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Additional Galactic Cepheids from the OGLE Survey*

I. Soszyński[1], A. Udalski[1], M.K. Szymański[1], P. Pietrukowicz[1], J. Skowron[1], D.M. Skowron[1], R. Poleski[1], S. Kozłowski[1], P. Mróz[1,2], K. Ulaczyk[3,1], K. Rybicki[1], P. Iwanek[1], M. Wrona[1] and M. Gromadzki[1]

[1] Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
[2] Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[3] Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, UK

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ABSTRACT

We report on the results of a comprehensive search for Cepheid variable stars in the fields photometrically monitored by the OGLE Galaxy Variability Survey. We identify 742 Cepheids not included in the first release of the OGLE Collection of Galactic Cepheids and reclassify several dozen previously published variables. The upgraded collection comprises 1974 classical, 1625 type II, and 119 anomalous Cepheids located in the area of about 3000 square degrees covering the disk and bulge of the Milky Way.

We present the most interesting objects in our sample: an isolated group of long-period double-mode classical Cepheids pulsating in the fundamental mode and first overtone, the first known Galactic double-mode Cepheid with the second and third overtone excited, double-mode type II Cepheids, candidates for single-mode first-overtone BL Her stars, and Cepheids showing simultaneous eclipsing variability. We also discuss type II and anomalous Cepheids that are potential members of globular clusters.

Key words: *Stars: variables: Cepheids – Stars: oscillations – Galaxy: bulge – Galaxy: disk – Catalogs*

1. Introduction

The Optical Gravitational Lensing Experiment (OGLE) has discovered the largest samples of classical, type II, and anomalous Cepheids known to date. The OGLE Collection of Galactic Cepheids (Udalski *et al.* 2018) more than doubled the number of known classical Cepheids in the Milky Way, from about 900 to

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

nearly 2500 objects. This sample was used by Skowron *et al.* (2019ab) for a comprehensive examination of the three-dimensional structure of the Galactic disk – its warping, flaring, and the scale height, as well as its radial metallicity gradient and the recent star formation history. This analysis was supplemented by Mróz *et al.* (2019) who used OGLE Cepheids to construct the most accurate rotation curve of the outer regions of our Galaxy.

The OGLE survey has a long tradition of detecting and studying variable stars in the Milky Way and nearby galaxies (*e.g.*, Udalski *et al.* 1994, 2015b, 2018, Soszyński *et al.* 2008, 2019abc, Pietrukowicz *et al.* 2013). The OGLE Collection of Variable Stars (OCVS) currently contains about one million carefully selected and classified variable stars. These samples are characterized by exceptionally high levels of completeness and purity and therefore they serve as a framework for various astrophysical applications. Our collection of Cepheids in the Galactic bulge and disk (Soszyński *et al.* 2017b, Udalski *et al.* 2018) was used, among others, to identify the first known double-mode type II Cepheids (Smolec *et al.* 2018), to explore the spatial distribution and kinematics of the old stellar population in the central regions of the Milky Way (Braga *et al.* 2018), to probe the hydrodynamics of outer envelope and evolutionary status of Cepheids (Das *et al.* 2020), as a training set for machine learning variable star classification algorithms (Dékány *et al.* 2019), and as a comparative sample for the identification of Cepheids in other regions of the sky (Žák *et al.* 2019).

Udalski *et al.* (2018) presented the first release of the OGLE Collection of Galactic Cepheids which is a part of the OCVS. This sample was limited to stars brighter than $I = 18$ mag with periods above 1 d and with the number of photometric data points larger than 100. In the analysis performed by Skowron *et al.* (2019b), this sample was extended with 200 classical Cepheids detected in the Galactic longitude range $20^\circ < l < 60^\circ$, however these additional fields were not searched for type II and anomalous Cepheids. In this paper, we supplement the OGLE collection with newly detected classical, type II, and anomalous Cepheids in the Milky Way. We also reclassify several dozen incorrectly categorized variable stars already included in the OCVS.

2. Observations and Data Reduction

The OCVS was compiled using observations taken by the Warsaw telescope at Las Campanas Observatory, Chile. The field of view of the OGLE-IV mosaic CCD camera is 1.4 square degrees, and the pixel scale is $0\farcs26$. In this paper, we use observations collected between 2013 and 2020 during the OGLE Galaxy Variability Survey (GVS) covering a total of about 3000 square degrees in the Galactic disk and bulge. Compared to the Udalski's *et al.* (2018) work, our study covers a larger area of the sky, in particular, we analyze additional GVS fields in the outer Galactic bulge and in the northern part of the disk.

