

**The OGLE Collection of Variable Stars.
Classical, Type II, and Anomalous Cepheids
toward the Galactic Center***

I. Soszyński¹, A. Udalski¹, M. K. Szymański¹, Ł. Wyrzykowski¹,
K. Ulaczyk², R. Poleski³, P. Pietrukowicz¹, S. Kozłowski¹,
D. M. Skowron¹, J. Skowron¹, P. Mróz¹, M. Pawlak¹, K. Rybicki¹
and A. Jacyszyn-Dobrzeńska¹

¹Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: soszynsk@astrouw.edu.pl

²Department of Physics, University of Warwick, Gibbet Hill Road, Coventry,
CV4 7AL, UK

³Department of Astronomy, Ohio State University, 140 W. 18th Ave., Columbus,
OH 43210, USA

Received December 5, 2017

ABSTRACT

We present a collection of classical, type II, and anomalous Cepheids detected in the OGLE fields toward the Galactic center. The sample contains 87 classical Cepheids pulsating in one, two or three radial modes, 924 type II Cepheids divided into BL Her, W Vir, peculiar W Vir, and RV Tau stars, and 20 anomalous Cepheids – first such objects found in the Galactic bulge. Additionally, we upgrade the OGLE Collection of RR Lyr stars in the Galactic bulge by adding 828 newly identified variables. For all Cepheids and RR Lyr stars, we publish time-series *VI* photometry obtained during the OGLE-IV project, from 2010 through 2017.

We discuss basic properties of our classical pulsators: their spatial distribution, light curve morphology, period–luminosity relations, and position in the Petersen diagram. We present the most interesting individual objects in our collection: a type II Cepheid with additional eclipsing modulation, W Vir stars with the period doubling effect and the RVb phenomenon, a mode-switching RR Lyr star, and a triple-mode anomalous RRd star.

Key words: *Stars: variables: Cepheids – Stars: variables: RR Lyrae – Stars: oscillations – Galaxy: center – Catalogs*

1. Introduction

Cepheids and RR Lyr stars, sometimes collectively called classical pulsators, undergo radial oscillations driven by the κ -mechanism in helium ionization zones.

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

Cepheid variables can be divided into several subclasses which exhibit markedly different masses, ages, and evolutionary histories. The youngest ones are classical (or type I) Cepheids which play a fundamental role in the calibration of the extragalactic distance scale thanks to their period–luminosity (PL) relations. On the contrary, type II Cepheids belong to an old stellar population, but the exact stage of their evolution depends on their pulsation periods. BL Her stars, with periods ranging between 1 d and 5 d, evolve away from the horizontal branch toward the asymptotic giant branch. W Vir stars (periods from 5 d to 20 d) likely undergo blueward loops from the asymptotic giant branch due to helium shell flashes. RV Tau stars (periods longer than 20 d) evolve away from the asymptotic giant branch toward a white dwarf domain. In turn, the evolutionary status of anomalous Cepheids is under debate. The two most popular scenarios are the evolution of a single, intermediate-age, metal-poor star with mass of $1\text{--}2 M_{\odot}$, and the evolution of coalescent binary systems of old, low-mass stars.

Classical pulsating stars in the central regions of the Milky Way have been the subject of extensive research in recent years. On the one hand, the Optical Gravitational Lensing Experiment (OGLE) published a large catalog of Cepheids and RR Lyr stars in the Galactic bulge (Soszyński *et al.* 2011, 2013, 2014). On the other hand, near-infrared surveys, like the VISTA Variables in the Vía Láctea (VVV, Minniti *et al.* 2010) or IRSF/SIRIUS (Nagashima *et al.* 1999), led to the discovery of classical pulsators in the highly-obscured regions of the bulge, mostly within $\approx 1^{\circ}$ from the Galactic plane (*e.g.*, Dékány *et al.* 2015, Matsunaga *et al.* 2011, 2013, 2015, 2016).

The previous version of the OGLE catalog (Soszyński *et al.* 2011, 2013) consisted of 32 candidates for classical Cepheids and 357 type II Cepheids detected in about 69 square degrees in the Galactic bulge covered by the OGLE-II and OGLE-III fields. These samples have been successfully used in several interesting studies on the stellar pulsations itself and on the structure of our Galaxy. Smolec *et al.* (2012) reported the discovery of the first BL Her stars exhibiting a period-doubling effect – a phenomenon theoretically predicted by Buchler and Moskalik (1992) and noticed for the first time in the OGLE catalog of type II Cepheids. Feast *et al.* (2014) used five fundamental-mode classical Cepheids from the OGLE-III catalog to discover flared outer disk of the Milky Way. Kovtyukh *et al.* (2016) studied metallicity of double-mode classical Cepheids from the OGLE Collection of Variable Stars (OCVS). Recently, Bhardwaj *et al.* (2017) matched the OGLE type II Cepheids with the VVV near-infrared photometry to determine the distance to the Galactic center and to investigate the spatial distribution of the old stellar population in the bulge.

In this paper, we extend the OGLE Collection of Cepheids in the Galactic bulge by objects identified in the OGLE-IV fields. The new version of our collection consists of classical Cepheids, type II Cepheids and, for the first time, anomalous Cepheids in the central regions of the Milky Way. We also supplement the OGLE

catalog of RR Lyr stars with 828 newly detected variables of this type and update the time-series photometry of the previously published stars.

The rest of the paper is organized as follows. In Section 2, we present the OGLE photometric data used in this study. Methods applied for the variable star identification and classification are introduced in Section 3. Section 4 describes the Cepheid collection itself. In Section 5, we discuss some interesting features of the published samples of pulsating stars. Finally, conclusions are presented in Section 6.

2. Observations and Data Reduction

The OGLE-IV data set used in this investigation was obtained between March 2010 and August 2017 with the 1.3-m Warsaw telescope located at Las Campanas Observatory, Chile (operated by the Carnegie Institution for Science). A mosaic camera composed of 32 CCD chips with Johnson-Cousins *VI* filters was used, providing a field of view of 1.4 square degrees with a pixel scale of 0''26. Details of the instrument can be found in Udalski *et al.* (2015).

In total, 121 OGLE-IV fields toward the Galactic center were searched for classical pulsating stars. Together with the OGLE-II and OGLE-III fields analyzed by Soszyński *et al.* (2011), we studied an area of about 182 square degrees. Owing to the OGLE observing strategy optimized to detect and monitor gravitational microlensing events, the number of collected data points varies significantly from field to field – from about 40 to 15 000 epochs per star in the *I* passband (median value: 773) and from 0 to 175 in the *V*-band (median: 37). Some of these light curves may be supplemented with observations obtained during the previous phases of the OGLE project and published by Soszyński *et al.* (2011). One should be aware that small offsets between individual light curves obtained during different stages of the OGLE project are possible, mostly because of contamination by neighboring stars in the dense bulge region. This should be taken into account when merging the photometry from different phases of the project.

Data reduction was carried out using the Difference Image Analysis software (Alard and Lupton 1998, Woźniak 2000). Detailed descriptions of the photometric reductions and astrometric calibrations of the OGLE-IV data are provided by Udalski *et al.* (2015).

3. Selection and Classification of Cepheids

Each of the 400 million *I*-band light curves collected by OGLE in the Galactic bulge was subjected to a period search procedure based on the Fourier technique implemented by Z. Kołaczkowski in the FNPEAKS code[†]. The probed frequency space ranged from 0 to 24 cycles per day, with a step of 0.00005 cycles per day. For each star the primary period was subtracted from the original light curve and the

[†]<http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks>

period search procedure was repeated on the residual data. Both periods (primary and secondary) were recorded with their amplitudes and signal-to-noise ratios. The light curves with the primary periods between 0.2 d and 100 d and amplitudes larger than 0.05 mag were fitted with a Fourier cosine series and the low-order Fourier coefficients R_{21} , ϕ_{21} , R_{31} , ϕ_{31} (Simon and Lee 1981) were derived.

