinaro et al. 2012; Nardetto et al. 2014, and references therein). In their analysis, Feast et al. (2008) derived and adopted a fixed  $p$ -factor  $= 1.23 \pm 0.03$ . However, several researchers suggested that the  $p$ -factor actually does depend on the period of the pulsator (see e.g. Barnes 2009; Laney & Jone 2009; Storm et al. 2011a; Nardetto et al. 2014, and references therein); hence, for example, different  $p$ -factor values should be used for BL Her and W Vir stars. Given the uncertainties on the projection factor discussed above, in the following, we will adopt the *HST*-based distance for  $\kappa$  Pav, and the ZP of the different PL, PW and PLC relations will be estimated including or not the BW-based distances for SW Tau and V533 Cen. Finally, we note that  $[Fe/H](\kappa \text{ Pav}) \approx +0.0$  dex (Feast et al. 2008), i.e. at least 1 dex more metal rich than expected for typical T2CEPs. Hence, some additional uncertainty when using this object as a distance indicator can be caused by a possible metallicity effect. However, as discussed in Section 3, the metal dependence of the T2CEP PLs, if any, should be very small, and we do not expect the high metallicity of  $\kappa$  Pav to be an issue for our purposes. To enlarge the number of reliable calibrators, a possibility is to use the five RR Lyrae stars whose parallaxes were measured with *HST* by Benedict et al. (2011). Indeed, as already hypothesized by Sollima, Cacciari & Valenti (2006) and Feast et al. (2008), RR Lyrae and T2CEPs follow the same  $PL(K_s)$  relation (Caputo et al. 2004 found similar results in the optical bands). To further test this possibility, we draw in Fig. 10 the  $PL(K_s)$  and  $PW(K_s)$  relations for the T2CEPs analysed in this paper, in comparison with the location occupied in the same planes by the RR Lyrae stars in the LMC (light blue filled circles, after Borissova et al. 2009). The periods of c-type RR Lyrae stars were fundamentalized by adding  $\delta \log P = 0.127$  (Bono et al. 1997a) and the magnitudes have been corrected for the metallicity term devised by Sollima et al. (2006), using the individual metallicity measurement compiled by Borissova et al. (2009). It can be seen that both the  $PL(K_s)$  and  $PW(K_s)$  relations (red lines) derived for T2CEPs in Section 5 tightly match the location of the RR Lyrae stars. On this basis, we decided to proceed using also the RR Lyrae with *HST* parallax to anchor the ZP of the  $PL(K_s)$  and  $PW(K_s, V)$  relations for T2CEPs. To this aim, we simply adopted the slopes of

**Table 5.** Relevant relationships derived in this work. Note that all the results are in the VISTA photometric system.  $DM_{0, LMC}$  stands for the LMC dereddened DM.

| Method        | Relation                                                                                              | rms (mag) |
|---------------|-------------------------------------------------------------------------------------------------------|-----------|
| $PL(J)$       | $M_{J,0} = (-2.19 \pm 0.04) \log P + (17.700 \pm 0.035) - DM_{0, LMC}$                                | 0.13      |
| $PL(K_s)$     | $M_{K_s,0} = (-2.385 \pm 0.03) \log P + (17.47 \pm 0.02) - DM_{0, LMC}$                               | 0.09      |
| $PW(J, V)$    | $M_J - 0.41(V - J) = (-2.290 \pm 0.035) \log P + (17.19 \pm 0.03) - DM_{0, LMC}$                      | 0.11      |
| $PLC(J, V)$   | $M_{J,0} = (-2.40 \pm 0.05) \log P + (0.35 \pm 0.07)(V - J)_0 + (17.385 \pm 0.065) - DM_{0, LMC}$     | 0.11      |
| $PW(K_s, V)$  | $M_{K_s} - 0.13(V - K_s) = (-2.49 \pm 0.03) \log P + (17.33 \pm 0.02) - DM_{0, LMC}$                  | 0.08      |
| $PLC(K_s, V)$ | $M_{K_s,0} = (-2.48 \pm 0.04) \log P + (0.125 \pm 0.040)(V - K_s)_0 + (17.33 \pm 0.05) - DM_{0, LMC}$ | 0.08      |
| $PW(K_s, J)$  | $M_{K_s} - 0.69(J - K_s) = (-2.52 \pm 0.03) \log P + (17.320 \pm 0.025) - DM_{0, LMC}$                | 0.085     |
| $PLC(K_s, J)$ | $M_{K_s,0} = (-2.45 \pm 0.04) \log P + (0.35 \pm 0.14)(J - K_s)_0 + (17.39 \pm 0.04) - DM_{0, LMC}$   | 0.085     |

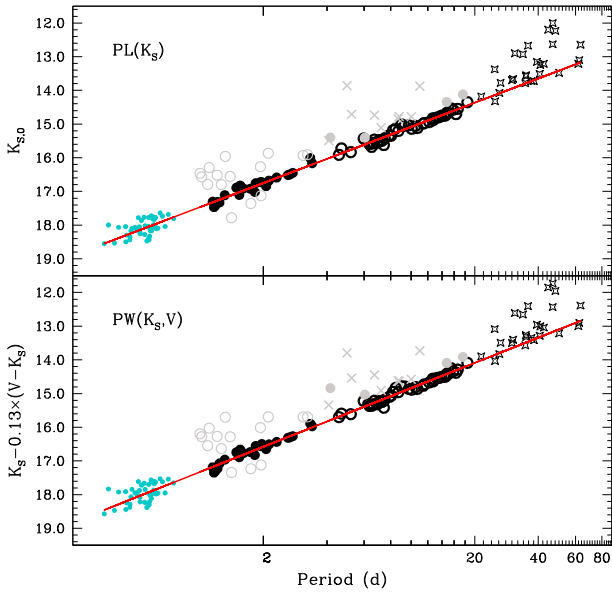


**Figure 10.** PL( $K_s$ ) and PW( $K_s, V$ ) relations for the T2CEPs analysed in this paper (symbols as in Fig. 5) and for the sample of RR Lyrae stars in the LMC observed by Borissova et al. (2009, light blue filled circles). The red lines show the relationships listed in Table 5 extended till the periods of the RR Lyrae stars.

the quoted relations from Table 5, corrected for metallicity the ZP for the five RR Lyrae stars with *HST* parallaxes and calculated the weighted average of the results in two cases: (i) including only stars with *HST* parallax, namely,  $\kappa$  Pav and the five RR Lyrae stars; (ii) using the stars at point (i) plus the two T2CEPs with BW analysis, namely SW Tau and V533 Cen.<sup>8</sup> The results of these procedures are outlined in Table 6 (columns 3 and 4) and in Fig. 11. For comparison, column (2) of Table 6 shows the ZPs obtained assuming  $DM_{0, LMC} = 18.46 \pm 0.03$  mag, as derived by Ripepi et al. (2012b) from LMC CC stars. We choose the work by Ripepi et al. (2012b) as reference for CCs because (i) these authors adopted a procedure similar to the one adopted in this work; (ii) their results are in excellent agreement with the most recent and accurate literature findings (see e.g. Storm et al. 2011b; Joner & Laney 2012; Laney et al. 2012; Walker 2012; Pietrzyński et al. 2013; de Grijs et al. 2014, and references therein). An analysis of Table 6 reveals that (i) the inclusion of the two stars with BW-based distances does not change significantly the ZPs and (ii) there is a difference of at least  $\sim 0.1$  mag between the ZPs calibrated on the basis of CCs and of Galactic T2CEPs (see Section 5).

#### 4.1 Comparison with the literature

The relationships presented in Tables 5 and 6 can now be compared to those available in the literature. As mentioned in the introduction, Matsunaga et al. (2006, 2009) published the PL relations in the  $JHK_s$  bands for BL Her and W Vir variables hosted by GGCs and the LMC, respectively. These results can be compared with ours, provided that we first transform all the  $J$  and  $K_s$  magnitudes into the VISTA system. With this aim, we transformed the Matsunaga et al. (2006) photometry from 2MASS to VISTA using the equations reported in Section 2.1. The results of Matsunaga

et al. (2009) are in the IRSF system, whose  $J$  and  $K_s$  can in principle be transformed to the 2MASS system (Kato et al. 2007), and in turn, into the VISTA system. However, this is not possible for the  $J$  band, because we lack  $H$ -band photometry (see table 10 in Kato et al. 2007). We can safely overcome this problem by noting that the  $(J - H)$  colour for BL Her and W Vir stars spans a very narrow range ( $0.25 < (J - H) < 0.4$  mag; see e.g. Matsunaga et al. 2011) so that, according to Kato et al. (2007), we can assume  $J(\text{IRSF}) = J(2\text{MASS}) + (0.005 \pm 0.005)$ . Finally, since our targets span the range  $0.25 < (J - K_s) < 0.6$  mag, we obtained  $J(\text{IRSF}) = J(\text{VISTA}) + (0.035 \pm 0.015)$ . As for the  $K_s$ , the transformation is straightforward:  $K_s(\text{IRSF}) = K_s(\text{VISTA}) + (0.014 \pm 0.001)$ .