The GVS project has collected *I*- and *V*-band time series toward the outer Galactic bulge and disk. The number of available *I*-band epochs varies across the survey area, with the majority of the light curves having between 100 and 200 points and a total baseline of 2–7 yr. Compared to the regular OGLE project, GVS is a relatively shallow survey, with 25 s and 30 s integration times for *I*-band and *V*-band, respectively. The GVS photometry saturates at ≈ 11 mag, while the faintest stars whose variability can be effectively studied have $I \approx 19.5$ mag. The most recent observations included in our collection were made on March 13, 2020 – just before the Las Campanas Observatory suspended operations due to the COVID-19 pandemic. Details of the instrumentation, image processing, photometric and astrometric calibrations are discussed by Udalski *et al.* (2015a, 2018).

3. Variability Search and Classification of Cepheids

The search for additional Cepheids in the GVS fields was carried out in the same manner as in the OGLE Collection of Galactic RR Lyr stars (Soszyński *et al.* 2019c). In brief, we ran the periodicity search algorithm over all GVS *I*-band light curves containing at least 15 data points. We used the FNPEAKS code† which provided us the most probable periods with amplitudes and signal-to-noise ratios. In the second step of the analysis, all targets with periods shorter than 50 d and the largest amplitudes and signal-to-noise ratios were fitted with template light curves obtained from the best-sampled pulsating stars and eclipsing variables observed by the OGLE survey (typical template light curves of Cepheids and RR Lyr stars were shown in the paper by Soszyński *et al.* 2019b). In the final stage of our variable stars' selection procedure, we visually inspected the light curves pointed by the template fitting algorithm as the best candidates for pulsating stars and eclipsing binaries. We isolated candidates for pulsating stars based on the characteristic attributes of their light curves.

In such a way, we chose a few hundred candidates for Cepheid variables, not included in the previous edition of the OGLE Collection of Galactic Cepheids (Udalski *et al.* 2018). The main diagnostics used to discriminate between different types of classical pulsators were their positions in the period – Fourier parameter diagrams, especially in the $\log P - \phi_{21}$ and $\log P - \phi_{31}$ diagrams, where $\phi_{k1} = \phi_k - k\phi_1$ are phase differences of the Fourier cosine series fitted to the *I*-band light curves (Simon and Lee 1981).

Since overtone classical Cepheids (including multimode variables) form a continuity with δ Sct stars, we had to adopt a boundary period to separate both types of pulsating variables. Following previous editions of the OCVS, we adopted the first-overtone pulsation period of 0.23 d (corresponding to the fundamental-mode period of about 0.3 d) as a transition between classical Cepheids and δ Sct variables. To distinguish between RR Lyr stars and (fundamental-mode) type II Cepheids, we

† *http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks*

traditionally used the boundary period of 1 d, although one should be aware that periods of both classes of pulsating stars partly overlap. Some of the shortest-period (1.0–1.2 d) BL Her stars in our collection have light curves similar to the light curves of the longest-period RRab variables.

Type II Cepheids have been divided into BL Her stars (periods in the range of 1–5 d), W Vir stars (5–20 d), and RV Tau stars (periods above 20 d[‡]). Additionally, we distinguished the subclass of peculiar W Vir variables (Soszyński *et al.* 2008) and first-overtone BL Her stars (Soszyński *et al.* 2019a, see Section 5.2).

We also updated the OGLE-IV light curves of the previously published Cepheids in the Milky Way (Soszyński *et al.* 2017b, Udalski *et al.* 2018). The new observations allowed us to correct in some cases our previous classification. We verified pulsation modes of several Cepheids, 12 other Cepheids were reclassified as a different type of classical pulsators (for example stars previously classified as classical Cepheids were recognized as anomalous Cepheids). Finally, 29 objects previously classified as classical Cepheids and 12 stars classified as type II Cepheids were completely removed from the OCVS, because longer light curves indicated other types of variable stars (usually spotted variables). Several dozen other Cepheids have been flagged as uncertain in our collection.

Finally, we matched our collection with the International Variable Star Index (VSX; Watson *et al.* 2006), VVV catalog of Cepheids (Braga *et al.* 2019, Dékány *et al.* 2019), WISE Catalog of Periodic Variable Stars (Chen *et al.* 2018), Gaia DR2 catalog of Cepheids (Clementini *et al.* 2019, Ripepi *et al.* 2019), ASAS-SN catalogs of variable stars (Jurcsik *et al.* 2018, Jayasinghe *et al.* 2020), and ATLAS catalog of pulsating stars (Heinze *et al.* 2018). We carefully inspected OGLE light curves of the stars that have not passed our selection process, but were classified as Cepheids in the above catalogs. The vast majority of these targets turned out to be non-pulsating variable stars (eclipsing binaries, spotted variables, irregular variables, etc.), but we also found several dozen *bona fide* Cepheids (mostly long-period type II Cepheids and faint classical Cepheids), which were overlooked during our selection and classification procedure. All these Cepheids were added to our collection, increasing its completeness.

