# The OGLE Collection of Variable Stars.
# Type II Cepheids in the Magellanic System[*]

I. S o s z y ń s k i[1], A. U d a l s k i[1], M. K. S z y m a ń s k i[1], Ł. W y r z y k o w s k i[1],
K. U l a c z y k[2], R. P o l e s k i[3], P. P i e t r u k o w i c z[1], S. K o z ł o w s k i[1],
D. S k o w r o n[1], J. S k o w r o n[1], P. M r ó z[1], K. R y b i c k i[1],
and P. I w a n e k[1]

[1] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: soszynsk@astrouw.edu.pl
[2] Department of Physics, University of Warwick, Gibbet Hill Road, Coventry,
CV4 7AL, UK
[3] Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus,
OH 43210, USA

### ABSTRACT

We present a nearly complete collection of type II Cepheids in the Magellanic System. The sample consists of 338 objects: 285 and 53 variables in the Large and Small Magellanic Clouds, respectively. Based on the pulsation periods and light-curve morphology, we classified 118 of our type II Cepheids as BL Her, 120 as W Vir, 34 as peculiar W Vir, and 66 as RV Tau stars. For all objects, we publish time-series *VI* photometry obtained during the OGLE-IV survey, from 2010 to the end of 2017.

We present the most interesting individual objects in our collection: 16 type II Cepheids showing additional eclipsing or ellipsoidal variability, two RV Tau variables more than 2.5 mag fainter than other stars of this type in the LMC, an RVb star that drastically decreased the amplitude of the long-period modulation, type II Cepheids exhibiting significant amplitude and period changes, and an RV Tau star which undergoes interchanges of deep and shallow minima. We show that peculiar W Vir stars have markedly different spatial distribution than other subclasses of type II Cepheids, which indicates different evolutionary histories of these objects.

**Key words:** *Stars: variables: Cepheids – Stars: oscillations – Stars: Population II – Magellanic Clouds – Catalogs*

## 1. Introduction

Type II Cepheids are low-mass radially pulsating stars belonging to the halo and old disk stellar populations. They are a relatively small group of variable stars

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compared to other types of classical pulsators: RR Lyr stars or classical Cepheids, but they have several important astrophysical applications. Type II Cepheids, like other classical pulsators, obey a well-defined period–luminosity (PL) relation, located 1.5–2 mag below the PL relation followed by classical Cepheids.

Type II Cepheids have been traditionally divided into three classes: BL Her, W Vir, and RV Tau stars. BL Her stars, with the shortest pulsation periods (1–4 d), evolve from the horizontal branch to the asymptotic giant branch (AGB). W Vir stars with intermediate periods (4–20 d) are thought to experience thermal pulses which result in blue loops into the instability strip region in the Hertzsprung-Russell (HR) diagram, however a convincing evolutionary model that would quantitatively describe this behavior still does not exist (see discussion in Groenewegen and Jurkovic 2017a). RV Tau variables with the longest periods ($> 20$ d) are post AGB stars, just prior to the expulsion of planetary nebulae. They cross the high-luminosity extension of the Cepheid instability strip. The defining feature of RV Tau stars are alternating deep and shallow minima in their light curves, but usually they show strong cycle-to-cycle variability. Closely related to the RV Tau stars are yellow semiregular variables (SRd stars) – pulsating stars that occupy the same area in the color–magnitude and PL diagrams, but do not show clear alternations of minima. Sometimes this may be an effect of strong cycle-to-cycle chaotic variations that mask the alternations or quick interchanges of deep and shallow minima that also occur in RV Tau stars. In this paper, both subclasses of long-period type II Cepheids are referred to as RV Tau stars.

In addition to these three groups, Soszyński *et al.* (2008) established another subtype of type II Cepheids – peculiar W Vir stars. They reveal distinct light curves and are usually brighter and bluer than "regular" W Vir variables. About 50% of the peculiar W Vir stars in the Magellanic Clouds show signs of binarity: eclipsing or ellipsoidal modulation superimposed on the pulsation light curves or cyclic period changes possibly caused by the light-time travel effect (Groenewegen and Jurkovic 2017a). This suggests that peculiar W Vir stars are related to the so called binary evolution pulsators (BEPs) – a class of pulsating stars discovered in the OGLE Collection of Variable Stars by Pietrzyński *et al.* (2012). Recently, Karczmarek *et al.* (2017) investigated possible contamination of BEPs among known samples of RR Lyr stars and classical Cepheids and obtained values of 0.8% and 5%, respectively. Since the number of type II Cepheids is much smaller than their classical siblings, one can suppose that the contamination of BEPs among type II Cepheids should be much larger than 5%.

Soszyński *et al.* (2008, 2010) published catalogs of type II Cepheids in the Magellanic Clouds obtained on the basis of the photometric data collected by the OGLE-III project. The Large Magellanic Cloud (LMC) sample consisted of 197 objects, later updated to 203 variables, while in the Small Magellanic Cloud (SMC) we detected 43 such pulsators in total. These type II Cepheids, in particular their PL, period–luminosity–color, and period–Wesenheit index relations, were exten-

sively studied (*e.g.*, Groenewegen and Jurkovic 2017b, Manick *et al.* 2017), also at near-infrared wavelengths (Matsunaga *et al.* 2009, 2011, Ciechanowska *et al.* 2010, Ripepi *et al.* 2015, Bhardwaj *et al.* 2017), and used for distance determinations inside our Galaxy and beyond (Majaess *et al.* 2009ab, 2010, Ciechanowska *et al.* 2010). Smolec (2016) compared his theoretical PL relation with the relation observed by OGLE. Spectral energy distributions for the OGLE type II Cepheids were constructed and studied by Groenewegen and Jurkovic (2017a), who found that about 60% of the RV Tau stars and about 10% of the W Vir stars show an infrared excess. Manick *et al.* (2018) found that all RV Tau stars with a clear infrared excess have disk-type spectral energy distribution, which suggests their binarity. The OGLE *I*-band light curves were used by Kiss and Bódi (2017) to study the RVb phenomenon (additional long-period variations of the mean brightness) in some RV Tau stars. They concluded that the long-term light modulation can be fully explained by periodic obscurations by a dusty disk around a binary system. The OGLE RV Tau stars were also used as tracers of the post-AGB stars (van Aarle *et al.* 2011, Woods *et al.* 2011, Kamath *et al.* 2014).

In this paper, we extend the OGLE-III collection of type II Cepheids in the Magellanic Clouds by objects identified in the OGLE-IV fields. We also supplement the OGLE-III light curves of the previously known variables with the newest OGLE observations, increasing the time-span of the OGLE photometry up to 21 years.

The paper is structured as follows. Section 2 provides a description of the observations and data reduction pipeline. Section 3 presents methods used for the identification and classification of type II Cepheids. In Section 4, we describe the collection and compare it with other samples of type II Cepheids in the Magellanic Clouds. In Section 5, we discuss some interesting features of the published samples of Cepheids and present the most interesting individual objects in our collection. Section 6 summarizes our results.

## 2. Observations and Data Reduction

OGLE observations of the Magellanic Clouds span more than two decades, although this study is based on about eight years of the OGLE-IV photometric monitoring: from March 2010 to December 2017. The light curves collected during previous stages of the OGLE project can be downloaded from the catalogs of Soszyński *et al.* (2008, 2010) and merged with the OGLE-IV data. However, one should take into account some possible offsets of the photometric zero points that can occur in individual objects.

The OGLE-IV observations have been acquired using the 1.3-m Warsaw telescope at Las Campanas Observatory, Chile, which is operated by the Carnegie Institution for Science. The telescope is equipped with a mosaic camera consisting of 32 CCD detectors ($2048 \times 4096$ pixels) providing a total field of view of 1.4 square

degrees with a pixel scale of $0.''26$. For stars located in technical gaps between the CCD detectors, we used the light curves from the OGLE-IV auxiliary photometric databases (Soszyński *et al.* 2017a). Most of the observations (typically 700 measurements) were taken with the standard *I*-band filter from the Cousins photometric system, while the remaining observations (typically 120 and up to 267 points) were secured in the Johnson *V* passband.