This dataset became a basis for our variable star detection and classification procedure. We visually examined the light curves with the Fourier parameters characteristic for classical pulsators. The final decision about the classification of each star was made after careful analysis of the light curve shape quantified by the Fourier coefficients. In ambiguous cases, we also considered other available parameters of the stars, like colors and period ratios (for multi-mode pulsators). Additionally, some candidates for pulsating stars were identified during the search for eclipsing binary systems in the Milky Way bulge area (Soszyński *et al.* 2016a).

Contrary to the fundamental-mode pulsators, the overtone classical Cepheids and δ Sct stars (both single- and multi-mode) constitute continuity and it is a matter of convention which period will be adopted as a borderline between both types of variables. In this study, we adopted the same discrimination period as in other parts of the OCVS: pulsators with the first-overtone periods shorter than 0.23 d were classified as δ Sct stars and will be published elsewhere. The longer-period (Population I) pulsators were classified as classical Cepheids.

The Fourier coefficients were crucial for the first unambiguous identification of anomalous Cepheids in the Galactic bulge. The complete samples of classical pulsators in the Magellanic Clouds published by the OGLE project (Soszyński *et al.* 2015, 2017) allowed us to show that different types of Cepheids are well separated in the period– ϕ_{21} and period– ϕ_{31} diagrams. Fig. 1 shows these diagrams for the bulge variables overplotted on their counterparts from the Large Magellanic Cloud (LMC). The distinction between anomalous Cepheids and classical Cepheids (and also RR Lyr stars) is very prominent for the fundamental-mode pulsators (shown in the left panels of Fig. 1), while for the first-overtone pulsators (right panels of Fig. 1) the distinction is not so clear, so our classification is less certain for these objects. We firmly detected 20 anomalous Cepheids (nineteen fundamental-mode and one first-overtone) in the Galactic bulge, eight of which were previously classified as classical Cepheids (Soszyński *et al.* 2011) and six as RR Lyr stars (Soszyński *et al.* 2014). Previous designations of the reclassified variables are given in the remarks of the collection.

Type II Cepheids have traditionally been divided into BL Her, W Vir, and RV Tau stars based upon their pulsation periods. We used the same discrimination periods as in the OGLE-III Catalog of Variable Stars (Soszyński *et al.* 2011) – 5 d – to distinguish between BL Her and W Vir stars[‡] and 20 d to separate W Vir and RV Tau variables.

[‡]Note that in the Magellanic Clouds (Soszyński *et al.* 2008) we adopted a period of 4 d as a borderline between the BL Her and W Vir classes.

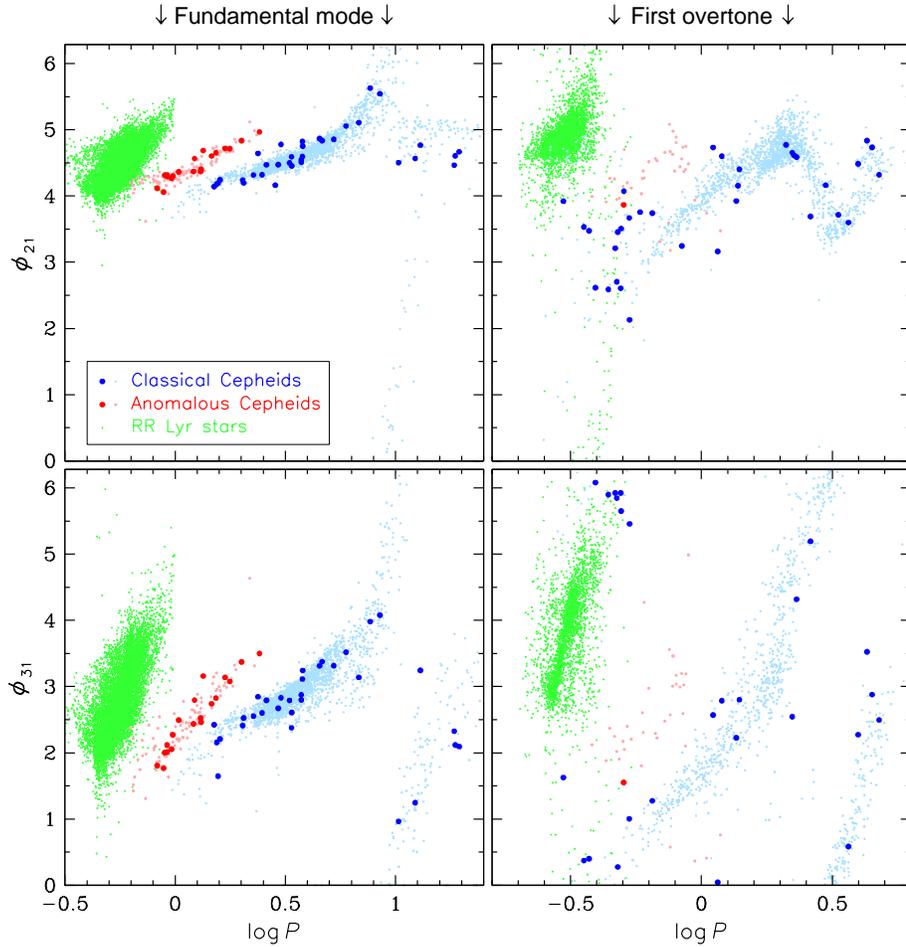


Fig. 1. Fourier coefficients ϕ_{21} and ϕ_{31} as a function of periods for single-mode classical Cepheids (blue points), anomalous Cepheids (red points), and RR Lyr stars (green points) in the Galactic bulge (larger and darker points) and Large Magellanic Cloud (smaller and lighter points). *Left* and *right panels* show diagrams for fundamental-mode and first-overtone pulsators, respectively.

We also distinguished 30 candidates for peculiar W Vir stars. This subclass of type II Cepheids was defined by Soszyński *et al.* (2008) based on the analysis of stars in the LMC. Peculiar W Vir stars are on average brighter and bluer than regular W Vir stars, and have different light curve morphology, with the rising branch being steeper than the declining one. This latter feature is reflected in the period – Fourier coefficients diagrams (Fig. 2), where the peculiar W Vir stars occupy a limited area, although with some overlap with the regular W Vir stars, so our classification should be treated with caution. In the Galactic bulge, we only found one peculiar W Vir star exhibiting additional eclipsing modulation (see Section 5.2), while in the Magellanic Clouds at least 30% of these pulsators show signs of binarity: eclipsing or ellipsoidal variations.