The PL relations by Matsunaga et al. (2006, 2009), corrected as discussed above, are presented in the first four rows of Table 7. We can compare directly the PL( $J$ ) and PL( $K_s$ ) relations for the LMC (lines 2 and 4 in Table 7) with our results (lines 1 and 2 in Table 5). There is very good agreement within  $1\sigma$  errors for the PL( $J$ ), whereas for the PL( $K_s$ ), the comparison is slightly worse, especially concerning the slope of the relation which is discrepant at the  $1.5\sigma$  level. It is also worth mentioning that the dispersion of our relations is significantly smaller, as a result of the much better light-curve sampling of the VMC data.

As for the PL( $J$ ) and PL( $K_s$ ) derived for GGCs by Matsunaga et al. (2006), their slopes are in very good agreement with ours, which suggest a ‘universal slope’ in the NIR filters, independent of the galactic environment. As for the ZPs, we can only compare them for the PL( $K_s$ ) relations (see Table 6). We found excellent agreement when the ZP is calibrated through the Galactic calibrators (irrespective of whether stars with BW measures are included or not), whereas there is a 0.12 mag discrepancy if the ZP is calibrated by means of the LMC DM coming from CCs. This occurrence is not surprising, since Matsunaga et al. (2006) used the  $M_V$  versus  $[\text{Fe}/\text{H}]$  relation for RR Lyrae variables by Gratton et al. (2003) to estimate the distances of the GGCs hosting T2CEPs and derive their PL( $K_s$ ). Hence, the two Population II calibrators, RR Lyrae and T2CEPs, give distance scales in agreement with each other.

A similar comparison can be performed with the theoretical predictions by Di Criscienzo et al. (2007), who in addition calculated the PWs for all the combinations of magnitudes and colours of interest in this work. Again, we converted the Di Criscienzo et al. (2007) results from Bessell & Brett (1988, BB) to the VISTA system. To do this, we used the transformations BB-2MASS from Carpenter (2001) and 2MASS-VISTA (see Section 2.1) and the same procedure as above to derive  $J(\text{BB}) = J(\text{VISTA}) + (0.04 \pm 0.010)$  and  $K_s(\text{BB}) = K_s(\text{VISTA}) + (0.030 \pm 0.015)$ . Secondly, since the predicted PL and PW relations mildly depend on metallicity and adopted a mixing length parameter ( $\alpha^9$ ), we have to make a choice for these parameters. We decided to evaluate the relations for  $\alpha = 1.5 \pm 0.5$  (to encompass reasonable values for  $\alpha$ ) and  $[\text{Fe}/\text{H}] = -1.5 \pm 0.3$  dex as an average value for the LMC old population (see e.g. Borissova et al. 2004, 2006; Gratton et al. 2004; Haschke et al. 2012). The uncertainties on these parameters were taken into account in re-deriving the ZP of the predicted PL and PW relations in the VISTA system. The result of this procedure is shown in the second part of Table 7. A comparison with

<sup>8</sup> The uncertainties on the DM of these two objects were obtained by summing the uncertainties reported in table 4 of Feast et al. (2008).

<sup>9</sup>  $\alpha = l/H_p$  is the ratio between the mean free path of a convective element ( $l$ ) and the pressure scale height ( $H_p$ ). Varying this parameter strongly affects the properties of a star’s outer envelope such as its radius and effective temperature.

**Table 6.** PL( $K_s$ ) and PW( $K_s$ ) relations for LMC T2CEPs with the ZP calibrated as follows: (2) by imposing a  $DM_{0, LMC} = 18.46 \pm 0.03$  mag (from CCs in the LMC; Ripepi et al. 2012b) in Table 5; (3) by adopting Galactic T2CEP ( $\kappa$  Pav) and RR Lyrae variables with *HST* parallaxes (Benedict et al. 2011) and T2CEPs with BW distance estimates (Feast et al. 2008); (4) by adopting only calibrators with the quoted *HST* parallaxes. See the text for additional details.

| Relation<br>(1)                                      | ZP <sub>CC</sub><br>(2) | ZP <sub><math>\pi</math> + BW</sub><br>(3) | ZP <sub><math>\pi</math></sub><br>(4) |
|------------------------------------------------------|-------------------------|--------------------------------------------|---------------------------------------|
| $K_{s,0} = (-2.385 \pm 0.03) \log P + ZP$            | $-0.99 \pm 0.04$        | $-1.09 \pm 0.10$                           | $-1.11 \pm 0.10$                      |
| $K_s - 0.13(V - K_s) = (-2.49 \pm 0.03) \log P + ZP$ | $-1.13 \pm 0.04$        | $-1.24 \pm 0.10$                           | $-1.26 \pm 0.10$                      |

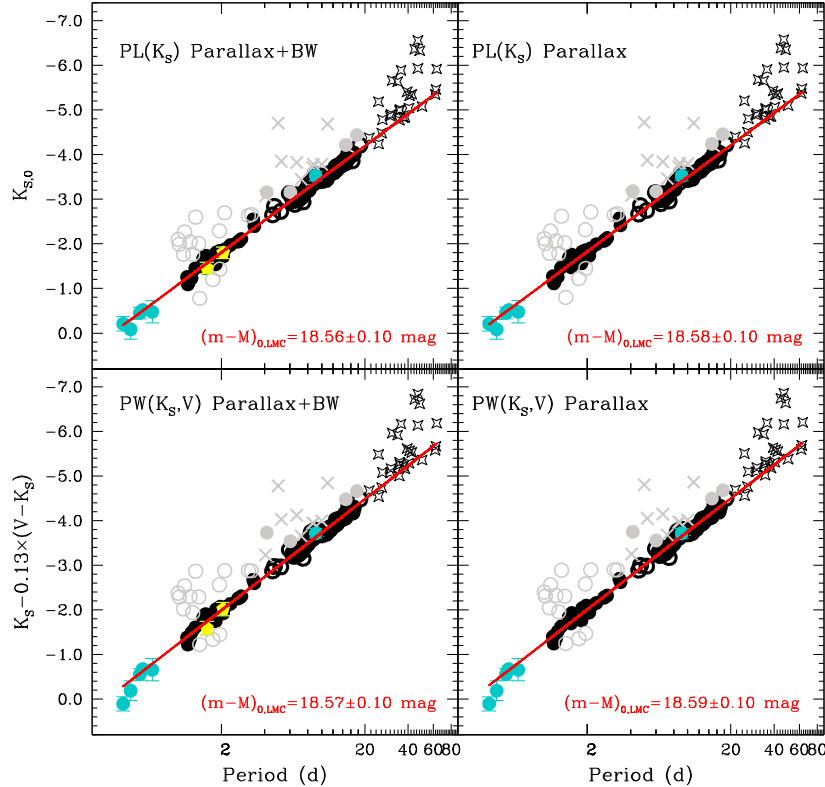


**Figure 11.** Absolute PL( $K_s$ ) and PW( $K_s, V$ ) relations for the T2CEPs analysed in this paper (symbols as in Fig. 5). Light blue and yellow filled circles show the objects whose distances were measured through *HST* parallaxes (Benedict et al. 2011) or through BW analysis (Feast et al. 2008), respectively. The red line shows the best-fitting line to the data adopting the slope from Table 5, while ZPs were calculated using the objects with *HST* parallaxes alone (right-hand panels), and by adding to them the objects with BW analysis (left-hand panels). The true DMs estimated in each case for the LMC are also labelled (see Section 5).

Table 6 shows that both for the PL( $K_s$ ) and PW( $K_s, V$ ) relations, there is excellent agreement between ours and theoretical results if the quoted relationships are calibrated with the Galactic T2CEPs and RR Lyrae, whereas there is an  $\sim 0.1$  mag discrepancy if we adopt the CC-based DM by Ripepi et al. (2012b) for the LMC to define the ZP. However, if we take into account the uncertainties, this discrepancy results formally not significant within  $1\sigma$ .

## 5 DISCUSSION

The results reported in Section 4 allow us to discuss the distance of the LMC as estimated from NIR observation of the T2CEPs hosted in this galaxy. Table 8 (columns 3 and 4) lists the  $DM_{0, LMC}$  calculated using the different ZP estimates for the PL( $K_s$ ) and PW( $K_s, V$ ) relations listed in Table 6. An inspection of the table reveals that the  $DM_{0, LMC}$  calculated by means of CCs (column 2 in Table 8) and by means of the T2CEPs differ by more than  $\sim 0.1$  mag, even if,

formally, there is agreement within  $1\sigma$ . Since both the Ripepi et al. (2012b) calibration for CCs and that presented here for T2CEPs are based on a weighted mix of *HST* parallaxes and BW analysis, this discrepancy, albeit only partially significant, seems to suggest that the distance scales calibrated on pulsating stars belonging to Population I and Population II give different results (for a recent comprehensive review of the literature and a discussion about this argument, see de Grijs et al. 2014).