The Difference Image Analysis package (Alard and Lupton 1998, Woźniak 2000) was used to obtain the instrumental photometry of all point sources. The light curves were then converted to Johnson-Cousins *VI* magnitudes using the transformations given in Udalski *et al.* (2015). We refer the reader to Udalski *et al.* (2015) for a detailed description of the data reduction and calibration.

### 3. Selection and Classification of Type II Cepheids

Type II Cepheids in the Magellanic Clouds were extracted from the OGLE-IV photometric database using essentially the same methods that were applied to other classical pulsators (*e.g.*, Soszyński *et al.* 2015, 2017a). First, a period search for all *I*-band light curves was performed through the Fourier analysis implemented in the FNPEAKS code[†]. Second, the light curves with the largest signal-to-noise ratios were evaluated by visual inspection and initially divided into three groups: pulsating stars, eclipsing binaries, and other variable objects. Third, from the group of pulsating stars we distinguished candidates for type II Cepheids based on their positions in the PL and color–magnitude diagrams, as well as characteristics of their light curves quantified by the Fourier coefficients.

Type II Cepheids were subdivided into four separate classes: BL Her, W Vir, peculiar W Vir, and RV Tau stars, depending on their pulsation periods and light curve shapes. Stars with periods between 1 d and 4 d were classified as BL Her stars, between 4 d and 20 d as W Vir and peculiar W Vir stars, and longer period variables were designated as RV Tau stars[‡]. We emphasize that periods of different subclasses of type II Cepheids partly overlap, so the adopted boundary periods have just statistical meaning and for individual objects one can use another classification. "Regular" and peculiar W Vir stars were distinguished based primarily on the parameters of the light curve Fourier decomposition (Fig. 1), but we also took into account mean brightness and colors (Fig. 2) of the stars (peculiar W Vir stars are on average brighter and bluer than "regular" W Vir Cepheids).

The new OGLE-IV photometry allowed us to verify the classification of the candidates for type II Cepheids published in the OGLE-III catalog of variable stars (Soszyński *et al.* 2008, 2010). Five objects were reclassified as other types of variable stars and removed from the OGLE collection of type II Cepheids in the

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[†] *http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks*
[‡] For all Cepheids we provide "single" periods, *i.e.*, intervals between successive minima, also when the period-doubling effect is present.
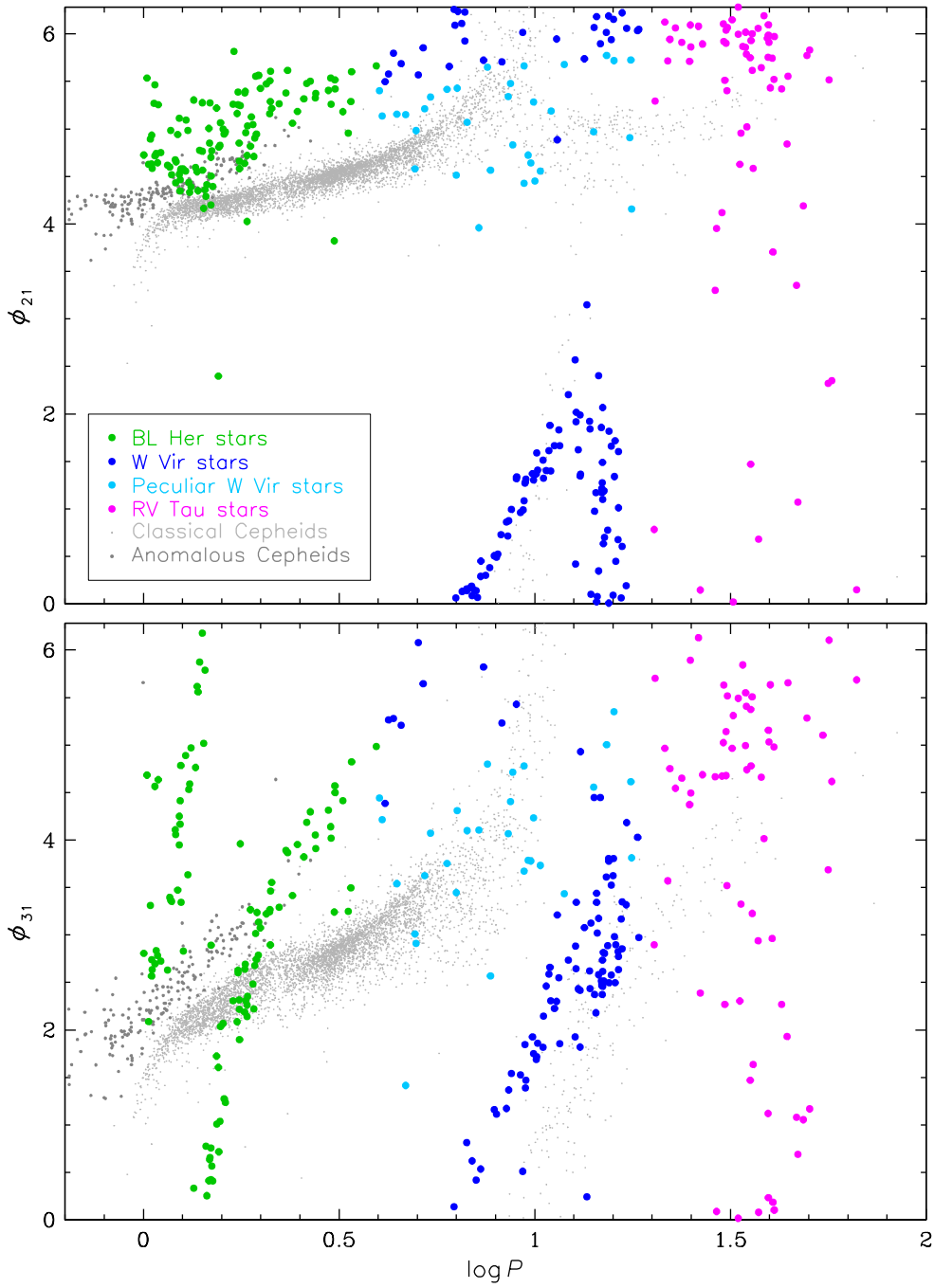
Fig. 1. Fourier coefficients $\phi_{21}$ and $\phi_{31}$ as a function of the pulsation periods for Cepheids in the Magellanic Clouds. Green, blue, light blue, and magenta points indicate BL Her, W Vir, peculiar W Vir, and RV Tau stars, respectively. Large and small gray points, respectively, show the location of classical and anomalous Cepheids pulsating in the fundamental mode.
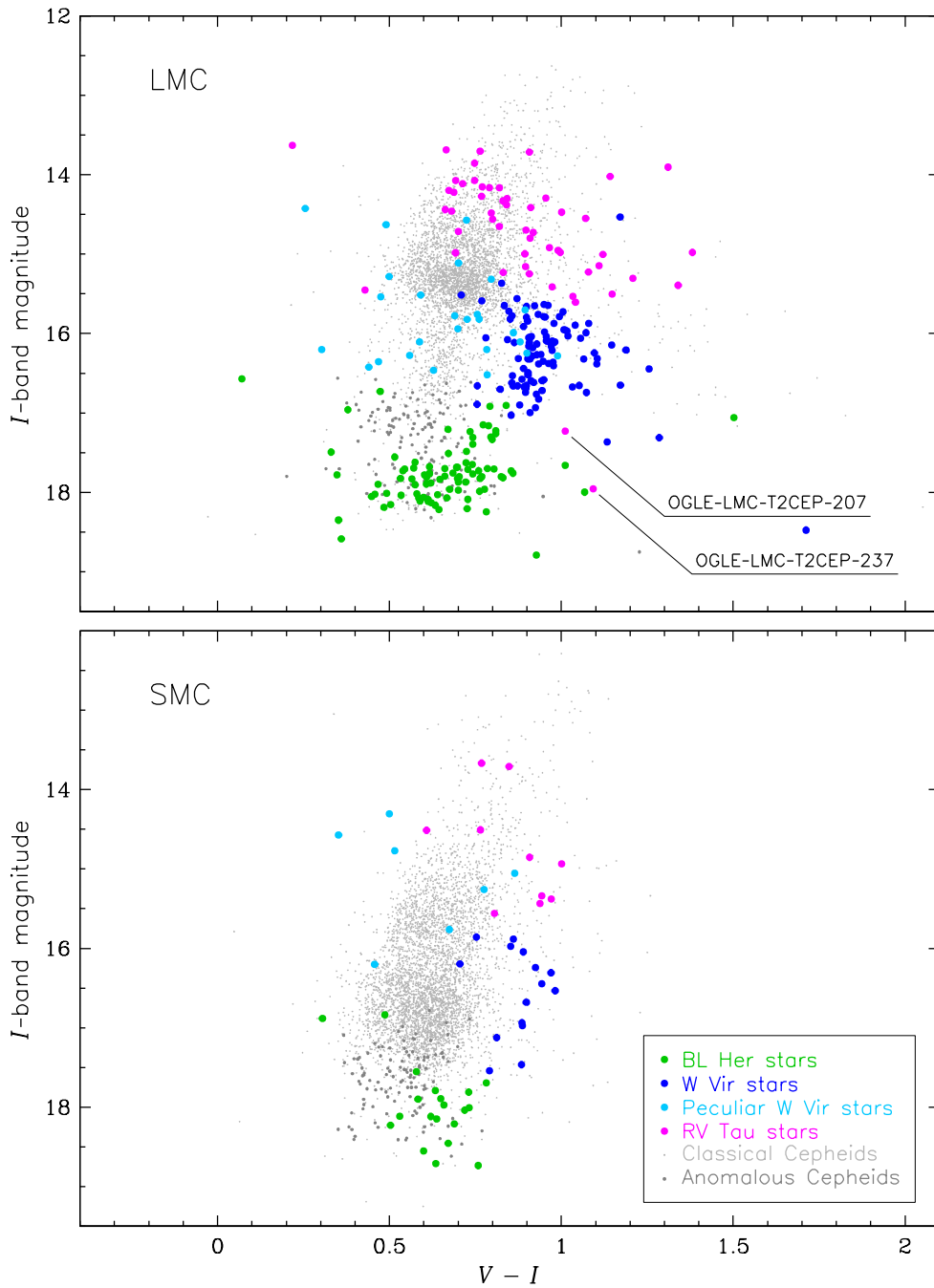
Fig. 2. Color $(V-I)$ *vs.* magnitude $I$ diagram for various types of Cepheids in the LMC (*upper panel*) and SMC (*lower panel*). Different colors correspond to the same types of pulsators as in Fig. 1. Labels show two candidates for ultra faint RV Tau stars described in Section 5.4.