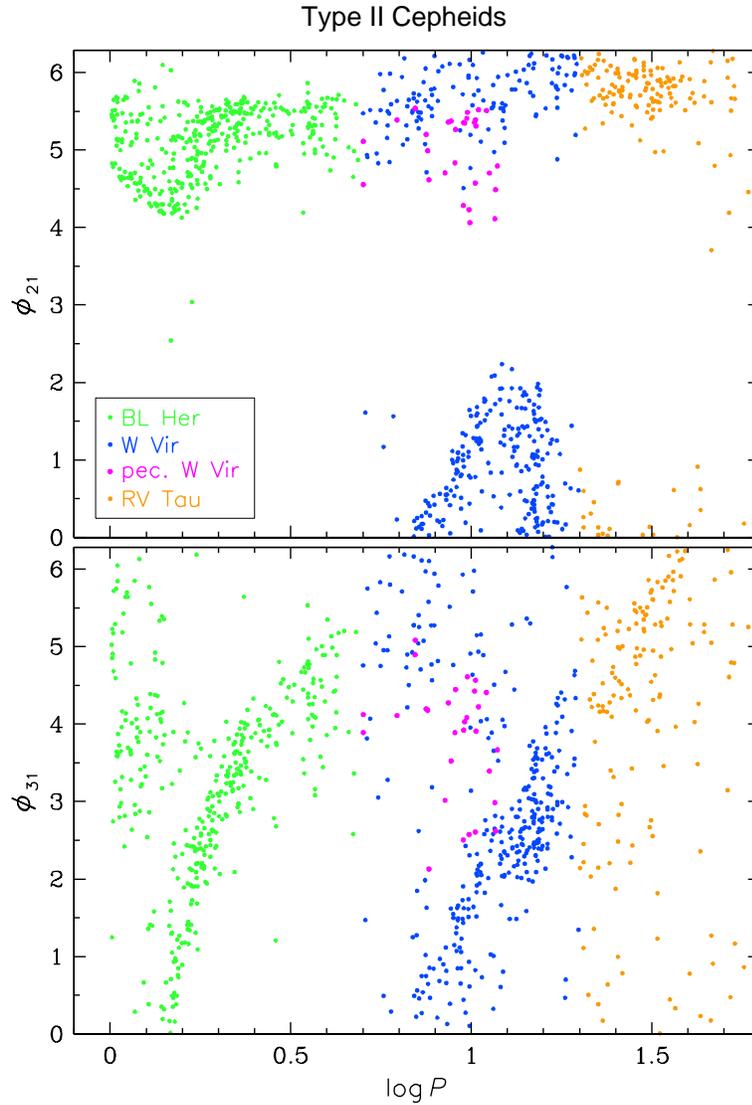


Fig. 2. Fourier coefficients ϕ_{21} and ϕ_{31} as a function of periods for type II Cepheids in the Galactic bulge. Green points indicate BL Her stars, blue points – regular W Vir stars, magenta points – peculiar W Vir stars, and orange points – RV Tau stars.

Our analysis revealed 68 classical Cepheids, 574 type II Cepheids and 828 RR Lyr stars that were not included in the previous versions of the OCVS. Some objects have been reclassified which is summarized in Table 1. In addition to the aforementioned pulsators that were reclassified as anomalous Cepheids, we removed from the collection several objects which likely belong to other (usually unknown) types of variable stars. We confirm that all the five stars in the flared disk of the Milky Way studied by Feast *et al.* (2014) are indeed the fundamental-mode classical Cepheids.

Table 1

Reclassified stars from the OGLE-III Catalog of Variable Stars in the Galactic bulge

Identifier	New classification	Identifier	New classification
OGLE-BLG-CEP-006	Anom. Cepheid	OGLE-BLG-T2CEP-245	Other
OGLE-BLG-CEP-008	Anom. Cepheid	OGLE-BLG-T2CEP-264	Other
OGLE-BLG-CEP-010	Anom. Cepheid	OGLE-BLG-T2CEP-295	Other
OGLE-BLG-CEP-011	Type II Cepheid	OGLE-BLG-T2CEP-323	Other
OGLE-BLG-CEP-012	Other	OGLE-BLG-RRLYR-08018	Other
OGLE-BLG-CEP-013	Other	OGLE-BLG-RRLYR-09254	Class. Cepheid
OGLE-BLG-CEP-014	Anom. Cepheid	OGLE-BLG-RRLYR-10224	Eclipsing
OGLE-BLG-CEP-017	Other	OGLE-BLG-RRLYR-18443	Anom. Cepheid
OGLE-BLG-CEP-022	Anom. Cepheid	OGLE-BLG-RRLYR-21455	Anom. Cepheid
OGLE-BLG-CEP-023	Anom. Cepheid	OGLE-BLG-RRLYR-25667	Anom. Cepheid
OGLE-BLG-CEP-025	Anom. Cepheid	OGLE-BLG-RRLYR-27874	Class. Cepheid
OGLE-BLG-CEP-026	Artifact	OGLE-BLG-RRLYR-28668	Anom. Cepheid
OGLE-BLG-CEP-028	Anom. Cepheid	OGLE-BLG-RRLYR-31394	Spotted
OGLE-BLG-T2CEP-042	Other	OGLE-BLG-RRLYR-33138	Anom. Cepheid
OGLE-BLG-T2CEP-070	Other	OGLE-BLG-RRLYR-36100	Anom. Cepheid
OGLE-BLG-T2CEP-099	Other	OGLE-BLG-ECL-297887	Type II Cepheid

4. OGLE Collection of Cepheids in the Galactic Bulge

The newly detected classical pulsators have been added to the previously published OGLE catalogs. In total, the OCVS now contains 87 classical Cepheids, 924 type II Cepheids, 20 anomalous Cepheids, and 39 074 RR Lyr stars in the Galactic bulge. 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/blg/cep/>

<ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/t2cep/>

<ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gal/acep/>

<ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/rrlyr/>

Each object in our collection received a unique identifier which, with some exceptions, follows the scheme proposed in the previous parts of the OCVS. For example, classical Cepheids are designated as OGLE-BLG-CEP-NNN, where NNN is a three-digit number. In the OGLE-III catalog (Soszyński *et al.* 2011), we used two-digit numbers in the identifiers of classical Cepheids, but in this work we reached number OGLE-BLG-CEP-100, which forced us to slightly change the naming scheme. Objects from OGLE-BLG-CEP-001 to OGLE-BLG-CEP-032 were included in the OGLE-III Catalog of Variable Stars (Soszyński *et al.* 2011),

while objects from OGLE-BLG-CEP-033 to OGLE-BLG-CEP-100 are the newly discovered classical Cepheids. These new pulsators are ordered by increasing right ascension. The names of anomalous Cepheids – OGLE-GAL-ACEP-NNN – follow the scheme proposed by Soszyński *et al.* (2017), who discovered seven Galactic anomalous Cepheids in front of the Magellanic Clouds.

All tables on the FTP site are in ASCII format and contain basic information about the stars: their pulsation modes, J2000 equatorial coordinates, intensity mean magnitudes in the *I*- and *V*-bands, periods in days with their uncertainties (derived with the TATRY code of Schwarzenberg-Czerny 1996), epochs of maximum light, peak-to-peak amplitudes in the *I*-band, and Fourier coefficients R_{21} , ϕ_{21} , R_{31} , ϕ_{31} derived for the *I*-band light curves. For the already known variables we provide their identifiers from the International Variable Star Index (Watson *et al.* 2006).

5. Discussion

5.1. Classical Cepheids

Fig. 3 shows the sky distribution of the OGLE classical Cepheids in the Galactic coordinates. Despite the fact that classical Cepheids are young (< 300 Myr), relatively massive ($3.5\text{--}20 M_{\odot}$) stars, a large fraction of our objects are located far from the Galactic plane, up to the Galactic latitudes $|b| = 5^{\circ}$. Feast *et al.* (2014) measured distances to five OGLE fundamental-mode Cepheids and showed that they are located in the flared outer disk of the Milky Way, from 0.9 kpc to 2.1 kpc from the Galactic plane. Our collection probably contains more classical Cepheids in the flared disk, not necessarily only the fundamental-mode pulsators.

The presence of classical Cepheids inside the Galactic bulge is currently a matter of debate. The VVV survey reported the discovery of 35 classical Cepheids in the highly-obscured regions of the Galactic bulge (Dékány *et al.* 2015) and suggested that the young stellar population form an inner thin disk surrounding the Galactic center. Matsunaga *et al.* (2016) used the IRSF/SIRIUS near-infrared observations to detect their own set of Cepheids in this area (partly overlapping with the VVV Cepheids), but they concluded that almost all of these variables are located behind the bulge and the Galactic center lacks classical Cepheids. The only exception from this rule are four classical Cepheids discovered by Matsunaga *et al.* (2011, 2015) in the very center of the Milky Way, in the so called Nuclear Bulge or Central Molecular Zone.

We cannot participate in this interesting discussion, because the Nuclear Bulge is inaccessible to optical observations owing to enormous interstellar extinction. However, the OGLE Collection of Variable Stars also contains several classical Cepheids relatively close ($|b| < 1^{\circ}$) to the plane of the Milky Way. These objects are probably located in the Galactic disk in front of the Galactic bulge. For most of these stars, the *V*-band data are not available, usually because of the high reddening which shifts the *V*-band magnitudes below the OGLE detection threshold.