An additional application of the absolute PL( $K_s$ ) relation for T2CEPs concerns the distance estimate of GGCs hosting such kind of pulsators. Homogeneous  $K_s$  photometry, as well as period of pulsation for most of the known T2CEPs in GGCs, was published by Matsunaga et al. (2006, see their table 2). We simply inserted the period of these variables in the PL( $K_s$ ) of Table 6, and by difference with the observed magnitudes, we derived the DM for each GGC. When more than one T2CEP was present in a cluster, we averaged the resulting DMs (we excluded from the calculations the variables

**Table 7.** Values for the coefficients of the PL, PW and PLC relations for BL Her and W Vir Cepheids taken from the literature. The PW functions are defined as in Table 5. The errors of ZP take into account the uncertainties in the transformation of the  $J$  and  $K_s$  photometry to the VISTA system (see the text for details).

| Method                                                                   | Relation                                                              | $\sigma$ (mag) |
|--------------------------------------------------------------------------|-----------------------------------------------------------------------|----------------|
| Results by Matsunaga et al. (2006, 2009) transformed to the VISTA system |                                                                       |                |
| PL( $J$ ) GCs                                                            | $M_{J,0} = (-2.23 \pm 0.05) \log P - (0.84 \pm 0.03)$                 | 0.16           |
| PL( $J$ ) LMC                                                            | $J_0 = (-2.16 \pm 0.04) \log P + (17.76 \pm 0.03)$                    | 0.21           |
| PL( $K_s$ ) GCs                                                          | $M_{K_s,0} = (-2.41 \pm 0.05) \log P - (1.11 \pm 0.03)$               | 0.14           |
| PL( $K_s$ ) LMC                                                          | $K_{s,0} = (-2.28 \pm 0.05) \log P + (17.40 \pm 0.03)$                | 0.21           |
| Results by Di Criscienzo et al. (2007) transformed to the VISTA system   |                                                                       |                |
| PL( $J$ )                                                                | $M_{J,0} = (-2.29 \pm 0.04) \log P - (0.73 \pm 0.13)$                 |                |
| PL( $K_s$ )                                                              | $M_{K_s,0} = (-2.38 \pm 0.02) \log P - (1.10 \pm 0.07)$               |                |
| PW( $J$ , $V$ )                                                          | $M_J - 0.41(V - J) = (-2.37 \pm 0.02) \log P - (1.15 \pm 0.08)$       |                |
| PW( $K_s$ , $V$ )                                                        | $M_{K_s} - 0.13(V - K_s) = (-2.52 \pm 0.02) \log P - (1.25 \pm 0.08)$ |                |
| PW( $K_s$ , $J$ )                                                        | $K_s - 0.69(J - K_s) = (-2.60 \pm 0.02) \log P - (1.27 \pm 0.08)$     |                |

**Table 8.** DM of the LMC estimated on the basis of the different PL( $K_s$ ) and PW( $K_s$ ) relations described in Table 6 (see the text).

| Relation<br>(1)   | DM <sub>CC</sub> <sup>LMC</sup><br>(2) | DM <sub><math>\pi</math>+BW</sub> <sup>LMC</sup><br>(3) | DM <sub><math>\pi</math></sub> <sup>LMC</sup><br>(4) |
|-------------------|----------------------------------------|---------------------------------------------------------|------------------------------------------------------|
| PL( $K_s$ )       | $18.46 \pm 0.04$                       | $18.56 \pm 0.10$                                        | $18.58 \pm 0.10$                                     |
| PW( $K_s$ , $V$ ) | $18.46 \pm 0.04$                       | $18.57 \pm 0.10$                                        | $18.59 \pm 0.10$                                     |

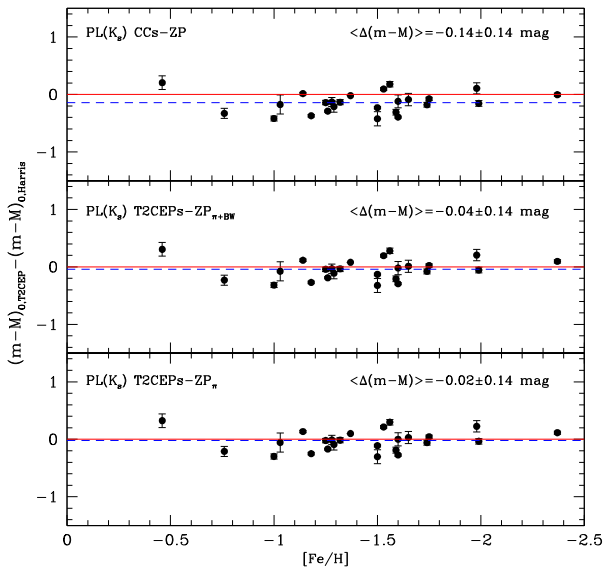


**Figure 12.** DM differences (this work–Harris 1996) for a sample of GGCs hosting T2CEPs as a function of  $[\text{Fe}/\text{H}]$ . The dashed blue line shows the average difference. The solid red line shows the line with zero difference. The DMs for the GGCs were estimated adopting the PL( $K_s$ ) for T2CEPs and ZP determined as follows: (top panel) on the basis of the  $\text{DM}_{0,\text{LMC}}$  measured by Ripepi et al. (2012b) using LMC CC with VMC NIR data; (middle panel) by means of a sample of Galactic T2CEPs whose distances were measured both through *HST* parallaxes (Benedict et al. 2011) and BW technique (Feast et al. 2008); (bottom panel) as in the previous case, but using objects with *HST* parallaxes only.

with periods longer than about 35 d because they are likely neither BL Her nor W Vir variables). The result of such a procedure is shown in Fig. 12 where for each GGC analysed here, we show (as a function of the metal content of the clusters) the difference between the DMs

estimated on the basis of the three different calibration of the PL( $K_s$ ) listed in Table 6 and the DMs reported by Harris (1996) in his catalogue of GGC parameters. In Fig. 12, the average discrepancy in DMs decreases from top to bottom, suggesting that, even if the statistical significance is low (due to the large dispersion in  $\Delta\text{DM}$  values  $\sim 0.14$  mag), the distance scale of GGCs, if estimated on the basis of the T2CEPs hosted in this system, is more consistent with Population II rather than Population I standard candles. This is not particularly surprising since most of the distances of GGCs in the Harris catalogue are based on RR Lyrae stars.

## 6 SUMMARY

In the context of the VMC survey, this paper shows the first results concerning T2CEPs in the LMC. We presented  $J$  and  $K_s$  light curves for 130 pulsators, including 41 BL Her, 62 W Vir (12 pW Vir) and 27 RV Tau variables, corresponding to 63, 63 (75 per cent) and 61 per cent of the known LMC populations of the three variable classes, respectively. The  $K_s$ -band light curves are almost always well sampled, allowing us to obtain accurate spline fits to the data and, in turn, precise intensity-averaged  $\langle K_s \rangle$  magnitudes for 120 variables in our sample. As for the  $J$  band, only about 1/3 of the  $J$  light curves were sufficiently sampled to allow a satisfactory spline fit to the data, and for the remaining 2/3 of pulsators, the intensity-averaged  $\langle J \rangle$  magnitudes were derived using the  $K_s$ -band spline fits as templates. On the basis of this data set for BL Her and W Vir, complemented by the  $\langle V \rangle$  magnitudes from the OGLE survey, we have built for the first time (apart from PL( $J$ ) and PL( $K_s$ )) a variety of empirical PL, PLC and PW relationships, for any combination of the  $V$ ,  $J$ ,  $K_s$  filters. Several outliers were removed from the calculation of these relations, and we provided an explanation for the presence of these divergent objects. All the quoted PL, PLC and PW relationships were calibrated in terms of the LMC distance. However, the availability of absolute  $M_V$  and  $M_{K_s}$  for a small sample of RR Lyrae and T2CEPs variables based on *HST* parallaxes allowed us to obtain an independent absolute calibration of the PL( $K_s$ ) and PW( $K_s$ ,  $V$ ) relationships [the PLC( $K_s$ ,  $V$ ) is identical to the PW( $K_s$ ,  $V$ )]. If applied to the LMC and to the GGCs hosting T2CEPs, these relations give DMs which are around 0.1 mag longer than those estimated for CCs by means of *HST* parallaxes and BW techniques. However, if we take into account the uncertainties at their face value, the quoted discrepancy is formally not significant within  $1\sigma$ .