Magellanic System. In Table 1 we list these stars with their new classification. Several other candidates for type II Cepheids were considered uncertain and flagged in the remarks of our collection.

T a b l e 1

Reclassified objects from the OGLE-III catalog of type II Cepheids in the Magellanic Clouds

| Identifier | New classification |
|---|---|
| OGLE-LMC-T2CEP-114 | Anomalous Cepheid |
| OGLE-LMC-T2CEP-150 | Other |
| OGLE-LMC-T2CEP-164 | Eclipsing binary |
| OGLE-LMC-T2CEP-202 | Long-period variable |
| OGLE-SMC-T2CEP-21 | Other |

## 4. The OGLE Collection of Type II Cepheids in the Magellanic System

The OGLE collection of type II Cepheids in the Magellanic System is composed of 118 BL Her, 120 W Vir, 34 peculiar W Vir, and 66 RV Tau variables – in total 338 objects, of which 285 are located in the LMC, and 53 in the SMC. Five of our type II Cepheids (four BL Her stars and one W Vir star) are probable members of four LMC globular clusters (NGC 1786, NGC 1835 – contains two Cepheids, NGC 1939, and Hodge 11), as the sky positions of these objects coincide with the positions of the clusters.

The entire collection can be downloaded *via* the WWW interface or from the FTP site:

*http://ogle.astrouw.edu.pl*
*ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/lmc/t2cep/*
*ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/smc/t2cep/*

The identifiers of our type II Cepheids follow the scheme introduced in the OGLE-III catalog (OGLE-LMC-T2CEP-NNN or OGLE-SMC-T2CEP-NN). The newly detected variables have numbers larger than 203 and 43 in the LMC and SMC, respectively, and are organized by increasing right ascension. For each star, we provide, among others, its equatorial coordinates (J2000.0), the cross-match with the extragalactic part of the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995), mean magnitudes in the *I*- and *V*-bands, pulsation period, epoch of the maximum light, peak-to-peak *I*-band amplitude, and Fourier parameters derived from the *I*-band light curves. The pulsation periods have been adjusted with the TATRY code of Schwarzenberg-Czerny (1996), based solely on the photo-
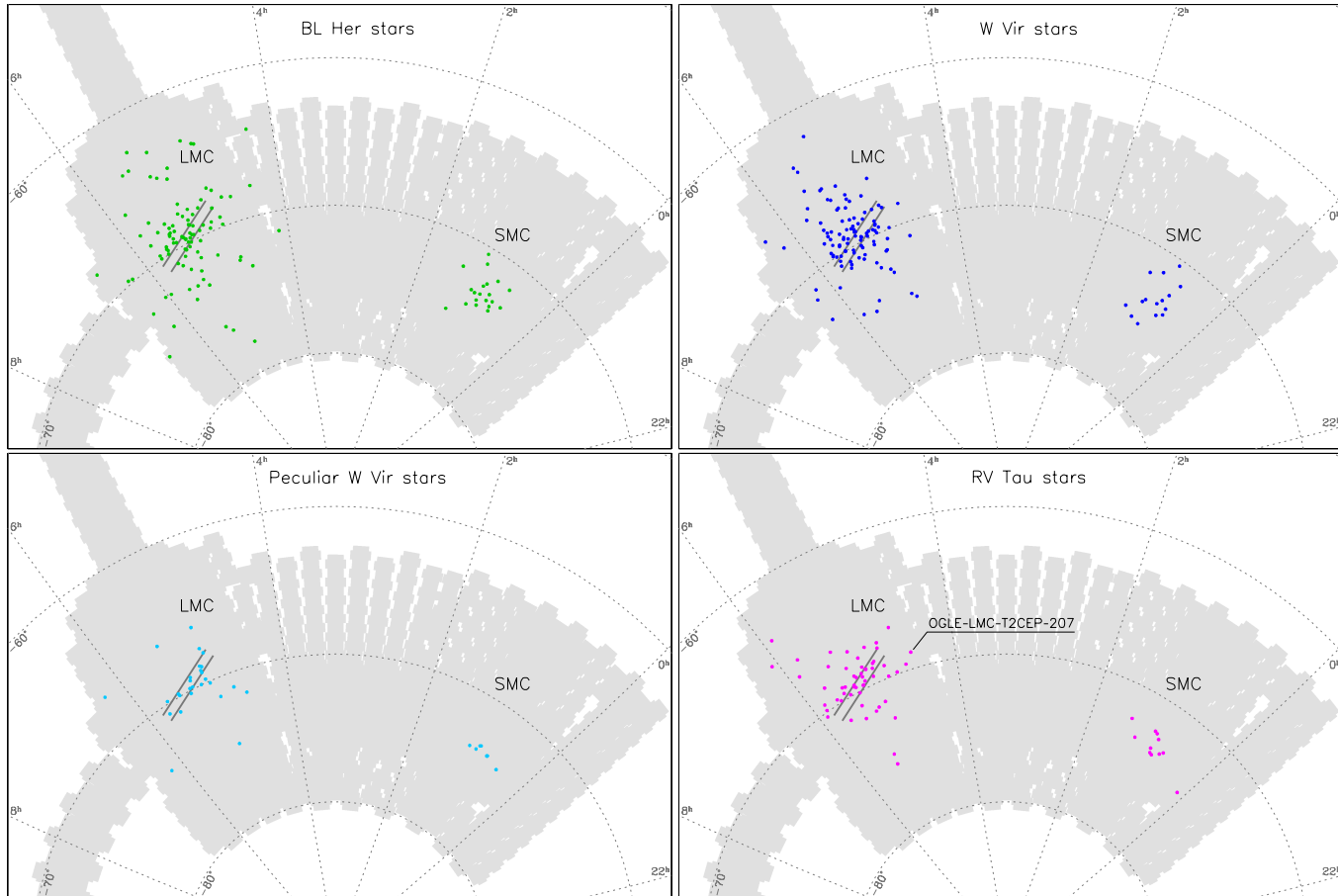
Fig. 3. Sky distribution of type II Cepheids in the Magellanic Clouds. Each panel presents positions of different subclasses of type II Cepheids. The gray area shows the OGLE-IV footprint. Two parallel lines in the LMC indicate the position of the bar.

metry collected in 2010–2017, *i.e.*, from the beginning of the fourth phase of the OGLE project. For some type II Cepheids, in particular W Vir and RV Tau stars, periods derived from light curves collected by the OGLE-II (1997–2000) or OGLE-III (2001–2009) surveys may be different than provided in this collection, because large and erratic period changes is a common feature in these objects (see Section 5.4). To obtain the amplitudes and intensity-averaged magnitudes of the variables, we fitted the light curves with a cosine Fourier series.