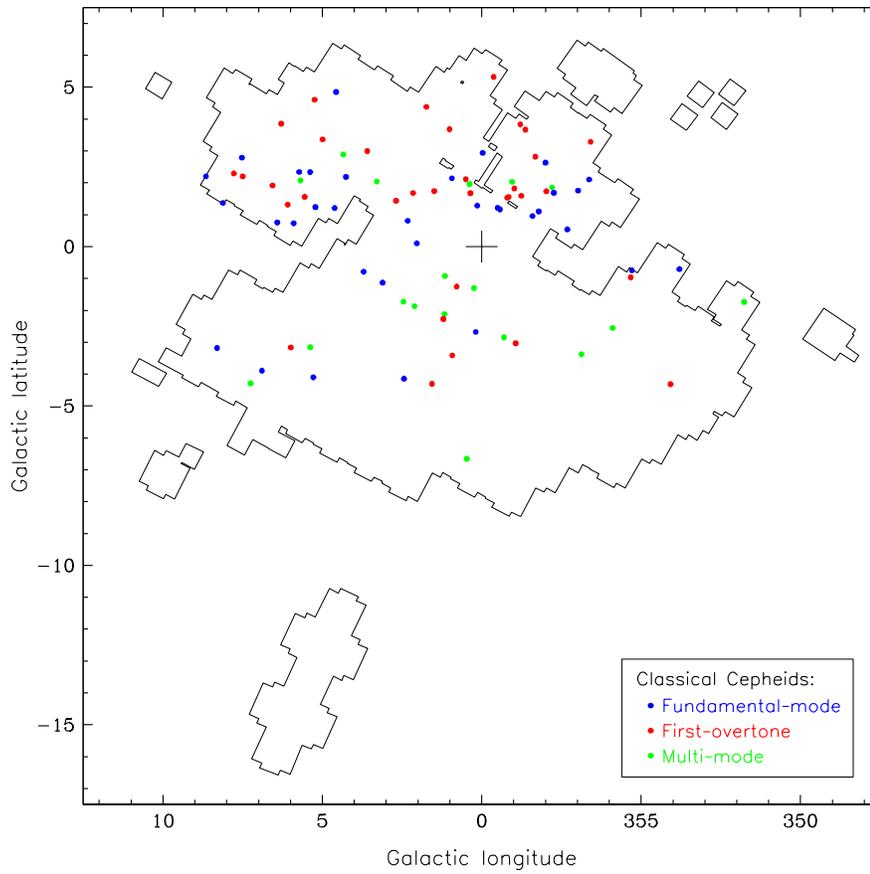


Fig. 3. Positions in the sky of the OGLE classical Cepheids (in Galactic coordinates). Blue, red and green points mark fundamental-mode, first-overtone, and multi-mode pulsators, respectively. Black contours show borders of the OGLE fields.

Our collection includes 16 double-mode and three triple-mode classical Cepheids. Positions of these stars in the Petersen diagram (shorter-to-longer period ratio vs. the longer period) overplotted on the LMC and SMC beat Cepheids are shown in Fig. 4. Soszyński *et al.* (2011) showed that period ratios of double-mode classical Cepheids in the Galactic bulge are smaller than in the Magellanic Clouds, which is probably caused by metallicity differences between these stellar environments. Our extended sample confirms that indeed double-mode Cepheids in the bulge, both F/1O and 1O/2O pulsators, have smaller period ratios than their counterparts in the Magellanic Clouds, but this rule is valid only for the short-period variables. The longest period beat Cepheids (two F/1O and two 1O/2O pulsators) have period ratios virtually the same as variables in the Magellanic Clouds.

Triple-mode Cepheids (marked with triangles in Fig. 4) have generally short periods and also tend to have smaller period ratios compared to the LMC and SMC variables.

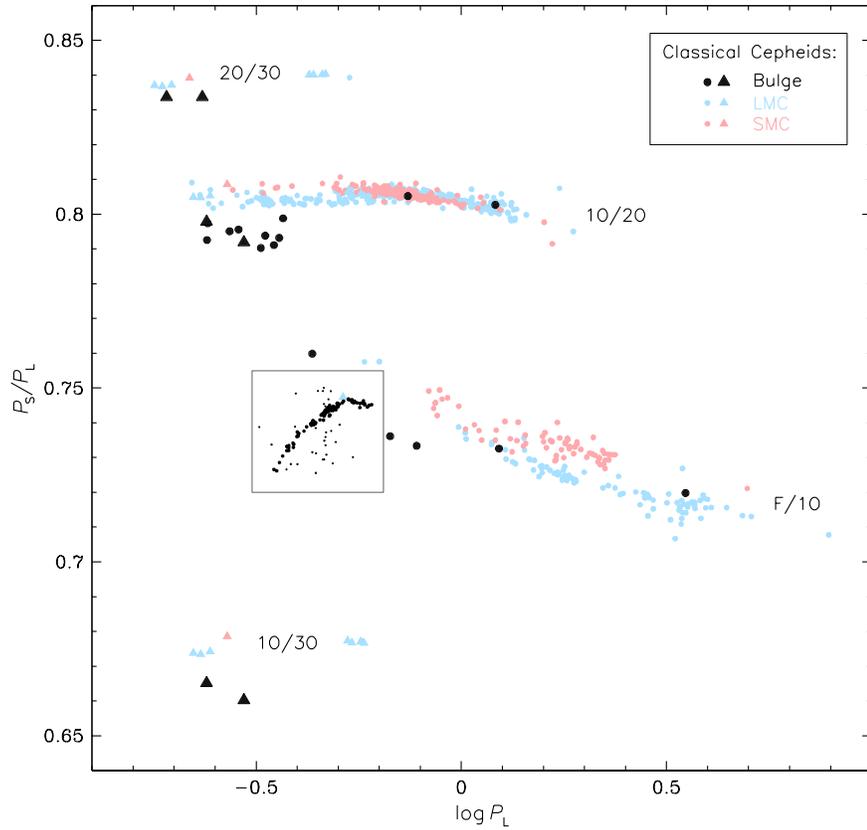


Fig. 4. Petersen diagram for double-mode (circles) and triple-mode (triangles) classical pulsators detected by the OGLE project toward the Galactic bulge (black symbols), LMC (light blue symbols), and SMC (light red symbols). Gray rectangle separates multi-mode RR Lyr stars – this region is zoomed in Fig. 11.

5.2. Type II Cepheids

In this paper, we present the most numerous sample of type II Cepheids detected in one stellar environment. Two-dimensional spatial distribution of 924 type II Cepheids from our collection is presented in Fig. 5. These stars generally show a strong concentration toward the Galactic center, but they avoid regions around the Galactic plane. This is of course caused by the large amount of interstellar matter toward these regions which obscures stars in the optical regime. Such a distribution suggests that the vast majority of our type II Cepheids are members of the Galactic bulge.

The same conclusion can be drawn from the analysis of the PL diagram (Fig. 6), where as the “luminosity” we used the reddening-independent Wesenheit index in the Galactic bulge defined by Pietrukowicz *et al.* (2015) as $W_I = I - 1.14(V - I)$ (Fig. 6 includes only those variables, for which both, I - and V -band, mean magnitudes are available). The majority of type II Cepheids populate a PL relation that is an extension of the relation for RRab stars in the bulge, which indicates that both