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# APPENDIX A: LIGHT CURVES

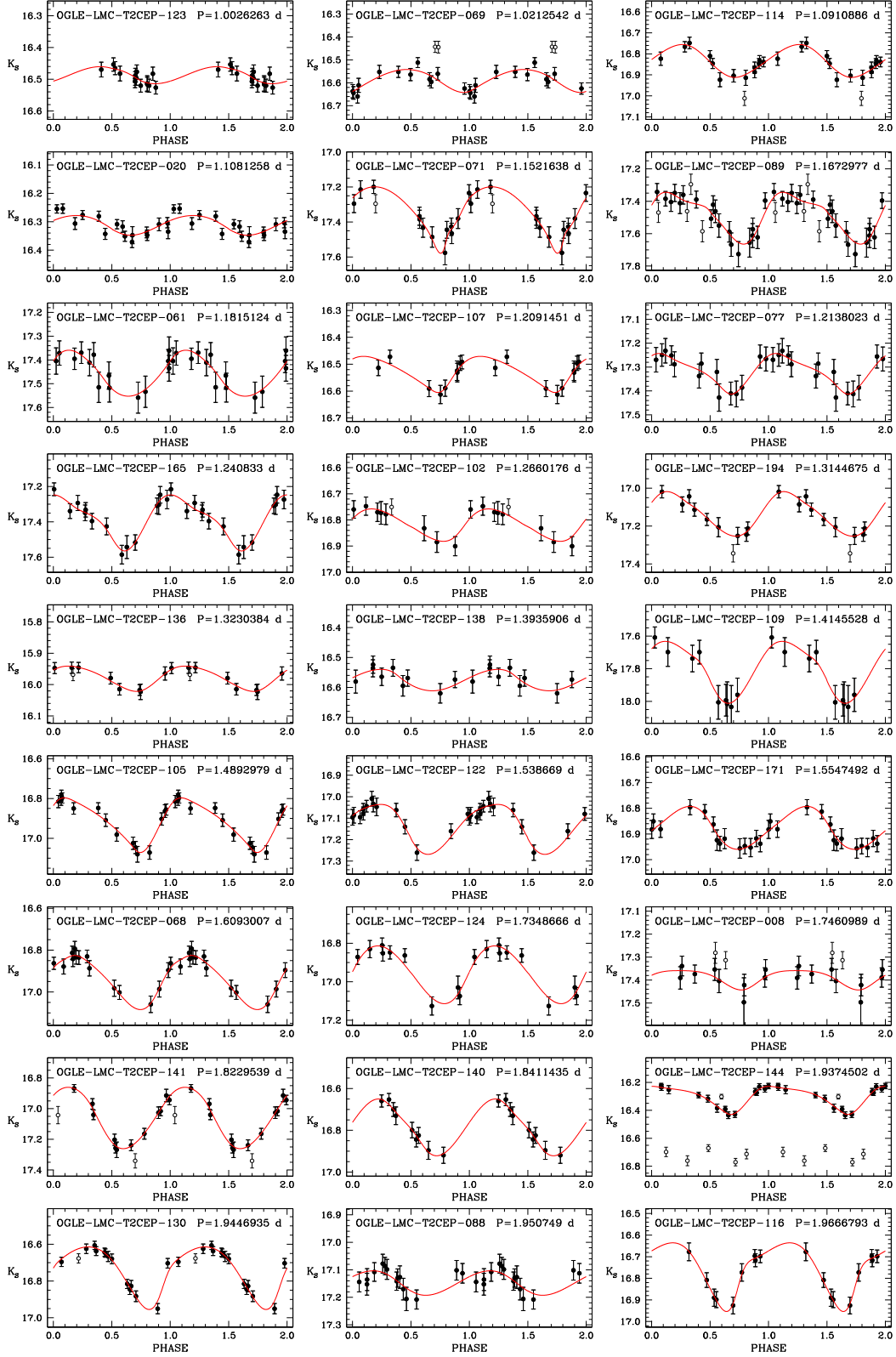


**Figure A1.**  $K_s$ -band light curves for T2CEPs with usable data discussed in this paper. Stars are displayed in order of increasing period. Filled and open circles represent phase points used or not used in the fitting procedure, respectively. Solid lines represent best-fitting splines to the data (see the text). In each panel, we report OGLE's identification number and period.