Sky maps showing the positions of the four classes of type II Cepheids are presented in Fig. 3. At the first glance, BL Her stars show the largest dispersion of their positions around the centers of the LMC and SMC, W Vir stars seem to be slightly more concentrated toward the centers, RV Tau stars are even more focused around the central parts of both galaxies, and the peculiar W Vir stars populate mostly the bar of the LMC and the very center of the SMC. The spatial distribution may be a key to understand the origin and current evolutionary status of various classes of type II Cepheids. It is worth noting that type II Cepheids avoid the region between both Clouds – the so called Magellanic Bridge. In this regard, type II Cepheids differ from anomalous Cepheids which populate very broad halos.

### 4.1. *Cross-Match with Other Catalogs*

In order to test the completeness of our collection of type II Cepheids in the Magellanic Clouds, we cross-matched it with the GCVS (Artyukhina *et al.* 1995), the catalog of periodic variable stars detected from the EROS-2 survey (Kim *et al.* 2014), and the catalog of Cepheids recently published as a part of the Gaia Data Release 2 (DR2, Clementini *et al.* 2018, Holl *et al.* 2018).

The extragalactic part of the GCVS (Artyukhina *et al.* 1995) contains 28 stars classified as type II Cepheids (of type CWA, CWB, RV, RVA) in the LMC and SMC. A preliminary version of the OGLE collection contained 21 of these objects. We carefully inspected the OGLE light curves of the remaining seven sources and decided to supplement our collection with one of these objects (HV 2522 = OGLE-LMC-T2CEP-251), which seems to be a yellow semiregular variable (SRd star). Other candidates for type II Cepheids from the GCVS are classical Cepheids, long-period variables or eclipsing binaries.

Kim *et al.* (2014) used automatic algorithms to select 117 234 candidates for periodic variable stars from the EROS-2 LMC photometric database. This list includes 343 objects classified as type II Cepheids, of which 182 stars were cataloged in the OGLE Collection. Most of the remaining candidates have their counterparts in the OGLE photometric database within $1''$ search radius, but only one additional object (lm0336k4219 = OGLE-LMC-T2CEP-246) was recognized as a real type II Cepheid (a W Vir star with nearly symmetrical light curve) and was included to our sample. The remaining EROS-2 candidates for type II Cepheids represent a wide spectrum of stellar variability classes: anomalous Cepheids, eclipsing binaries, long-period variables, spotted stars, etc.

A cross-match of our sample with the Gaia DR2 catalog of 191 potential type II Cepheids in the Magellanic Clouds[§] (Clementini *et al.* 2018) did not bring new discoveries. This and the previously published parts of the OGLE Collection of Variable Stars contain in total 159 objects from the Gaia list: 138 true type II Cepheids, 16 classical Cepheids, and five anomalous Cepheids (Soszyński *et al.* 2017a). We successfully identified OGLE-IV light curves for all 32 remaining Gaia candidates for type II Cepheids and, after a visual inspection, we classified them as long-period variables, eclipsing or ellipsoidal binaries, irregular variables or other types of variable stars.

These tests show that the completeness of our collection of type II Cepheids in the Magellanic Clouds is very high, close to 100%. We suppose that at most several variables may be located outside the OGLE-IV fields, in the far outskirts of the Magellanic System. Also, it cannot be excluded that a few type II Cepheids were overlooked due to the unusual morphology of their light curves or the location in the immediate vicinity of bright stars.

## 5. Discussion

### 5.1. Period–Luminosity Relation

The PL relation obeyed by type II Cepheids is probably the most-studied feature of these stars in the Magellanic Clouds. Fig. 4 presents PL diagrams for type II Cepheids in the LMC (upper panel) and SMC (lower panel), where as a "luminosity" we used a reddening-independent Wesenheit index, $W_I = I - 1.55(V - I)$. For comparison, classical and anomalous Cepheids (Soszyński *et al.* 2015, 2017a) are also plotted in Fig. 4.

Our nearly complete PL diagrams confirm earlier findings. In the LMC, BL Her and W Vir stars are roughly co-linear in the period–$W_I$ plane, while RV Tau stars are located above the regression line fitted to the BL Her and W Vir variables and show larger scatter of the PL sequence. Manick *et al.* (2017) attributed this to the extinction by circumstellar dust. On the other hand, in the SMC, BL Her stars seem to be located above the PL relation delineated by "regular" W Vir and RV Tau stars. Peculiar W Vir stars are on average brighter than "regular" W Vir stars, which can be partly attributed to the additional light from their potential companions (see Section 5.2), although note that the solution of Pilecki *et al.* (2017) for OGLE-LMC-T2CEP-098 (a peculiar W Vir star in an eclipsing binary system) placed this pulsating star about 1 mag above the PL relation for type II Cepheids.

A number of outliers visible among "ordinary" BL Her, W Vir, and RV Tau variables may also be explained by the blending by unresolved stars, although some of these stars are uncertain objects, which is flagged in the remarks of the collection. Two faint RV Tau stars labeled in the upper panel of Fig. 4 are described in Section 5.4.

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[§]We defined the region of the Magellanic Clouds as a box $0° <$ R.A. $< 100°$, $-80° <$ Dec $< -60°$ – a larger area than that defined by Clementini *et al.* (2018).
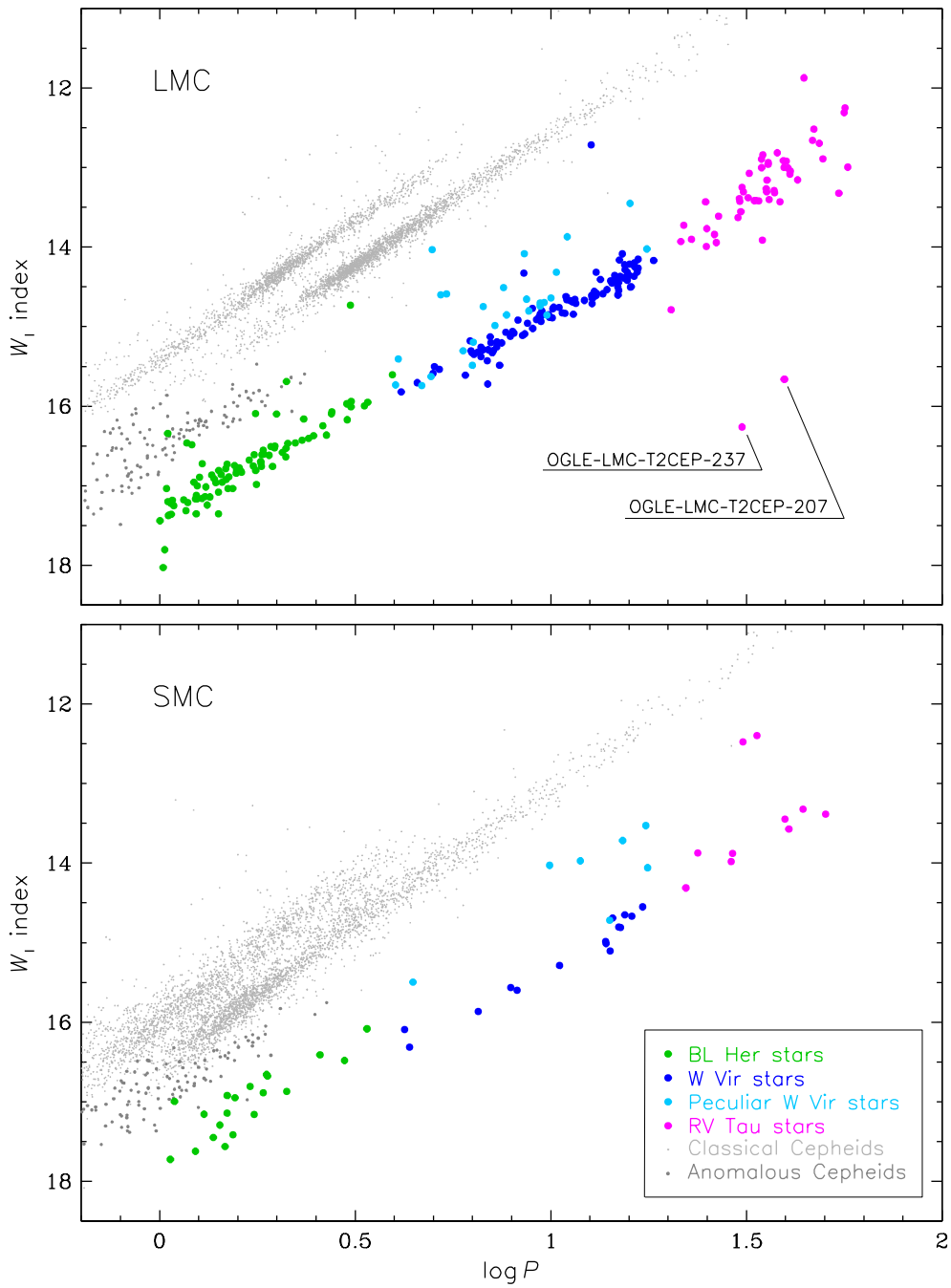
Fig. 4. Period *vs.* Wesenheit index diagram for various types of Cepheids in the LMC (*upper panel*) and SMC (*lower panel*). Different colors correspond to the same types of pulsators as in Fig. 1. Labels show two candidates for ultra faint RV Tau stars described in Section 5.4.