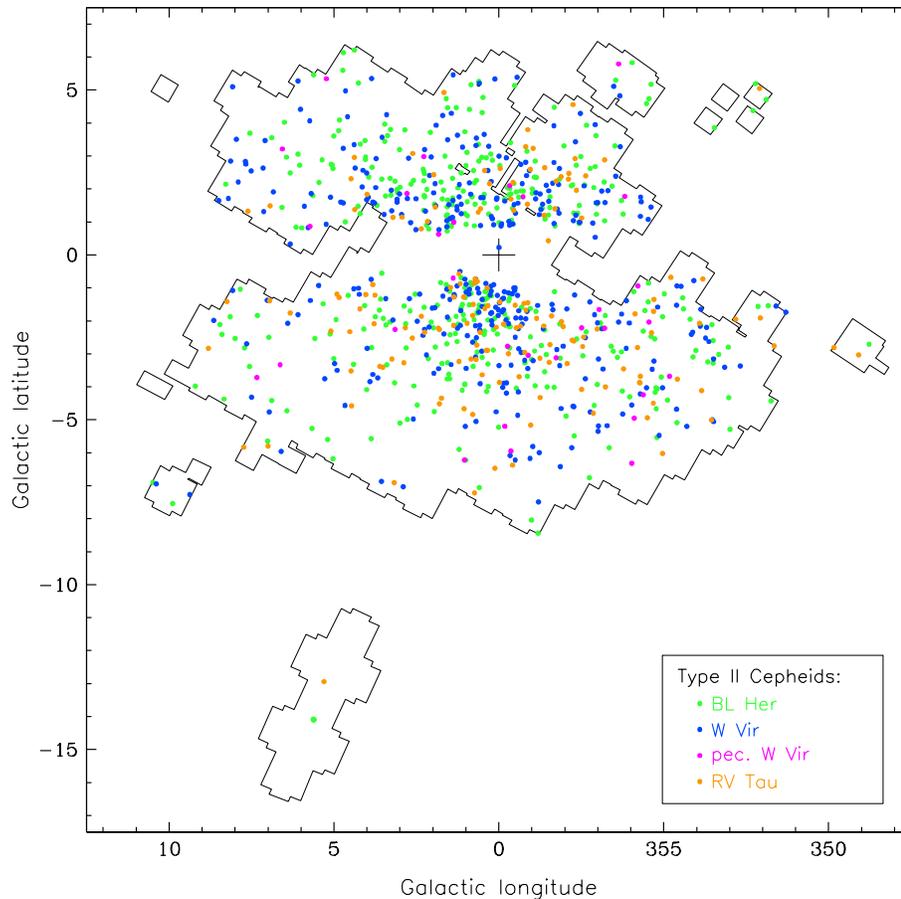


Fig. 5. Positions in the sky of the OGLE type II Cepheids (in Galactic coordinates). Green, blue, magenta, and orange points mark BL Her, W Vir, peculiar W Vir, and RV Tau stars, respectively. Black contours show borders of the OGLE fields.

classes are on average at the same distance from us. In turn, most of the classical Cepheids are fainter than type II Cepheids with the same periods, which suggests that the most classical Cepheids in our sample are located far behind the Milky Way center, also in the flared disk (Feast *et al.* 2014). As already mentioned, a number of classical Cepheids in our sample lie in front of the Galactic bulge, but most of them do not have V -band measurements and they are not included in the period vs. Wesenheit index diagram.

Our collection covers the full range of periods observed in type II Cepheids: from 1 d to 66 d[§]. BL Her variables with the shortest periods are adjacent to the longest-period RR Lyr stars and the boundary period between these groups is not strictly defined. We traditionally used a 1.0 d period as a borderline between RR Lyr and BL Her stars.

[§]In the OCVS we provide “single” periods, *i.e.*, intervals between successive minima, even if the period-doubling effect is present

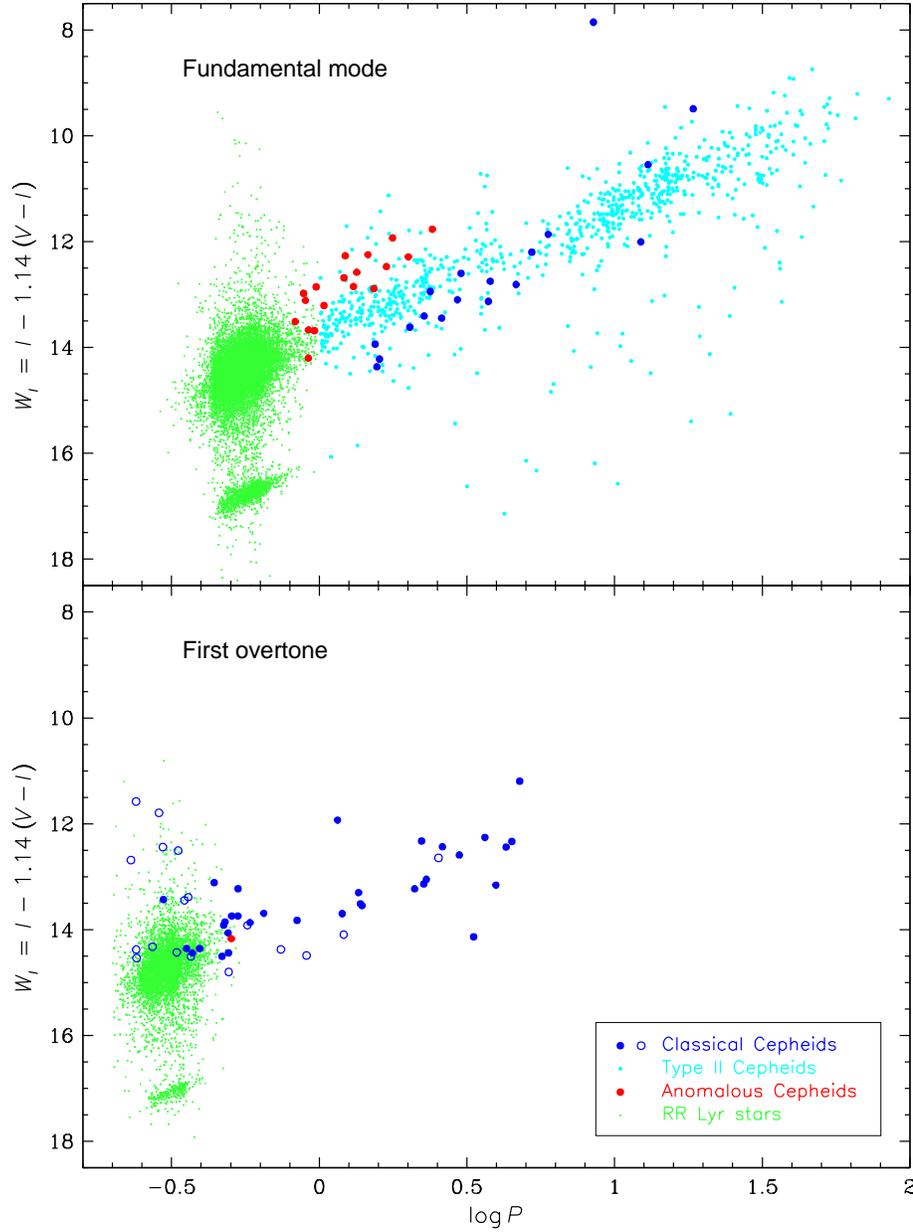


Fig. 6. Period vs. Wesenheit index diagram for classical Cepheids (blue points), type II Cepheids (cyan points), anomalous Cepheids (red points), and RR Lyr stars (green points). *Upper panel* shows fundamental-mode variables, while *lower panel* presents first overtone pulsators. Open blue circles mark the first-overtone periods of the multi-mode Cepheids.

In our collection, type II Cepheids with pulsation periods longer than 20 d are classified as RV Tau stars. The characteristic feature of RV Tau variables – alternating deep and shallow minima (period doubling) – seems not to be a distinctive classification characteristic. On the one hand, the period doubling is a common

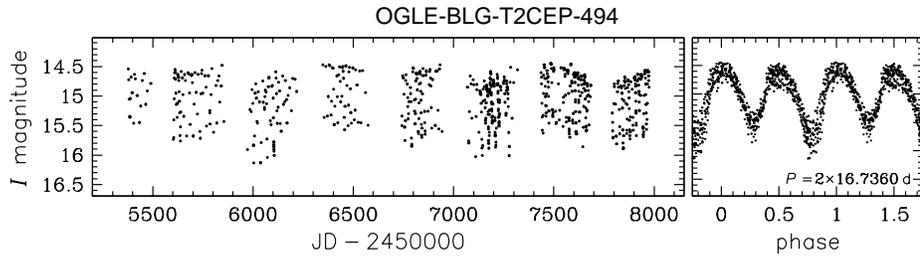


Fig. 7. *I*-band light curve of OGLE-BLG-T2CEP-494 – one of the shortest-period type II Cepheid with a prominent RV-Tau-like behavior: periodic alternations of deep and shallow minima and the long-term variations of the mean brightness (RVb type). *Left panel* presents unfolded light curve collected in the years 2010–2017. *Right panel* shows the same light curve folded with the doubled pulsation period.

phenomenon also among long-period W Vir stars, down to a period of about 16 d. Fig. 7 shows the light curve of OGLE-BLG-T2CEP-494 ($P = 16.736$ d) which exhibits alternations of minima and maxima. On the other hand, our collection contains some long-period type II Cepheids ($P > 20$ d) with no clear alternations of minima, but in our catalog they are formally categorized as RV Tau stars. Such stars may also be classified as yellow semiregular variables (SRd stars).