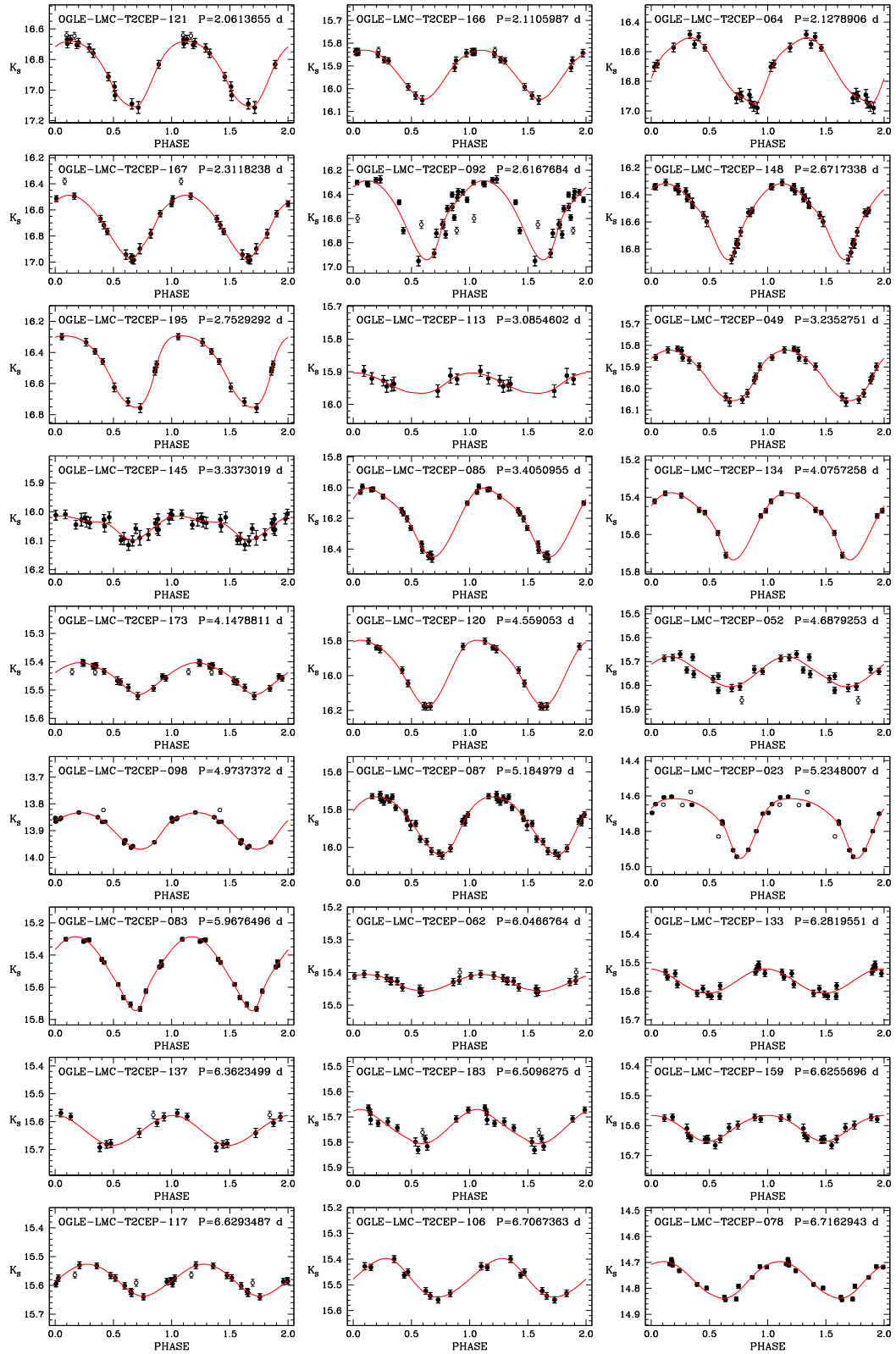


Figure A1 – continued

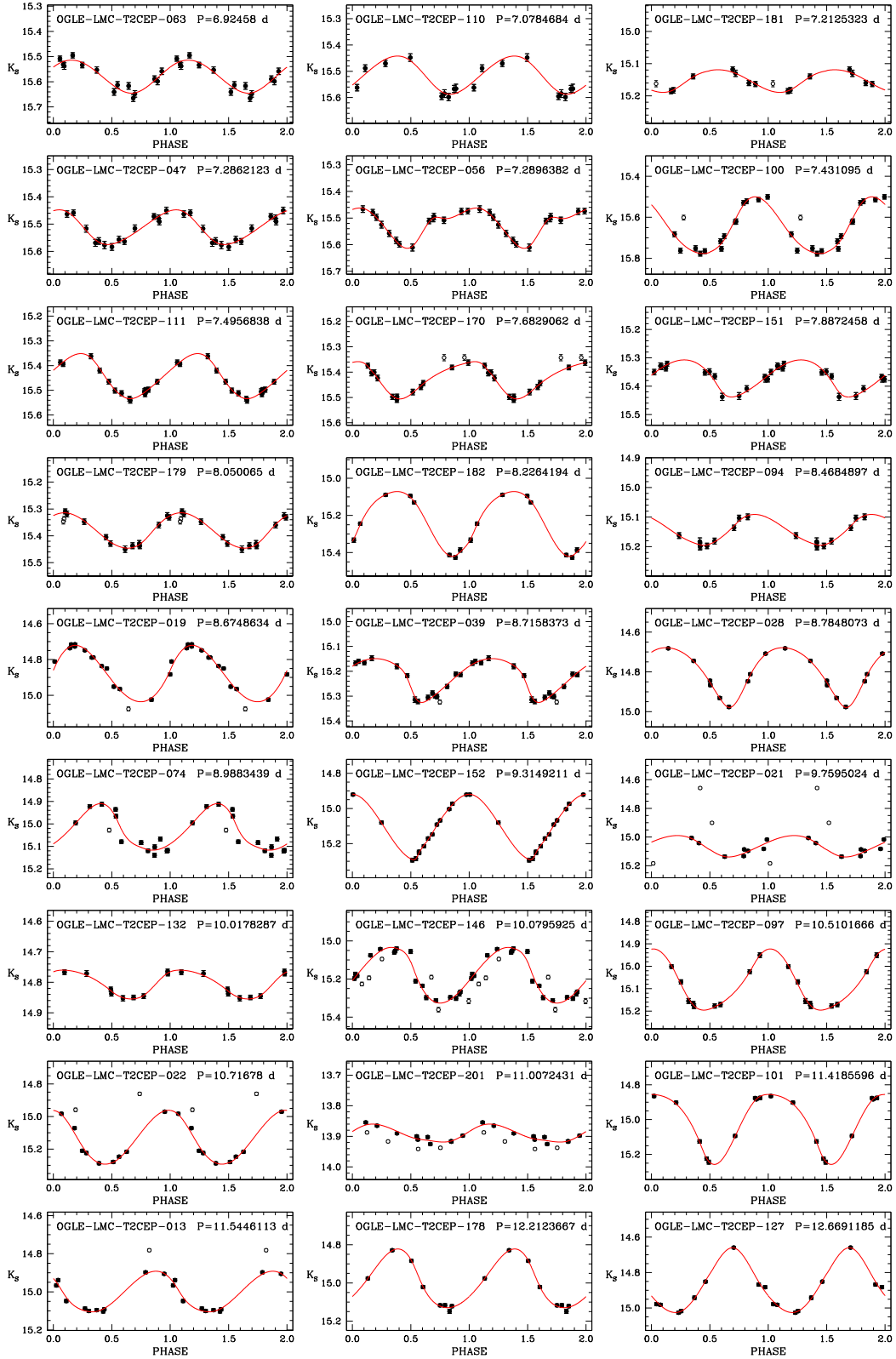


Figure A1 – continued

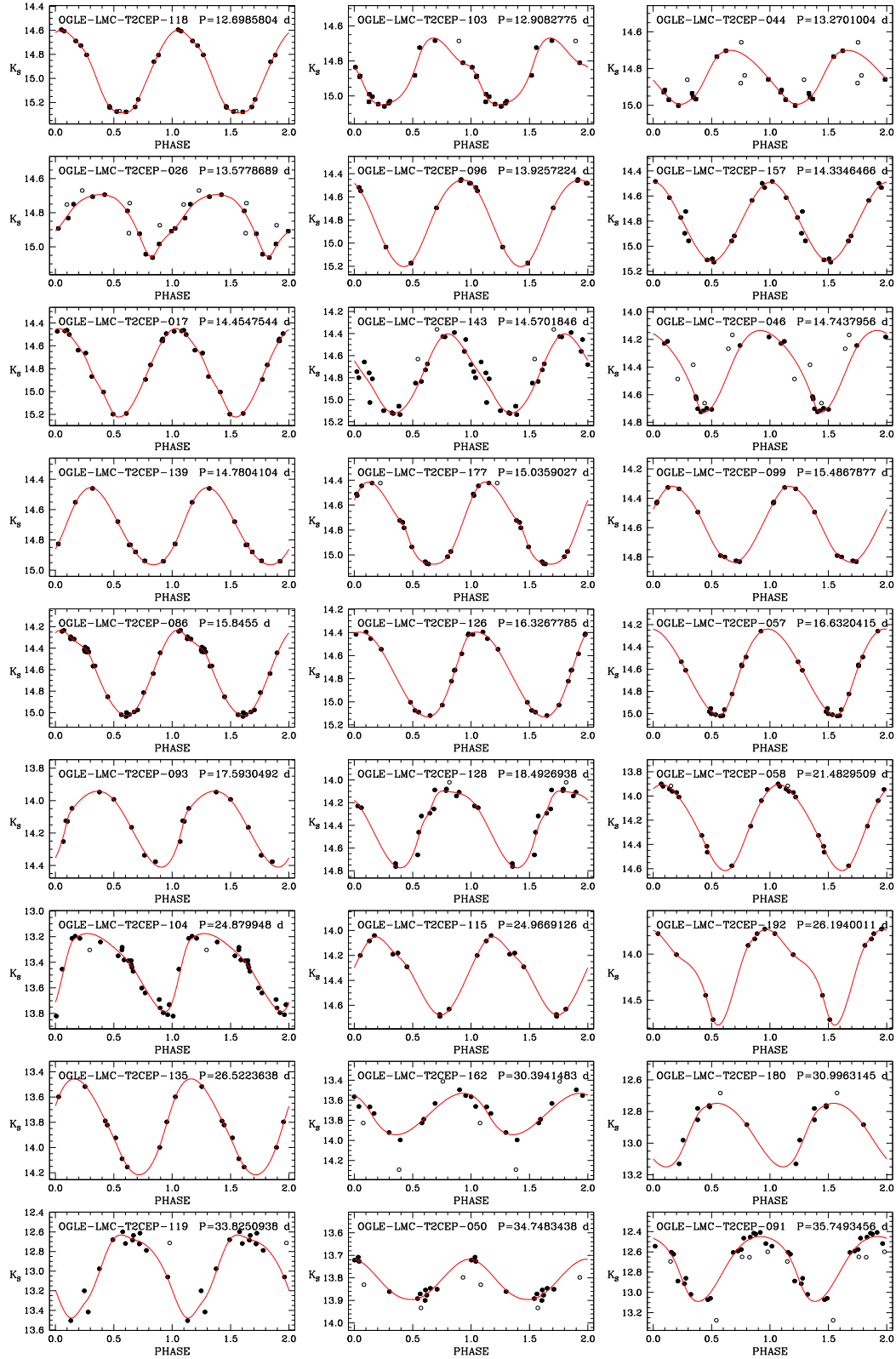


Figure A1 – continued

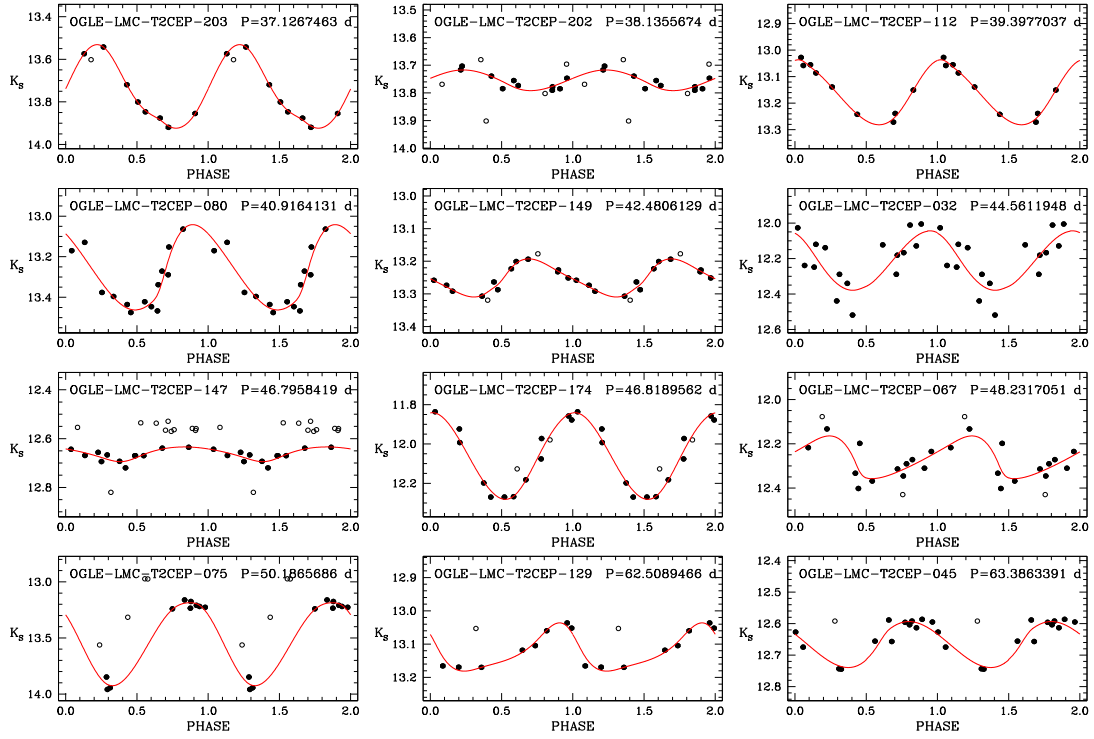
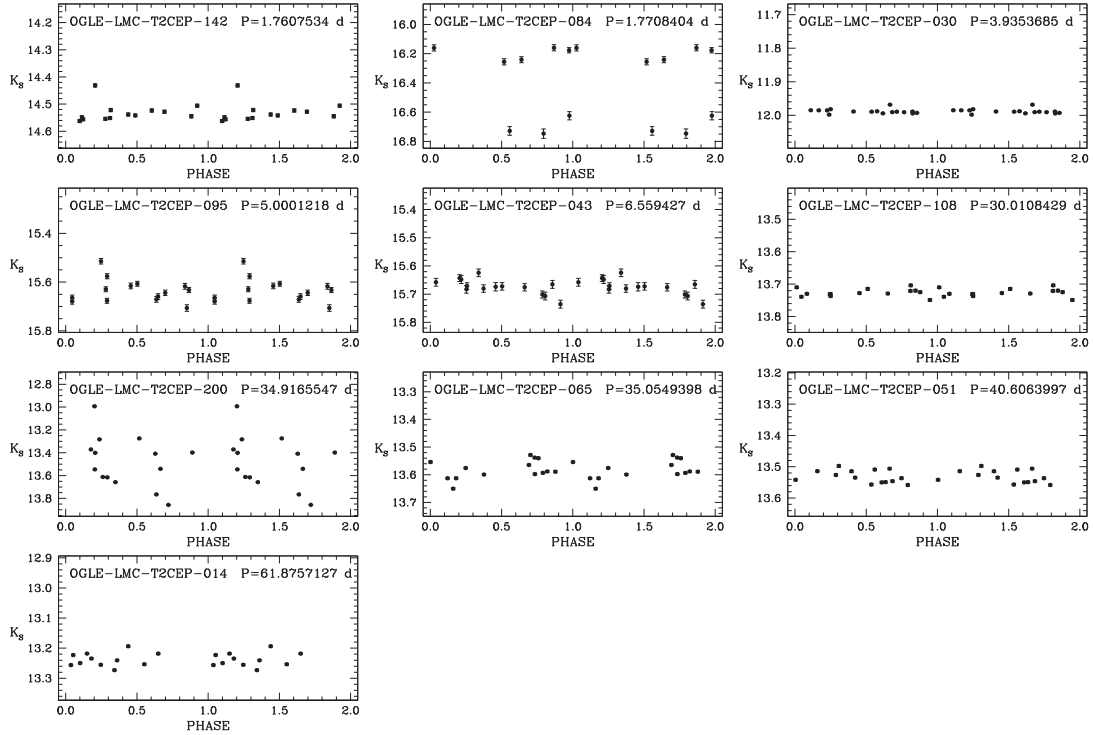


Figure A1 – continued


 Figure A2.  $K_s$ -band light curves for problematic stars (see the text).