As a result, we identified 742 Cepheid variables (273 classical Cepheids, 404 type II Cepheids, and 65 anomalous Cepheids), not included in the previous editions of the OCVS. In total, 229 (31%) of these objects have been found in at least one of the external catalogs of variable stars, so the remaining Cepheids are likely new discoveries. Among others, we found three new triple-mode classical Cepheids, two unique double-mode 2O/3O Cepheids (Section 5.1), candidates for type II Cepheids pulsating solely in the first-overtone (Section 5.2), and two additional Cepheids in eclipsing binary systems (Section 5.3).

[‡]For RV Tau stars and other Cepheids showing period-doubling effect, we provide "single" periods, *i.e.*, intervals between successive minima.

4. The OGLE Collection of Galactic Cepheids

The newly identified Cepheids have been added to the OGLE Collection of Galactic Cepheids. The collection contains now 1974 classical Cepheids, 1625 type II Cepheids, and 119 anomalous Cepheids in the Galactic bulge and disk. The exact numbers of Cepheids belonging to different subtypes are provided in Table 1. The entire collection is available *via* the WWW interface or anonymous FTP sites:

http://ogle.astrouw.edu.pl
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gd/cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gd/t2cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/t2cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/gal/acep/

Table 1

Number of Galactic Cepheids in the OCVS

Type	Subtype	Bulge	Disk/Halo	Total
Classical Cepheids	all	189	1784	1973
	F	98	1103	1201
	1O	56	495	551
	F/1O	12	45	57
	1O/2O	19	133	152
	2O/3O	1	1	2
	F/1O/2O	0	2	2
	1O/2O/3O	3	5	8
Type II Cepheids	all	1320	306	1626
	BL Her (F)	541	120	661
	BL Her (1O)	1	2	3
	BL Her (F/1O)	3	2	5
	W Vir	494	98	592
	pec. W Vir	45	20	65
	RV Tau	236	64	300
Anomalous Cepheids	all	65	54	119
	F	46	35	81
	1O	18	19	37
	F/1O/2O	1	0	1

For each star, we provide its equatorial coordinates (J2000.0), pulsation periods, intensity-averaged mean magnitudes in the *I*- and *V*-bands, epochs of the maximum light, peak-to-peak *I*-band amplitudes, and Fourier parameters derived from the *I*-band light curves. The photometric time series in the *I*- and *V*-bands (if available) and finding charts are also provided for each Cepheid.