At least 15 RV Tau variables in our collection belong to the RVb class, which means that these stars experience long-term variations of the mean brightness, with periods of 470–2800 d and amplitudes from 0.2 mag to 2.5 mag. Also two W Vir stars (with pulsation period shorter than 20 d) exhibit such modulation (Fig. 7). The long-term changes are commonly interpreted as being caused by periodic obscuration of a binary system by a circumbinary dust disk (*e.g.*, Evans 1985, Pollard *et al.* 1996, Van Winckel *et al.* 1999). The long-term homogeneous OGLE light curves in two standard filters may provide important constraints on theoretical models of the RVb phenomenon. In some objects, the depths of the RVb modulation significantly change from cycle to cycle.

The OGLE catalog of type II Cepheids in the Magellanic Clouds (Soszyński *et al.* 2008, 2010) contains an exceptionally large fraction of pulsators that are members of binary systems. Over a dozen type II Cepheids show additional eclipsing or ellipsoidal modulation. Most of these objects were classified as peculiar W Vir stars, which suggests that the binarity might be related to the origin of this class of pulsating stars (see the discussion in Pilecki *et al.* 2017).

It appears that the fraction of eclipsing Cepheids in the Galactic bulge is much lower than in the Magellanic Clouds. In our collection we found only one type II Cepheid that exhibits additional eclipsing modulation: OGLE-BLG-T2CEP-674. Its light curve is shown in the upper panel of Fig. 8, while middle panels show disentangled pulsation and eclipsing variabilities. The orbital period of this system is close to 2 years (714 d), which interferes with annual gaps in the OGLE photometry, but luckily both, primary and secondary, eclipses are well visible in the light curve.

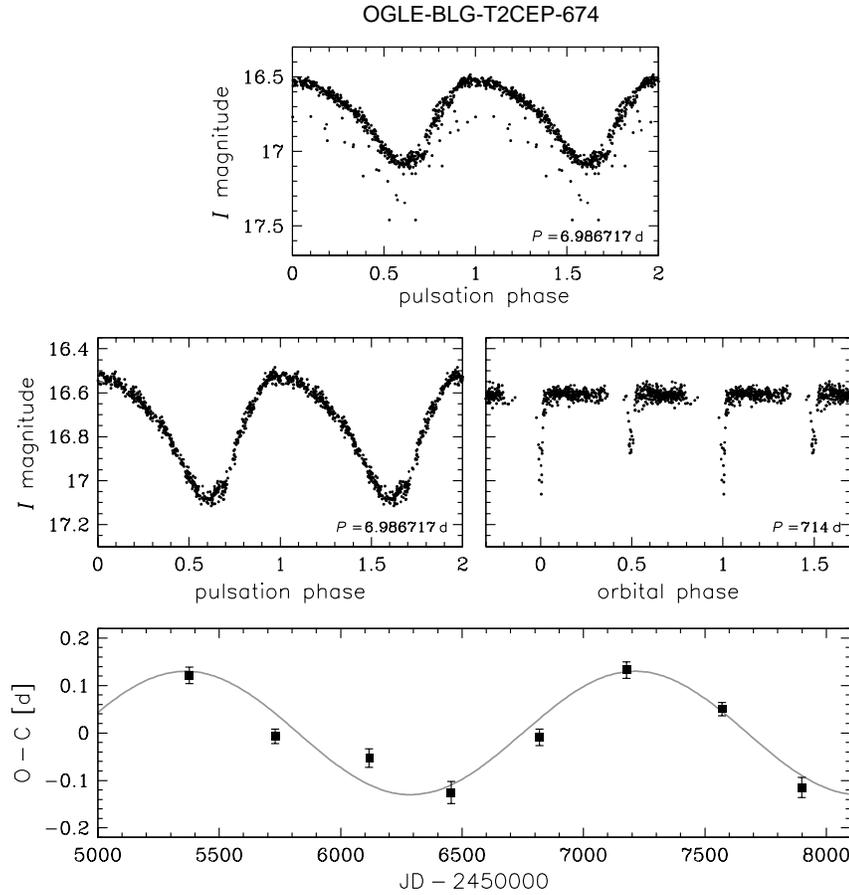


Fig. 8. OGLE-BLG-T2CEP-674 – a type II Cepheid with additional eclipsing variability. *Upper panel* shows the original light curve folded with the pulsation period, *middle left panel* presents the pulsation light curve after removing the eclipses, *middle right panel* presents the eclipsing light curve prewhitened with the pulsations, *lower panel* shows the $O - C$ diagram obtained in the years 2010–2017.

A closer look at the photometric data of OGLE-BLG-T2CEP-674 reveals yet another interesting feature. Based on the pulsation light curve we constructed an observed-minus-calculated ($O - C$) diagram which is presented in the lower panel of Fig. 8. This diagram shows a long-term sinusoidal-like variations which may be caused by the light-travel time effect in a binary system. Surprisingly, a possible period of the sinusoidal variations visible in the $O - C$ diagram (about 1900 d) is much longer than the orbital period measured from the eclipsing modulation (714 d), which suggests that OGLE-BLG-T2CEP-674 is a member of at least a triple system with the third body on a ~ 1900 d orbit. However, we must stress here that this period is comparable to the total time span of the OGLE-IV photometry (the star was not observed during the previous phases of the OGLE survey) so we cannot be sure that the variations in the $O - C$ diagram are indeed periodic ones.

5.3. Anomalous Cepheids

In this paper, we present the first *bona fide* anomalous Cepheids detected in the Galactic bulge. Eight of these stars were published by Soszyński *et al.* (2011) as classical Cepheids and six other objects were previously classified as RR Lyr stars (Soszyński *et al.* 2014), because at that time there was no reliable method to distinguish anomalous Cepheids from other types of classical pulsators based solely on their light curve shape. This situation changed when Soszyński *et al.* (2015, 2017) selected the richest known population of anomalous Cepheids in the Magellanic Clouds and showed that the shape of their light curves (quantitatively assessed by the Fourier coefficients ϕ_{21} and ϕ_{31}) is an efficient diagnostic to separate these groups. Positions in the sky of the 20 anomalous Cepheids in the Galactic bulge are shown in Fig. 9. Despite a small number of objects, we may notice a lack of anomalous Cepheids close to the Galactic plane due to high interstellar extinction in these regions.

Fundamental-mode anomalous Cepheids are well separated from classical Cepheids in the PL diagram (Fig. 6), but, paradoxically, anomalous Cepheids have