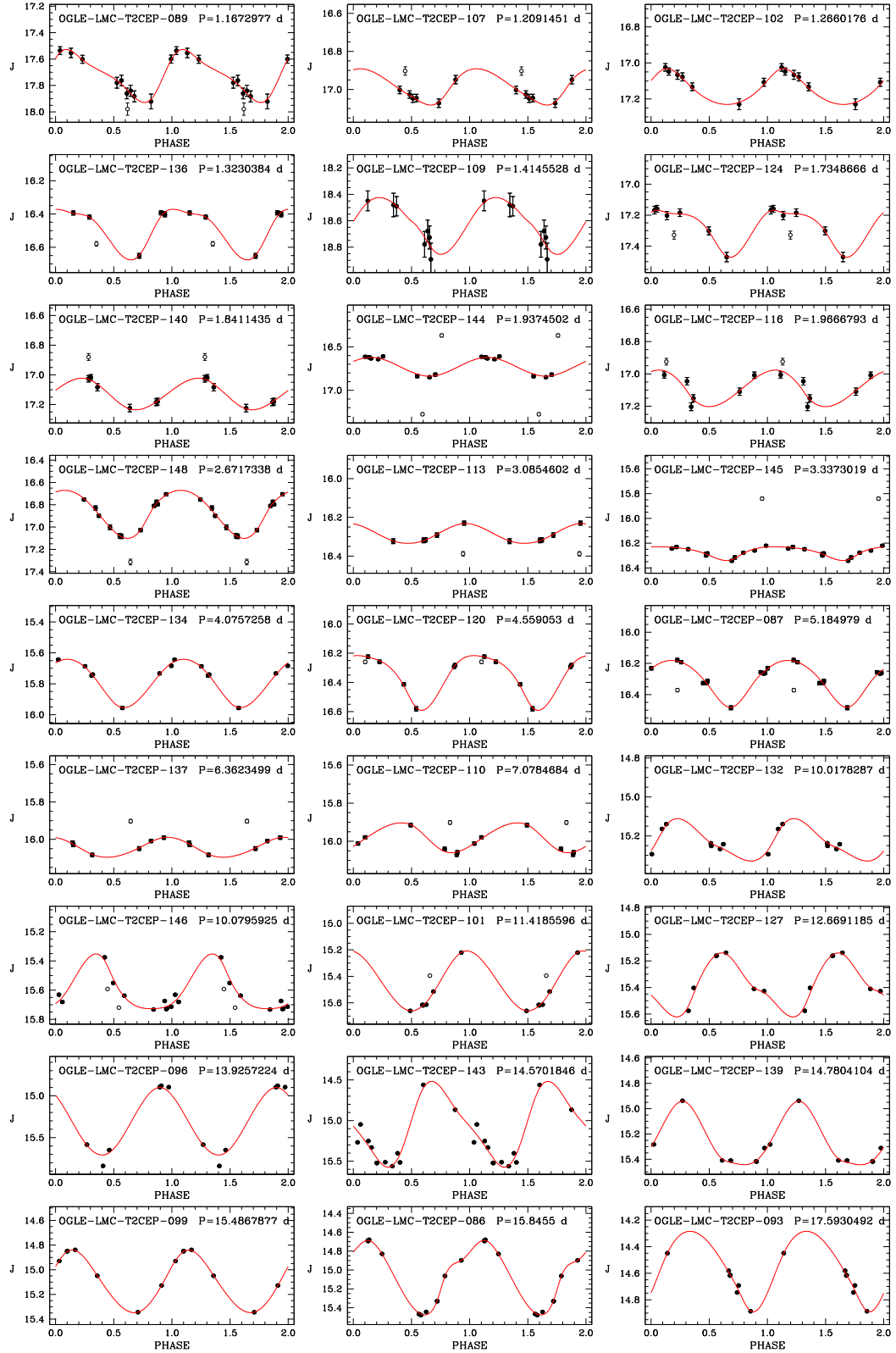


**Figure A3.** *J*-band light curves for T2CEP stars with a sufficient number of epochs to perform the spline fit to the data. Stars are displayed in order of increasing period. Solid lines represent spline best fits to the data (see the text). In each panel, we report OGLE's identification number and period.