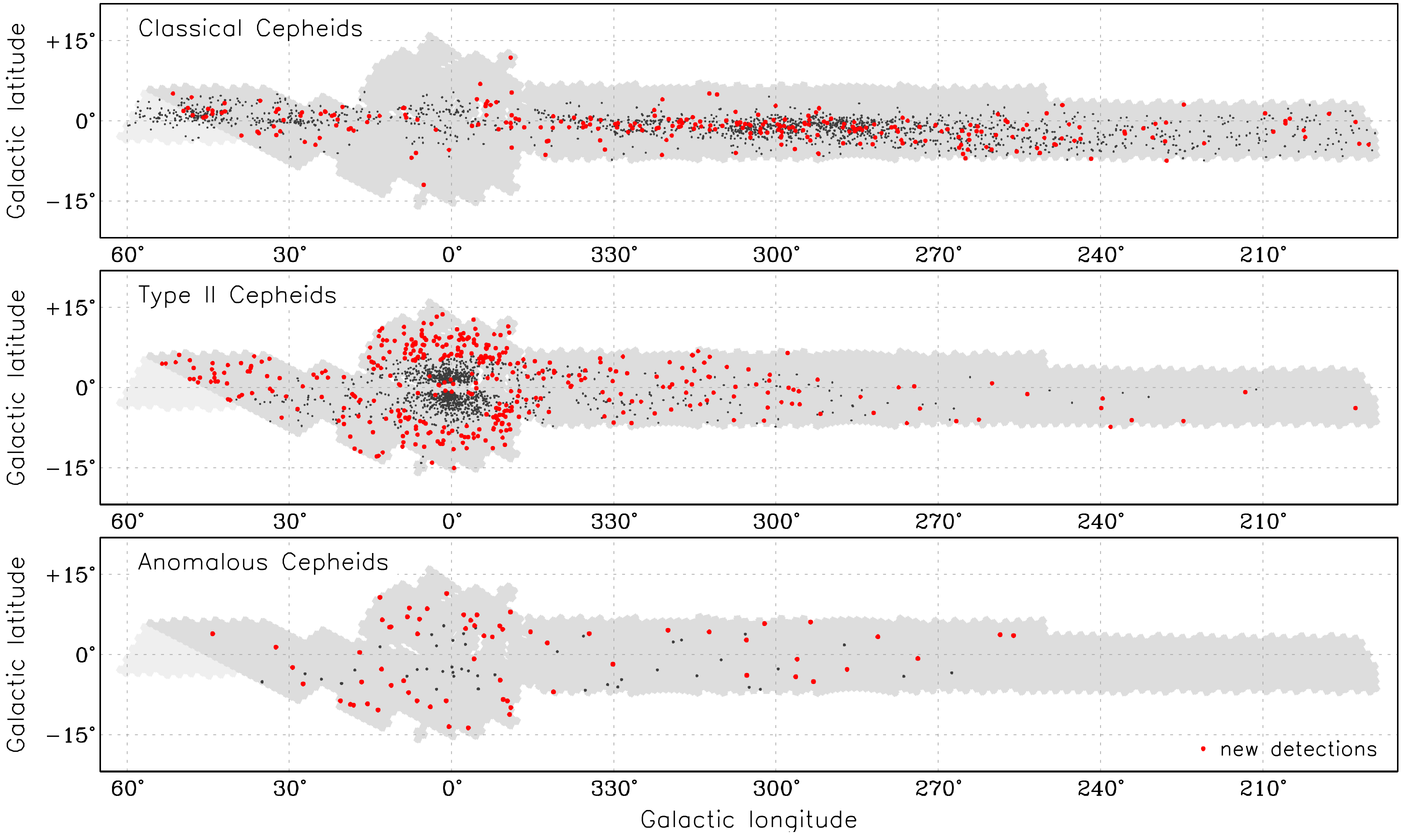

Fig. 1. On-sky distribution of classical Cepheids (*upper panel*), type II Cepheids (*middle panel*), and anomalous Cepheids (*lower panel*) in Galactic coordinates. Dark gray dots mark objects included in the previous edition of the OCVS, while red dots indicate the newly detected and reclassified Cepheids. The gray area shows the OGLE footprint in the Galactic bulge and disk (the lighter shade indicates an area not included in this investigation because of an insufficient number of observations).

The light curves of previously published Cepheids have been supplemented with the newest OGLE-IV observations. These extended photometric data were used to update the pulsation periods and other observational quantities. Note that a fraction of type II Cepheids, in particular W Vir stars, exhibits variable periods which makes it impossible to phase their OGLE-IV light curves using constant periods. To recompute the periods we used the TATRY code, which implements the multiharmonic analysis of variance algorithm (Schwarzenberg-Czerny 1996).

The updated list of all known Galactic classical Cepheids is available from the OGLE Internet archive:

ftp://ogle.astrouw.edu.pl/ogle/ogle4/OCVS/allGalCep.listID

The celestial distributions of classical, type II and anomalous Cepheids are shown in Fig. 1. The distribution of classical Cepheids (upper panel of Fig. 1) clearly reveals the warping of the Galactic disk (Skowron *et al.* 2019ab): most of the Cepheids are located below the Galactic plane at the Galactic longitudes $l < 330°$ and above the Galactic plane at $l > 30°$. The width of the distribution grows with increasing distance from the center of the Galaxy, which provides evidence for the disk flaring.

The middle panel of Fig. 1 shows that type II Cepheids are strongly concentrated toward the Galactic center, which resembles the spatial distribution of RR Lyr stars (Soszyński *et al.* 2019c). We identified more than 30 type II Cepheids per square degree in the most populated fields in the central Galactic bulge, but their surface density drops to below 0.5 objects per square degree in the outer bulge, while close to the Galactic anticenter there are only a few type II Cepheids in the area of several hundred square degrees. Anomalous Cepheids (lower panel of Fig. 1) also exhibit a Galactocentric distribution, but the gradient of their surface density is much less steep than that for type II Cepheids. It is worth noting that anomalous Cepheids in the Large (LMC) and Small Magellanic Cloud (SMC) show similar smooth distributions around the centers of these galaxies (Soszyński *et al.* 2017a).