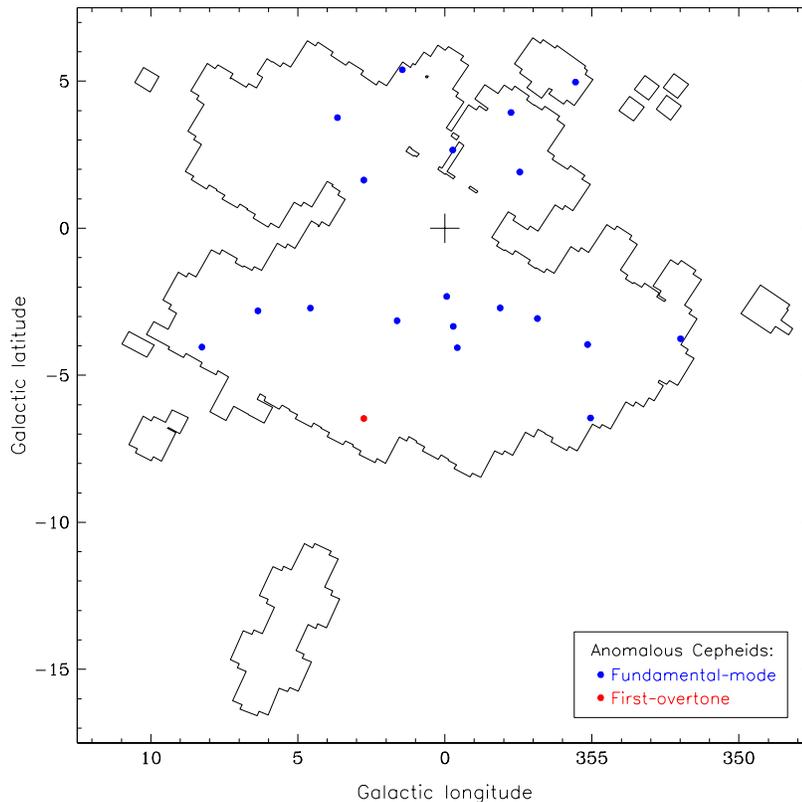


Fig. 9. Positions in the sky of the OGLE anomalous Cepheids (in Galactic coordinates). Blue and red symbols mark fundamental-mode and first-overtone pulsators, respectively. Black contours show borders of the OGLE fields.

brighter apparent magnitudes than their classical siblings. An analysis of pulsating stars in the LMC (Soszyński *et al.* 2015) shows that anomalous Cepheids are intrinsically fainter by about 0.7 mag than classical Cepheids. On the other hand, anomalous Cepheids are on average brighter than type II Cepheids, just like in the Magellanic Clouds, so we can safely assume that our sample of anomalous Cepheids belongs to the Galactic bulge.

5.4. RR Lyr stars

The newly detected 828 RR Lyr stars represent about 2% of all variables of this type discovered by OGLE in the central regions of the Galaxy (Soszyński *et al.* 2014). These new detections were previously overlooked for various reasons. Most of the new RR Lyr variables (72%) are first-overtone pulsators (RRc stars) which usually show nearly sinusoidal light curves that can be confused with other classes of variable stars, for example close binary systems. Some variables were missed because of a small number of data points, or very low amplitudes, or pulsation periods close to 1 or 2/3 of the sidereal day which affected the period determinations.

The time-series photometry of RR Lyr stars published by Soszyński *et al.* (2014) have been supplemented with new observations collected by the OGLE-

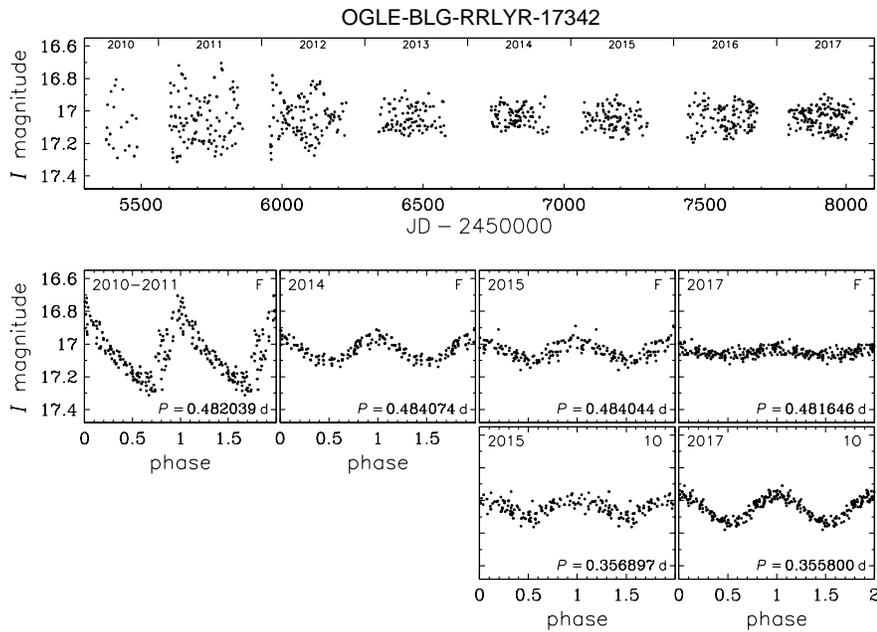


Fig. 10. *I*-band light curve of OGLE-BLG-RRLYR-17342 – an RR Lyr star that switched from a single-mode (RRab) to double-mode (anomalous RRd) pulsation. *Upper panel* shows unfolded OGLE-IV light curve collected in the years 2010–2017. *Lower panels* show folded light curves obtained in the selected seasons: 2010–2011, 2014, 2015, and 2017. From 2015, when the first-overtone mode turned on, we present disentangled light curves of both modes. Note changes of the pulsation periods in the different seasons.

IV survey up to August 2017. At present, the time-span of the OGLE-IV light curves exceeds 7 years and for some stars it can be increased to even 20 years by joining the OGLE-II and OGLE-III data points. These light curves can be used for follow-up studies of all stationary and non-stationary phenomena in pulsating stars: non-radial modes, Blazhko effect, period changes, mode switching, light-time effect in binary system hosting pulsating stars, etc.

Fig. 10 shows an example of such non-stationary behaviors: the light curve of OGLE-BLG-RRLYR-17342 – a Blazhko RR Lyr star that switched from a single-mode R Rab star to a double-mode RRd star. Lower panels of Fig. 10 display folded light curves of OGLE-BLG-RRLYR-17342 obtained by OGLE in selected seasons. The amplitude of the fundamental-mode pulsation has continuously decreased over the eight years of the monitoring and at present it is slightly above to the detection limit of the OGLE photometry. In 2015, the first-overtone mode appeared in the light curve and the star became a double-mode pulsator. Three other mode-switching RR Lyr stars in the Galactic bulge were reported by Soszyński *et al.* (2014).

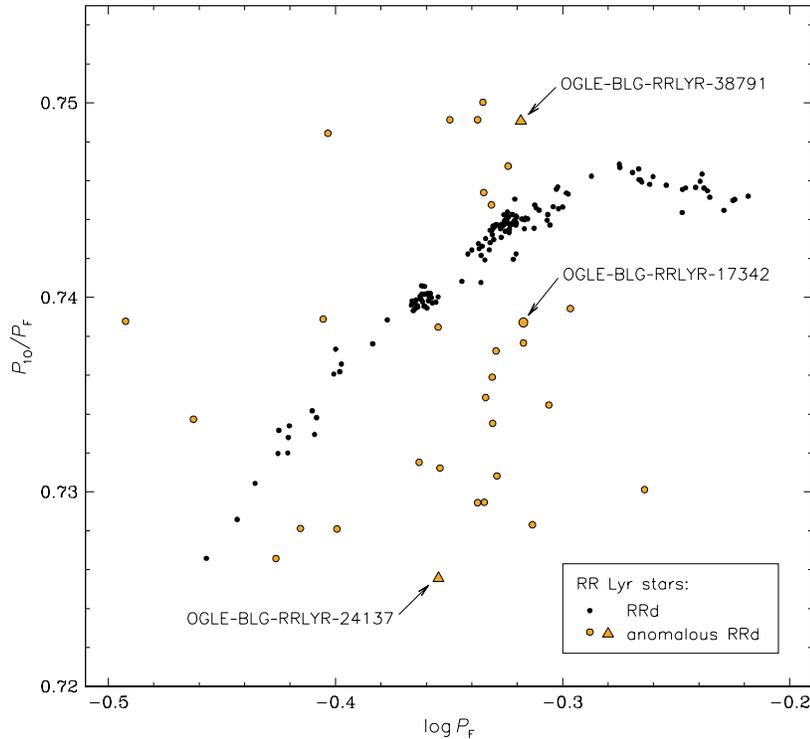


Fig. 11. Petersen diagram for double-mode (circles) and triple-mode (triangles) RR Lyr stars in the Galactic bulge. Black points mark “regular” RRd stars, yellow symbols represent anomalous RRd stars (Soszyński *et al.* 2016b). Triple-mode stars – OGLE-BLG-RRLYR-24137 and OGLE-BLG-RRLYR-38791 – and a mode-switching pulsator – OGLE-BLG-RRLYR-17342 – are indicated by arrows.