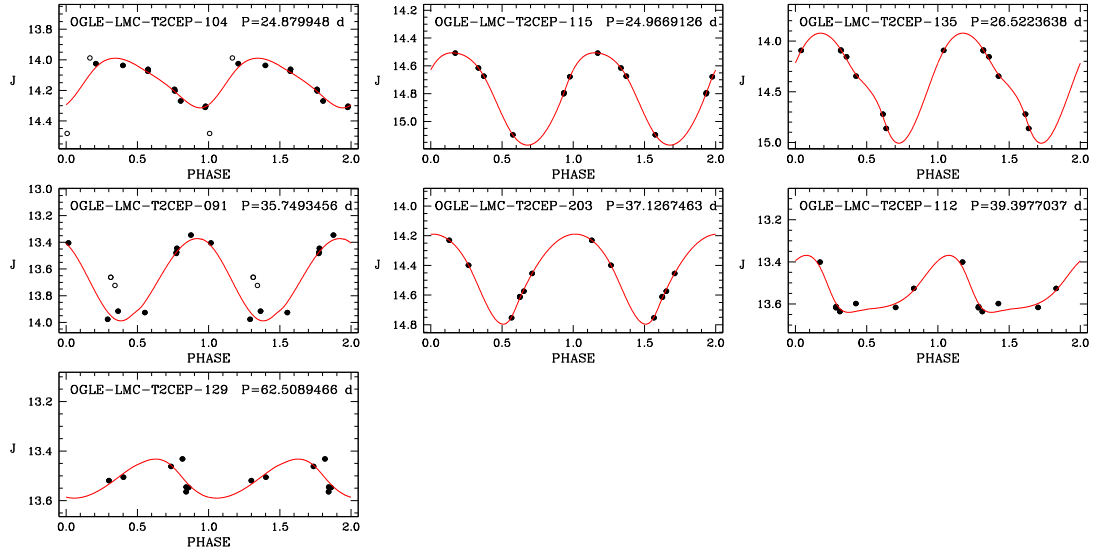


Figure A3 – continued

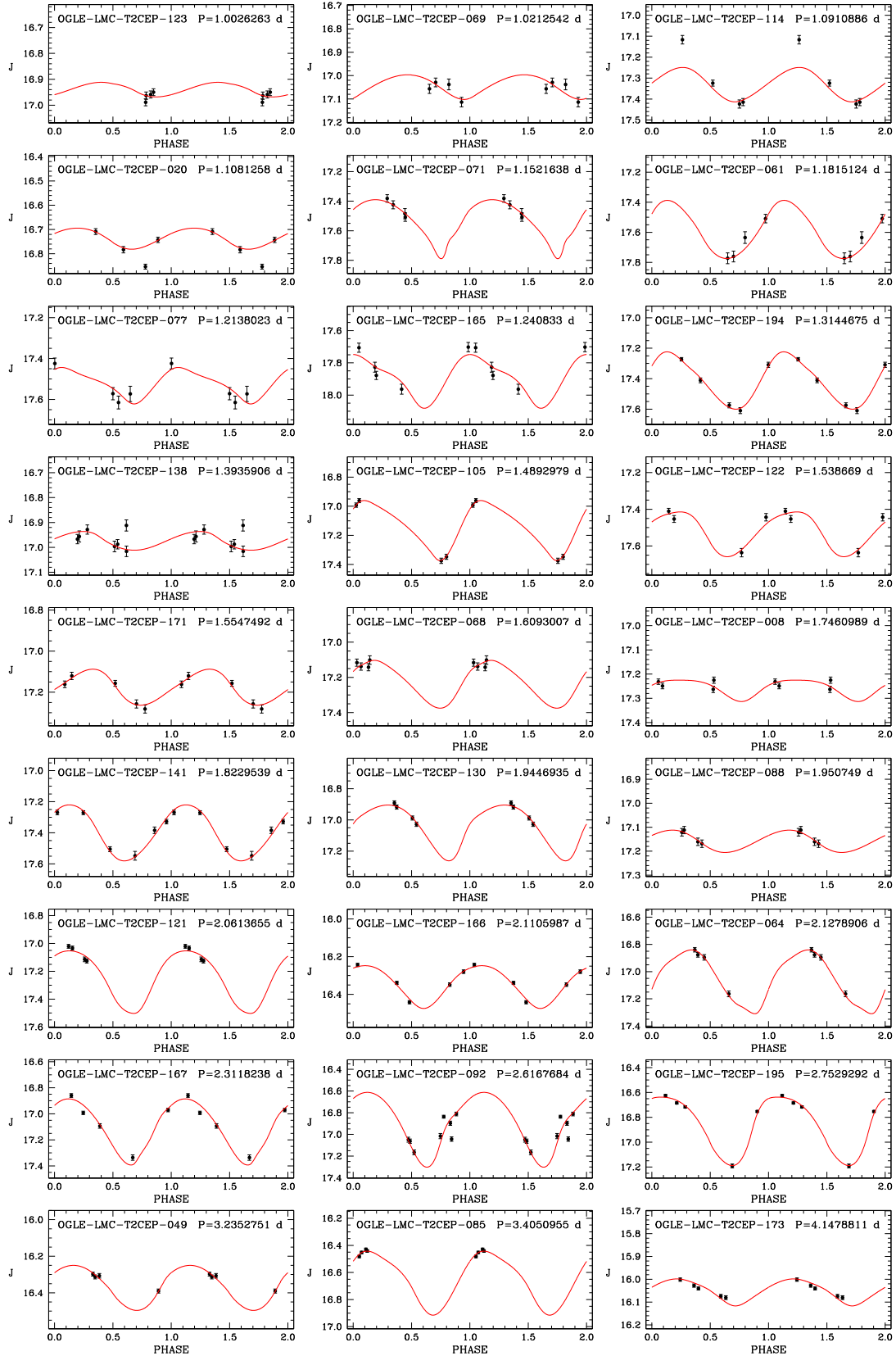


**Figure A4.** *J*-band light curves for T2CEP stars not possessing a sufficient number of epochs to perform the spline fit to the data and for which template fitting was used (see the text). Stars are displayed in order of increasing period. Solid lines represent spline best fits to the data (see the text). In each panel, we report OGLE's identification number and period.