## 5.2. *Type II Cepheids in Binary Systems*

The OGLE-III catalog of type II Cepheids in the Magellanic Clouds (Soszyński *et al.* 2008, 2010) contains as many as 13 pulsating stars with eclipsing or ellipsoidal modulation. In the present investigation, we supplement this group with three additional objects: OGLE-LMC-T2CEP-211, OGLE-LMC-T2CEP-224, and OGLE-LMC-T2CEP-250. The disentangled light curves of all 16 Cepheids with eclipsing or ellipsoidal variations are presented in Fig. 5 and their periods and identifiers (with additional identifiers from the OGLE collection of eclipsing binary systems in the Magellanic Clouds, Pawlak *et al.* 2016) are summarized in Table 2.

T a b l e 2

Type II Cepheids in eclipsing and ellipsoidal binary systems

| Identifier as a type II Cepheid | Classification | Pulsation period [d] | Identifier as a binary system | Orbital period [d] |
|---|---|---|---|---|
| OGLE-LMC-T2CEP-021 | pec. W Vir | 9.77937 | OGLE-LMC-ECL-28274 | 174.923 |
| OGLE-LMC-T2CEP-023 | pec. W Vir | 5.23514 | OGLE-LMC-ECL-28388 | 88.616 |
| OGLE-LMC-T2CEP-052 | pec. W Vir | 4.68061 | OGLE-LMC-ECL-30076 | 123.879 |
| OGLE-LMC-T2CEP-077 | BL Her | 1.21380 | OGLE-LMC-ECL-31119 | 34.621 |
| OGLE-LMC-T2CEP-084 | BL Her | 1.77031 | OGLE-LMC-ECL-31272 | 52.351 |
| OGLE-LMC-T2CEP-093 | pec. W Vir | 17.6067 | OGLE-LMC-ECL-31746 | 419.43 |
| OGLE-LMC-T2CEP-098 | pec. W Vir | 4.97375 | OGLE-LMC-ECL-31922 | 397.272 |
| OGLE-LMC-T2CEP-211 | pec. W Vir | 9.39323 | OGLE-LMC-ECL-26653 | 242.220 |
| OGLE-LMC-T2CEP-224 | pec. W Vir | 6.34001 | OGLE-LMC-ECL-29309 | 84.230 |
| OGLE-LMC-T2CEP-250 | pec. W Vir | 15.9391 | | 198.31 |
| OGLE-SMC-T2CEP-07 | RV Tau | 30.9945 | | 393.13 |
| OGLE-SMC-T2CEP-10 | pec. W Vir | 17.4943 | | 198.04 |
| OGLE-SMC-T2CEP-23 | pec. W Vir | 17.6975 | OGLE-SMC-ECL-3123 | 156.882 |
| OGLE-SMC-T2CEP-25 | pec. W Vir | 14.1516 | | 174.66 |
| OGLE-SMC-T2CEP-28 | pec. W Vir | 15.2606 | OGLE-SMC-ECL-7243 | 141.82 |
| OGLE-SMC-T2CEP-29 | RV Tau | 33.6492 | OGLE-SMC-ECL-7250 | 608.04 |

In most of these objects, we are confident that the pulsating stars belong to the binary systems (so they are not physically unrelated blends observed by chance along the same line-of-sight), because we can detect combination frequencies in their light curves. Usually, the combination frequencies are equal to $(1/P_{\text{puls}} \pm 1/P_{\text{orb}})$ or $(1/P_{\text{puls}} \pm 2/P_{\text{orb}})$, which reflects complex oscillations of stars which are distorted by tidal interactions from their companions.

The majority of our eclipsing and ellipsoidal type II Cepheids are classified as peculiar W Vir stars. The only exceptions are OGLE-LMC-T2CEP-077 and OGLE-LMC-T2CEP-084, classified as a BL Her star, and OGLE-SMC-T2CEP-07 and OGLE-SMC-T2CEP-29, classified as RV Tau stars, but they are likely equivalents of the peculiar W Vir stars in the range of pulsation periods assigned to RV Tau variables. It is worth noting that Groenewegen and Jurkovic (2017a) derived and in-
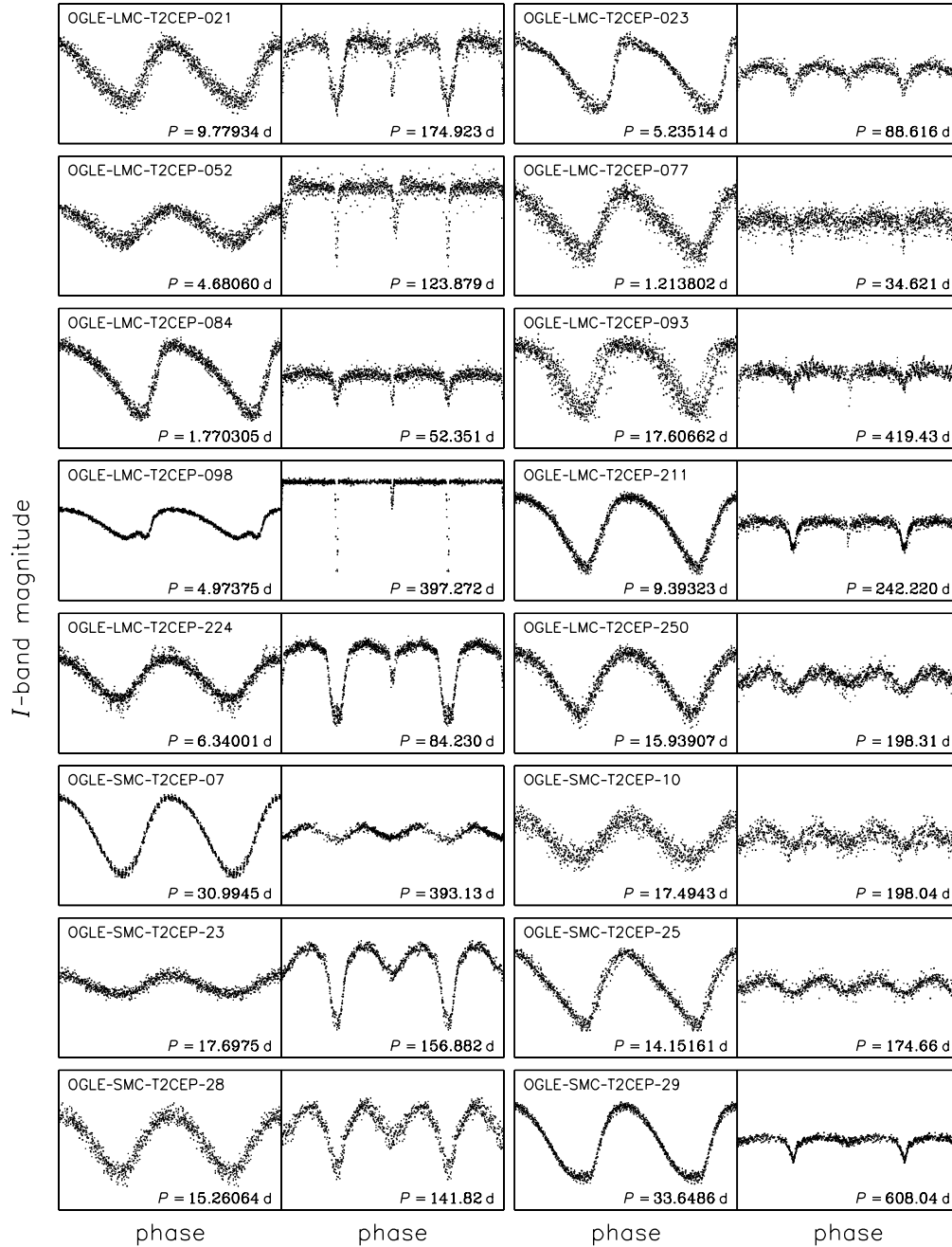
Fig. 5. Disentangled *I*-band light curves of type II Cepheids with additional eclipsing or ellipsoidal variability. Each object is presented in two panels showing pulsating light curves (*left panels*) and eclipsing or ellipsoidal light curves (*right panels*). All the data come from the OGLE-IV database with the exception of OGLE-LMC-T2CEP-077 which light curve was taken from the OGLE-III database (there are very few OGLE-IV observations for this star).