We reclassified 24 double-mode RR Lyr stars from ordinary to anomalous RRd stars. This latter class of pulsators was defined by Soszyński *et al.* (2016b) who noticed a distinct group of double-mode RR Lyr variables in the Magellanic Clouds. Anomalous RRd stars have different period and amplitude ratios than typical RRd stars and most of them show Blazhko modulation (Smolec *et al.* 2015a). In the present investigation, the main classification criterion was the position of a given pulsator in the Petersen diagram (Fig. 11). All multi-mode RR Lyr variables that are located outside the curved sequence in the Petersen diagram (both, above and below, this sequence) were classified as anomalous RRd stars. Thus, we have expanded the definition of anomalous double-mode RR Lyr variables introduced by Soszyński *et al.* (2016b) for the Magellanic Clouds members by adding objects with the P_{10}/P_F period ratios higher than observed for “classical” RRd stars. The majority of our candidates for anomalous RRd stars in the Galactic bulge share the features of their Magellanic Clouds counterparts: usually the fundamental mode is the dominant one and most of these objects exhibit the Blazhko effect. Currently, the OCVS contains 31 anomalous RRd stars, both reclassified and newly discovered variables. This group includes also two mode-switching RR Lyr stars: OGLE-BLG-RRLYR-13442 and OGLE-BLG-RRLYR-17342.

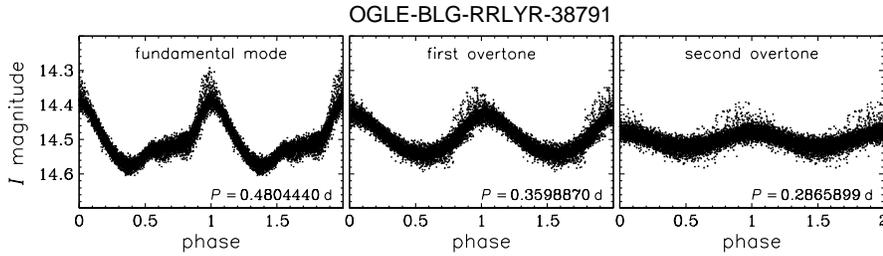


Fig. 12. *I*-band light curve of OGLE-BLG-RRLYR-38791 – a triple-mode anomalous RRd star. Each panel shows a folded light curve of this star prewhitened with the two other pulsation modes.

One of the new detections deserves special attention. OGLE-BLG-RRLYR-38791 is a triple-mode star pulsating likely in the fundamental, first-overtone, and second-overtone modes. Its disentangled light curves corresponding to the three pulsation modes are displayed in Fig. 12. The classification of this object is unclear. We decided to list it among anomalous RRd stars for a few reasons. First, its fundamental-mode and first-overtone periods place this object among anomalous RRd pulsators in the Petersen diagram (Fig. 11). Second, the fundamental-mode has the largest amplitude. And third, the shape of the fundamental-mode light curve resembles those in some anomalous RRd stars.

Another triple-mode RR Lyr star was found in the OCVS by Smolec *et al.* (2015b). OGLE-BLG-RRLYR-24137 (in the present work also classified as an anomalous RRd star) exhibits two radial fundamental and first-overtone modes and the third periodicity that may correspond to the radial third-overtone mode or a non-radial mode.

6. Conclusions

We present the largest collection of classical, type II, and anomalous Cepheids in and toward the central regions of the Milky Way. We release the long-term time-series photometry obtained by the OGLE project for all the stars. The OGLE samples of classical pulsators provide us with a tool to test evolutionary and stellar pulsation models, as well as to study the structure and star formation history in the Galactic bulge region, which is crucial for our understanding of the Milky Way evolution.

In the near future, the OCVS will be extended by classical pulsators found within the OGLE Galaxy Variability Survey regularly observing an area of about 2000 square degrees in the Galactic disk and outer regions of the Galactic bulge. This sub-project of the OGLE survey has been carried out since 2013 and currently it accumulated long-term multi-epoch photometric data which can be used to perform an effective search for variable stars with their reliable classification. This dataset promises to be a powerful tool to improve our understanding of the Galactic structure.

Acknowledgements. We would like to thank Profs. M. Kubiak and G. Pietrzyński, former members of the OGLE team, for their contribution to the collection of the OGLE photometric data over the past years. We are grateful for discussions and constructive comments to R. Smolec. We thank Z. Kołaczkowski and A. Schwarzenberg-Czerny for providing software used in this study.

This work has been supported by the National Science Centre, Poland, grant MAESTRO 2016/22/A/ST9/00009. The OGLE project has received funding from the Polish National Science Centre grant MAESTRO 2014/14/A/ST9/00121.

REFERENCES

- Alard, C., and Lupton, R.H. 1998, *ApJ*, **503**, 325.
 Bhardwaj, A., *et al.* 2017, *A&A*, **605**, A100.
 Buchler, J.R. and Moskalik, P. 1992, *ApJ*, **391**, 736.
 Dékány, I., *et al.* 2015, *ApJ*, **812**, L29.
 Feast, M.W., Menzies, J.W., Matsunaga, N., and Whitelock, P.A. 2014, *Nature*, **509**, 342.
 Kovtyukh, V., *et al.* 2016, *MNRAS*, **460**, 2077.
 Evans, T.L. 1985, *MNRAS*, **217**, 493.
 Matsunaga, N., *et al.* 2011, *Nature*, **477**, 188.
 Matsunaga, N., *et al.* 2013, *MNRAS*, **429**, 385.
 Matsunaga, N., *et al.* 2015, *ApJ*, **799**, 46.
 Matsunaga, N., *et al.* 2016, *MNRAS*, **462**, 414.
 Minniti, D., *et al.* 2010, *New Astronomy*, **15**, 433.
 Nagashima C., *et al.* 1999, in: “Star Formation 1999”. Ed., Nakamoto T., Nobeyama Radio Observatory, Nagano, p. 397.
 Pietrukowicz, P., *et al.* 2015, *ApJ*, **811**, 113.
 Pilecki, B., *et al.* 2017, *ApJ*, **842**, 110.
 Pollard, K.R., Cottrell, P.L., Kilmartin, P.M., and Gilmore, A.C. 1996, *MNRAS*, **279**, 949.

- Schwarzenberg-Czerny, A. 1996, *ApJ*, **460**, L107.
- Simon, N.R., and Lee, A.S. 1981, *ApJ*, **248**, 291.
- Smolec, R., *et al.* 2012, *MNRAS*, **419**, 2407.
- Smolec, R., *et al.* 2015a, *MNRAS*, **447**, 3756.
- Smolec, R., *et al.* 2015b, *MNRAS*, **447**, 3873.
- Soszyński, I., *et al.* 2008, *Acta Astron.*, **58**, 293.
- Soszyński, I., *et al.* 2010, *Acta Astron.*, **60**, 91.
- Soszyński, I., *et al.* 2011, *Acta Astron.*, **61**, 285.
- Soszyński, I., *et al.* 2013, *Acta Astron.*, **63**, 37.
- Soszyński, I., *et al.* 2014, *Acta Astron.*, **64**, 177.
- Soszyński, I., *et al.* 2015, *Acta Astron.*, **65**, 233.
- Soszyński, I., *et al.* 2016a, *Acta Astron.*, **66**, 405.
- Soszyński, I., *et al.* 2016b, *MNRAS*, **463**, 1332.
- Soszyński, I., *et al.* 2017, *Acta Astron.*, **67**, 103.
- Udalski, A., Szymański, M.K., and Szymański, G. 2015, *Acta Astron.*, **65**, 1.
- Van Winckel, H., Waelkens, C., Fernie, J.D., and Waters, L.B.F.M. 1999, *A&A*, **343**, 202.
- Watson, C.L., Henden, A.A., and Price, A. 2006, The Society for Astronomical Sciences 25th Annual Symposium on Telescope Science, Eds. B. Warner, *et al.*, p. 47.
- Woźniak, P.R. 2000, *Acta Astron.*, **50**, 421.