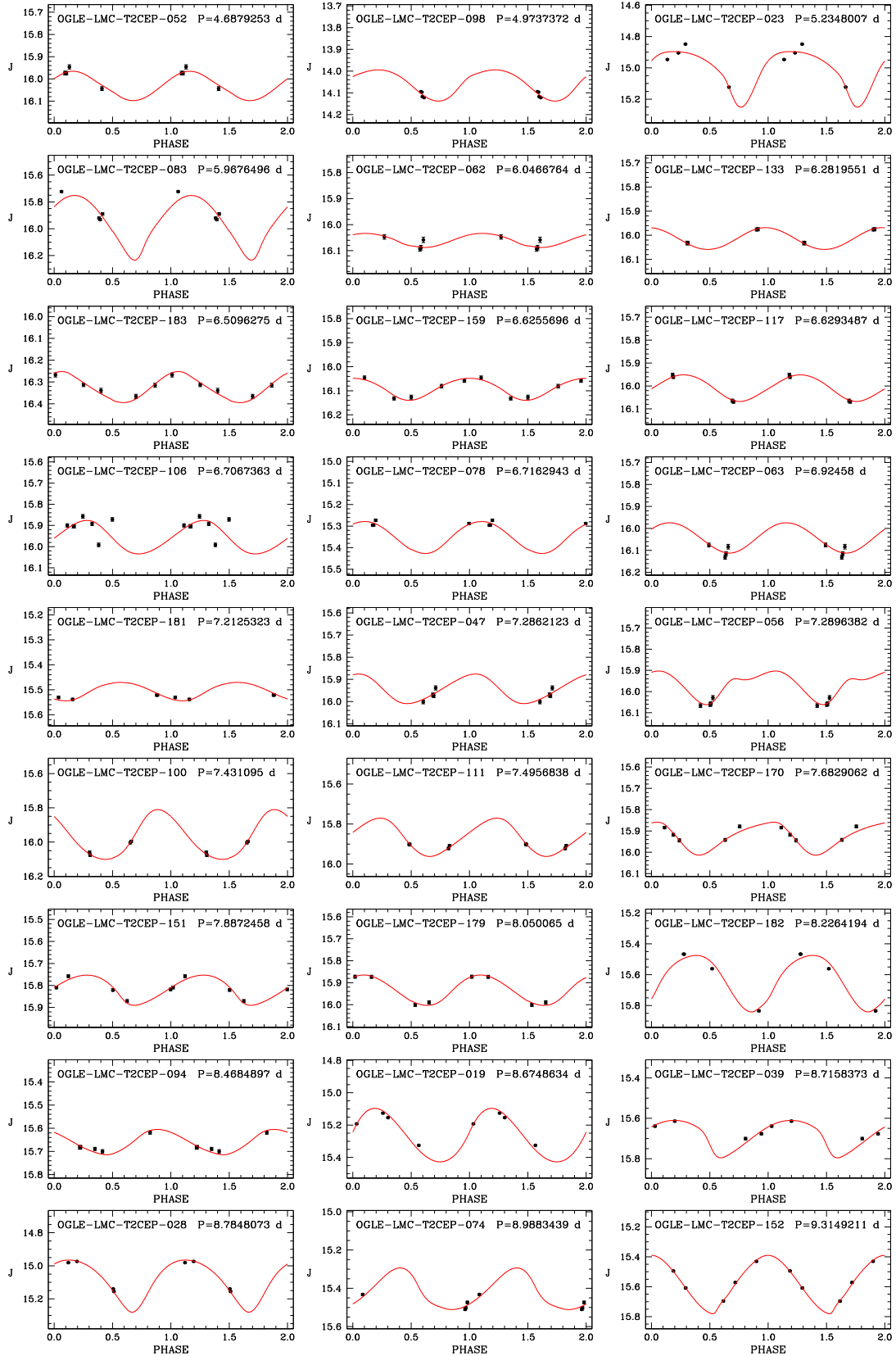
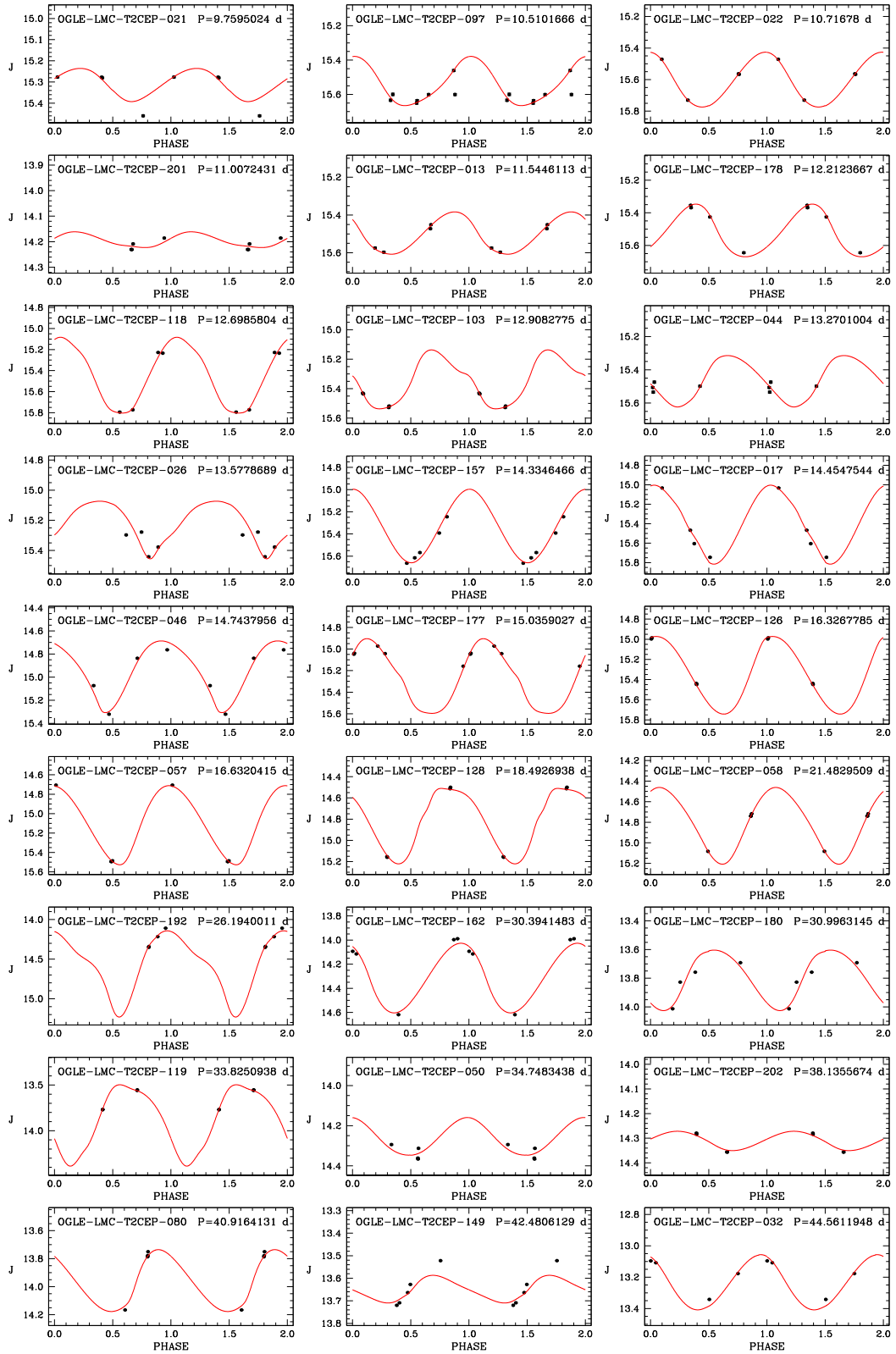


Figure A4 – continued

Figure A4 – *continued*

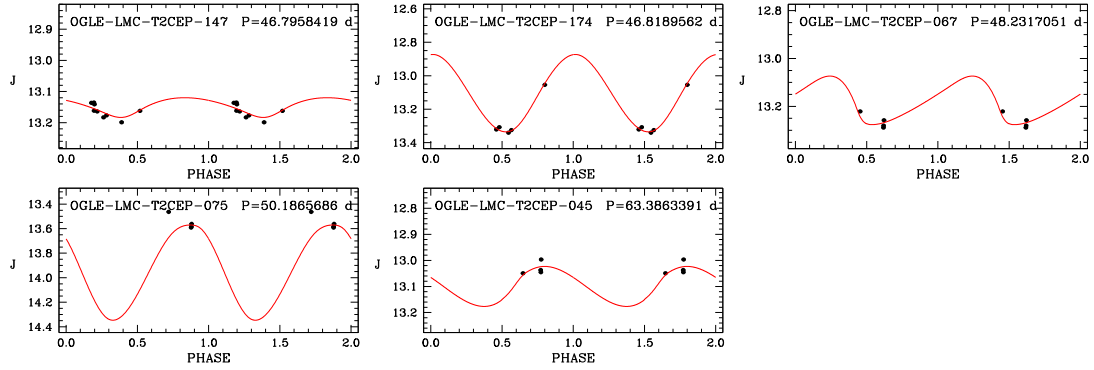


Figure A4 – continued

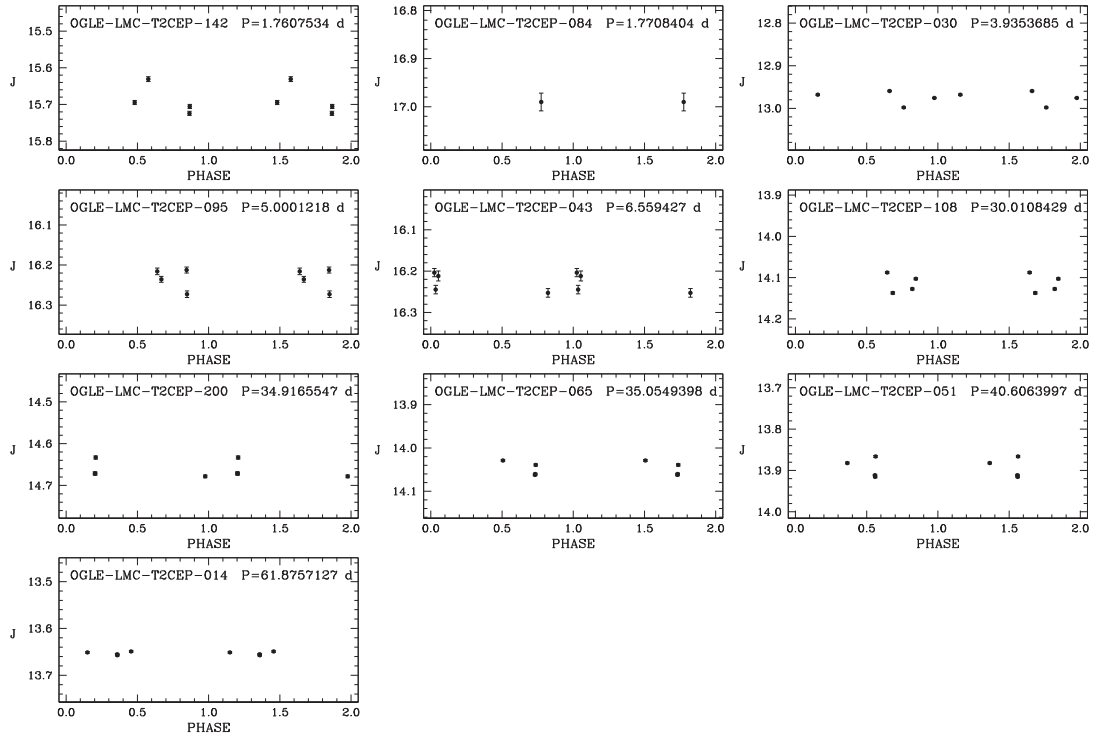


Figure A5. Light curves for stars showing problems in the  $J$  and  $K_s$  bands (see the text).

## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Table 3.**  $J$  and  $K_s$  time-series photometry for the T2CEPs investigated in this paper (<http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu2260/-/DC1>).

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