vestigated the observed minus calculated ($O-C$) diagrams for the OGLE-III light curves of type II Cepheids in the Magellanic Clouds and found about 20 additional candidates for binary Cepheids.

Careful spectroscopic analysis of the peculiar W Vir stars in binary systems may solve the problem of their origin. Recently, the "Araucaria" collaboration (Pilecki *et al.* 2017) presented a study of OGLE-LMC-T2CEP-098 – a peculiar W Vir star in an eclipsing binary system. The mass of the pulsating component was estimated to be $1.51 \pm 0.09$ M$_\odot$ – significantly larger than expected for ordinary type II Cepheids. It was suggested that the current evolutionary status of the Cepheid and its companion could be explained by episodes of mass transfer between the components of the binary systems, and thus OGLE-LMC-T2CEP-098 meets the definition of binary evolution pulsators (Pietrzyński *et al.* 2012).

### 5.3. Peculiar W Vir Stars

Our collection contains 34 peculiar W Vir stars in the Magellanic Clouds, of which 35% exhibit eclipsing or ellipsoidal variations. Additional candidates for binaries among OGLE peculiar W Vir variables were found by Groenewegen and Jurkovic (2017a) through the light-time effect, so the percentage of peculiar W Vir stars with signs of binarity reaches 50%. This clearly indicates that binarity is evolutionary essential to explain pulsations of peculiar W Vir stars.

Our distinction between "regular" and peculiar W Vir stars was based on their light curve shapes. In particular, both groups occupy different regions in the period–$\phi_{21}$ and period–$\phi_{31}$ diagrams (Fig. 1). The same feature was recently used to distinguish 30 candidates for peculiar W Vir stars in the Galactic bulge (Soszyński *et al.* 2017b). It is worth noting, however, that compared to the Magellanic Clouds sample, the peculiar W Vir stars in the center of the Milky Way have a much smaller rate of eclipsing binary systems. We found there only one type II Cepheid (OGLE-BLG-T2CEP-674) with the eclipsing modulation.

Matsunaga *et al.* (2009) noticed that peculiar W Vir stars are absent in globular clusters which suggests that this class of pulsating stars may belong to a younger stellar population than other type II Cepheids. This conclusion is supported by the spatial distribution of these stars in the LMC and SMC (Fig. 3). The vast majority of peculiar W Vir stars are located in the central regions of both galaxies, in agreement with the distribution of a young stellar population (for example classical Cepheids, Soszyński *et al.* 2017a).

### 5.4. Particularly Interesting Type II Cepheids

Two candidates for RV Tau stars in the LMC – OGLE-LMC-T2CEP-207 and OGLE-LMC-T2CEP-237 – are surprisingly faint, more than 2.5 mag fainter than other RV Tau variables with the same periods (Fig. 4), but with $(V-I)$ color indices typical for RV Tau stars (Fig. 2). Light curves of these two objects are presented in Fig. 6. OGLE-LMC-T2CEP-207 shows long-period (850 d) variations of the mean
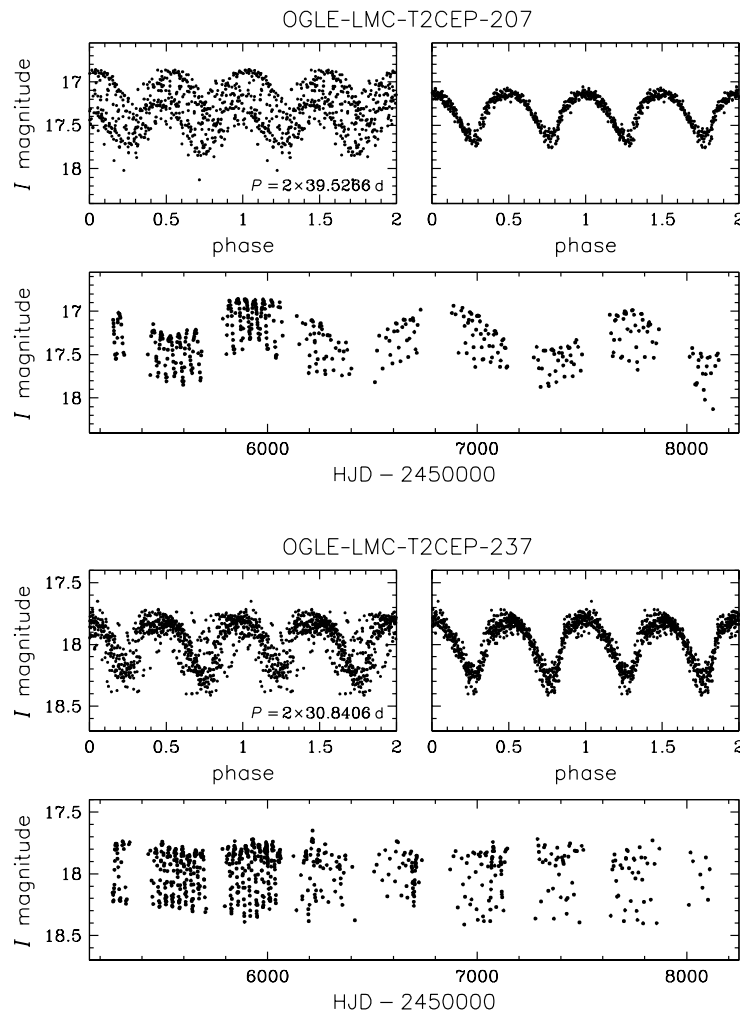
Fig. 6. Light curves of OGLE-LMC-T2CEP-207 and OGLE-LMC-T2CEP-237 – candidates for extremely faint RV Tau stars. For each star we plot the original *I*-band light curve folded with the mean period (*upper left panels*), the folded light curve corrected for the period changes and the long-term brightness modulations (*upper right panels*), and the unfolded light curve (*lower panels*).

brightness, which place this object in the group of RVb stars. Both variables exhibit changes of periods, which is also a common feature of RV Tau stars. In the upper right panels of Fig. 6, we present light curves of both stars corrected for the period changes and the long-term modulation. In both stars, the alternations of deeper and shallower minima are small but detectable, at least when studying observations obtained in individual observing seasons.

If these objects are indeed RV Tau stars, there are two explanations of their origin. First, they are located in the LMC and belong to a new subclass of ultra faint RV-Tau-like variables. Second, they are classical RV Tau stars, but located behind the LMC, more than three times farther than the center of this galaxy. The

positions of these two stars is the sky (Fig. 3) suggest that they belong to the LMC, although OGLE-LMC-T2CEP-207 is located outside the center of the LMC, the most to the West of all RV Tau stars in this galaxy. On the other hand, OGLE-LMC-T2CEP-237 (not labeled in Fig. 3) is located in the sky at the very center of the LMC. Further research is necessary to explain the nature of these stars.
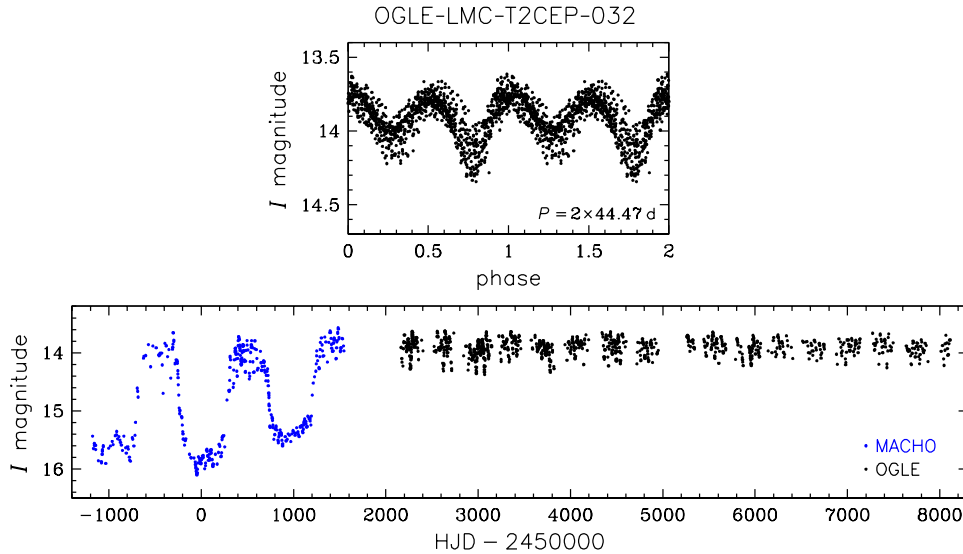


Fig. 7. MACHO and OGLE light curves of OGLE-LMC-T2CEP-032 – an RVb star which dramatically decreased the amplitude of the long-period variations of the mean brightness. *Upper panel*: folded OGLE-III and OGLE-IV *I*-band light curve. *Lower panel*: unfolded light curve – blue points indicate the MACHO $R_M$-band magnitudes, black points indicate the OGLE light curve. The zero point of the MACHO photometry was shifted to agree with the OGLE magnitudes.

Beside OGLE-LMC-T2CEP-207, our collection contains only one RVb star with large-amplitude modulations of the mean brightness – OGLE-LMC-T2CEP-200. Additionally, a few RV Tau stars show long-term modulations of the mean luminosity, but with small amplitudes. One of the most interesting objects of this type is OGLE-LMC-T2CEP-032, which in 1990s was an RVb star with a large (but variable) amplitude of the long-period (about 960 d) variability. Because at that time this star was not monitored by the OGLE project, in Fig. 7 we plot its $R_M$-band magnitudes obtained by the MACHO survey (Alcock *et al.* 1993). Since 2001, when OGLE began regular observations of this star, the long-period modulation is still detectable in the light curve, but has a much smaller amplitude of about 0.1 mag.

The OGLE light curves of point sources in the Magellanic Clouds span from 8 years (OGLE-IV) to 21 years (OGLE-II + OGLE-III + OGLE-IV), depending on the region. These continuous, long-term observations are an excellent tool for studying non-stationary processes in variable stars, like period changes, amplitude modulations, or additional periodicities.
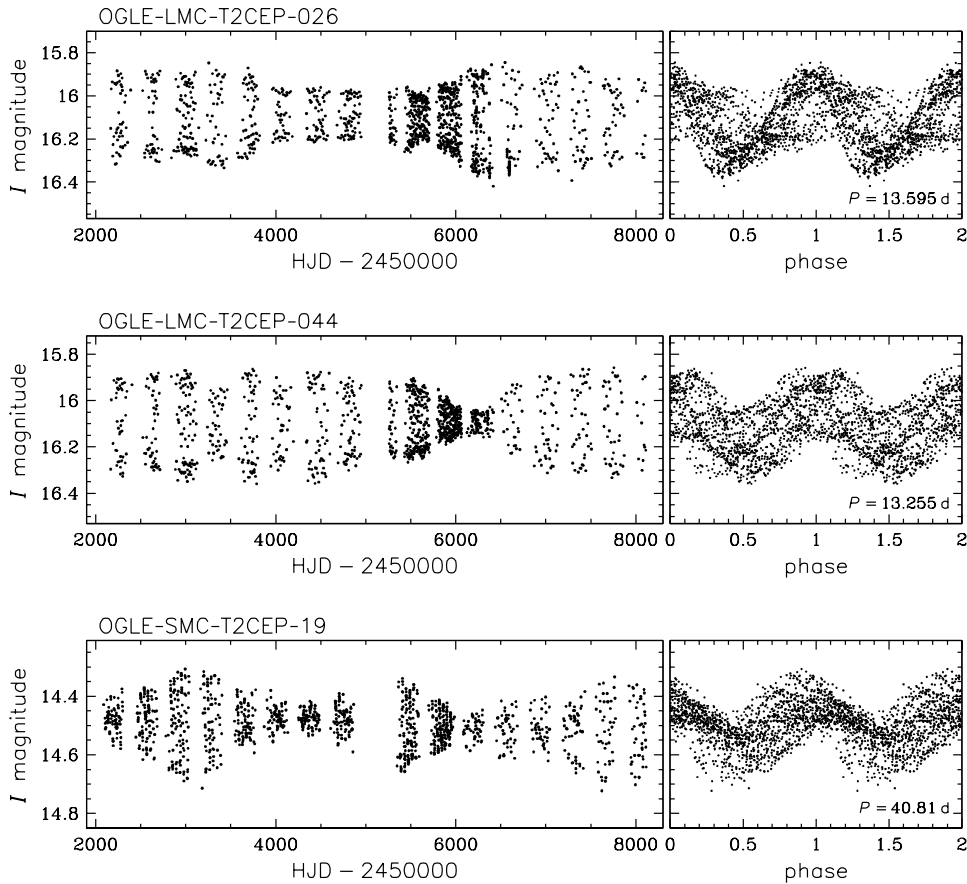
Fig. 8. Light curves of OGLE-LMC-T2CEP-026, OGLE-LMC-T2CEP-044, and OGLE-SMC-T2CEP-19 – type II Cepheids with significant amplitude changes. *Left panels* show unfolded OGLE-III and OGLE-IV *I*-band light curves, *right panels* present the same light curves folded with the mean pulsation periods. Note that the scatter of the points is partly caused by the period changes experienced by all these objects.

Unstable light curves are the most common among W Vir and RV Tau stars, which is particularly evident when the OGLE-IV photometry is merged with the older OGLE observations. Fig. 8 shows the OGLE-III + OGLE-IV light curves of three type II Cepheids with a significant amplitude modulation. Note that in some cases the amplitude changes are quasi-periodic (lower panel of Fig. 8), which resembles the Blazhko effect in RR Lyr-type stars. Right panels of Fig. 8 present the same light curves folded with the best matching constant periods. The substantial scattering of points is caused not only by the amplitude modulation, but also by the erratic period changes – another very common feature of long-period type II Cepheids.

In Fig. 9, we present other two examples of period-changing variables: a W Vir star OGLE-LMC-T2CEP-100 and an RV Tau star OGLE-LMC-T2CEP-119. In both cases, the light curves cannot be properly phased using a constant period (up-
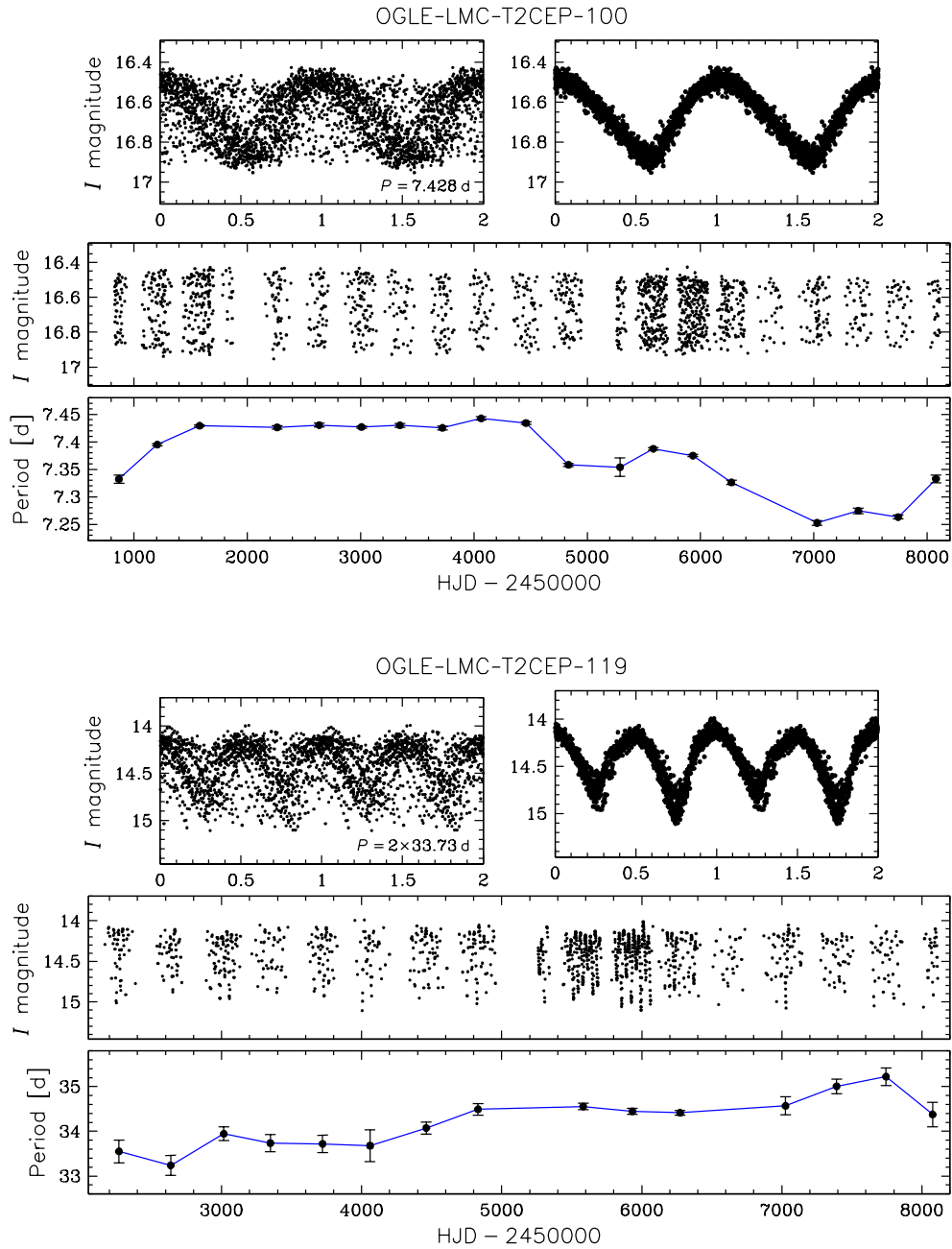
Fig. 9. Light curves of OGLE-LMC-T2CEP-100 and OGLE-LMC-T2CEP-119 – type II Cepheids with significant period changes. For each star we plot the original *I*-band light curve folded with the mean period (*upper left panels*), the folded light curve corrected for the period changes (*upper right panels*), the unfolded light curve (*middle panels*), and a diagram showing changes of the period with time (*lower panels*).

per left panels), but phasing with periods measured separately in each observing season produces well defined light curves (upper right panels). Period changes in W Vir and RV Tau stars are usually irregular (lower panels) and probably are not directly related to the evolution of type II Cepheids inside the instability strip. Our observations may indicate that the observed amplitude and period variations are a manifestation of deterministic chaos (*e.g.*, Buchler *et al.* 1996, Smolec 2016).
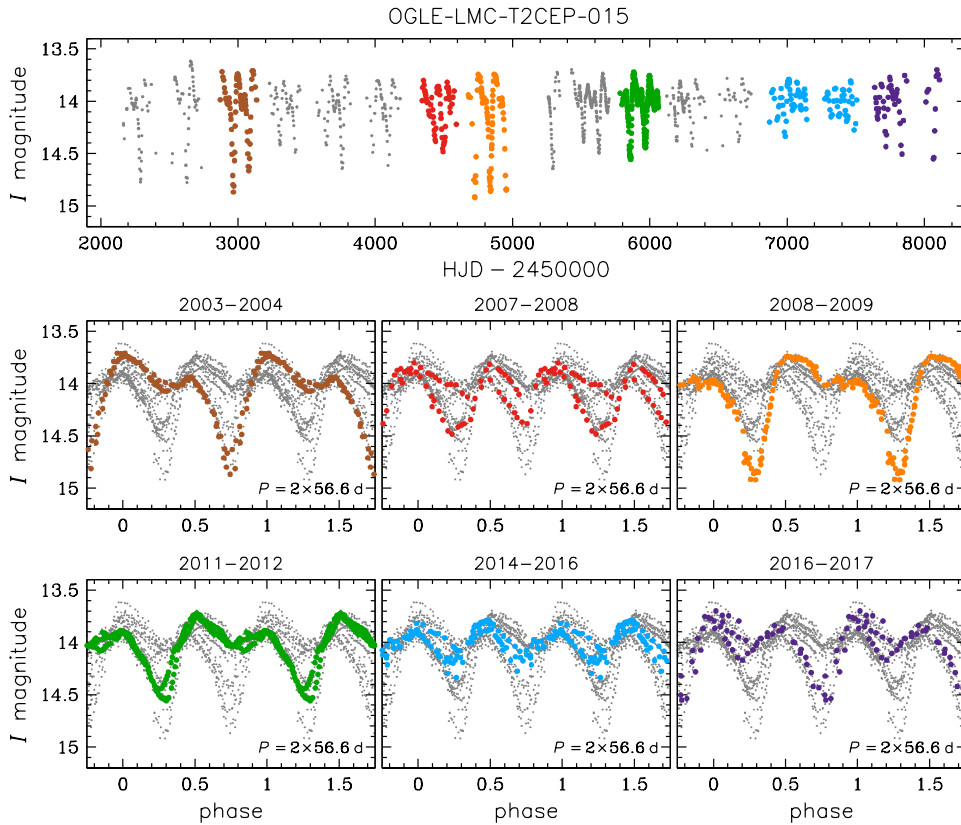


Fig. 10. OGLE-III and OGLE-IV *I*-band light curve of OGLE-LMC-T2CEP-015 – an RV Tau star that underwent two interchanges of deep and shallow minima during 16 years of the OGLE monitoring. *Upper panel* shows the unfolded light curve, *lower panels* present folded light curves. Different colors indicate observations obtained in selected observing seasons. Note the interchanges of deep and shallow minima that occurred in years 2004–2008 and 2012–2016.

The low-dimensional chaotic behavior may also be responsible for occasional interchanges of deep and shallow minima observed in some RV Tau stars (Plachy *et al.* 2014). Fig. 10 presents the OGLE light curve of OGLE-LMC-T2CEP-015, which underwent two interchanges during 16 years when it was monitored by OGLE. The lower panels of Fig. 10 display folded light curves from selected observing seasons, marked with the same colors in the upper panel. The order of the deep and shallow minima reversed between 2004 and 2008 and returned to the previous state in 2016. Both interchanges were separated by episodes of smaller

amplitudes and nearly equal depths of minima, during which OGLE-LMC-T2CEP-015 might have been classified as a yellow semiregular variable (SRd star).

## 6.    Conclusions

We presented the most extensive collection of type II Cepheids in the Magellanic System. Our sample consists of 338 carefully selected variables which constitute almost a complete census of type II Cepheids in the LMC and SMC. Together with the lists of variable stars, we provide their high-quality, long-term light curves in the standard *I*- and *V* photometric bands, well suited for exploring properties of individual objects and their environments. The most obvious directions for further studies include analyzes of the evolutionary status of type II Cepheids based on the spatial distribution, calibrations of the PL relations, spectroscopic observations of the binary systems with pulsating components, which may resolve the mystery of peculiar W Vir stars.

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