5. Discussion

5.1. Multi-Mode Cepheids

Classical Cepheids

Stars revealing the simultaneous presence of two or three radial modes constitute a significant fraction of the total sample of classical Cepheids. In the virtually complete OGLE collection of classical Cepheids in the Magellanic Clouds (Soszyński *et al.* 2019b), multimode oscillations occur in about 6% variables in the SMC and about 9% Cepheids in the LMC. In our sample of Galactic classical Cepheids, as many as 11% objects are double- or triple-mode pulsators, so the incidence rate of the beat Cepheids seems to be higher in the environments of higher

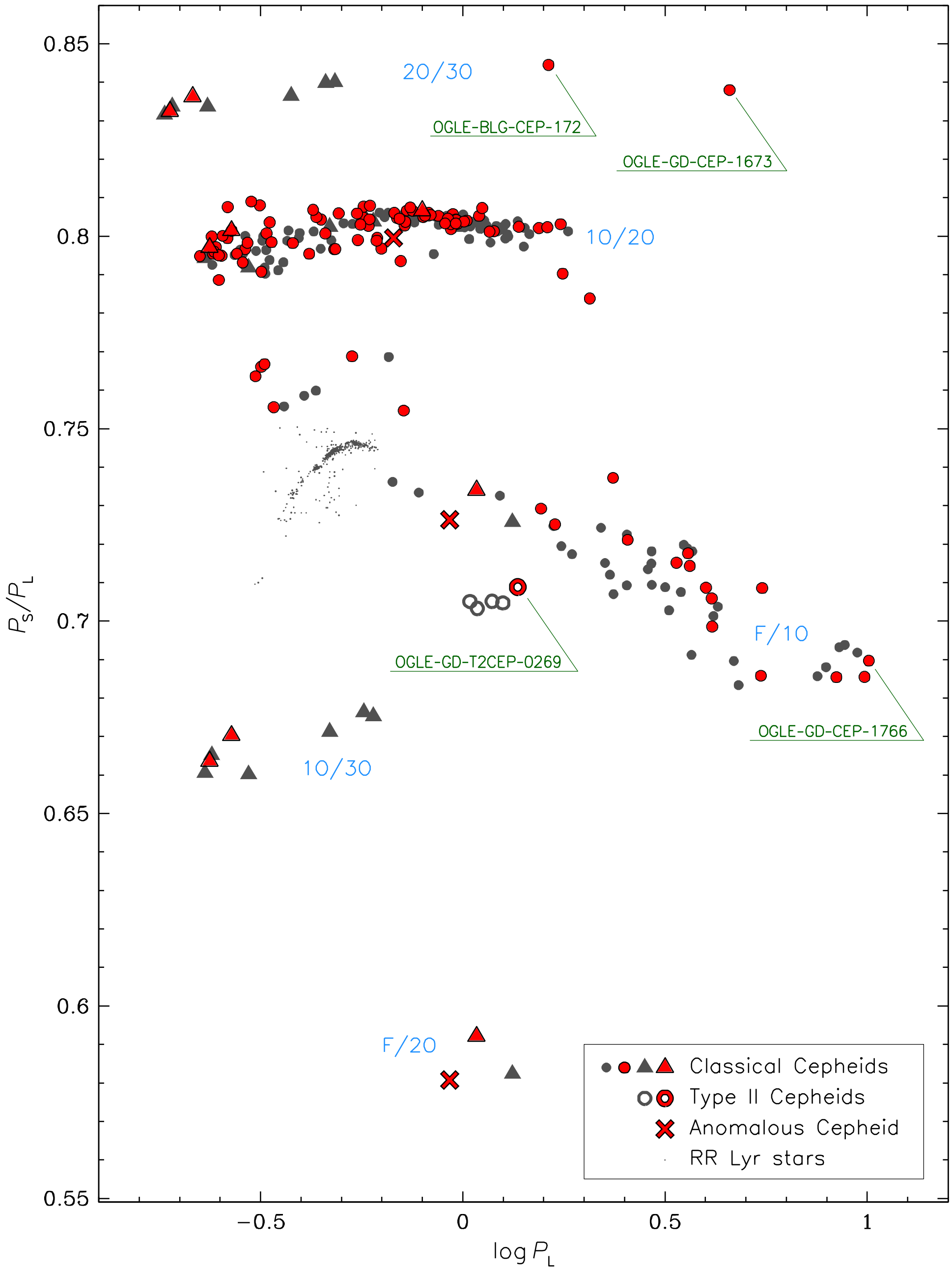

Fig. 2. Petersen diagram for multi-mode Cepheids in the Milky Way. Filled circles mark double-mode classical Cepheids, triangles – triple-mode classical Cepheids (three points per star), empty circles – double-mode type II Cepheids, crosses – a triple-mode anomalous Cepheid OGLE-GAL-ACEP-091. Gray and red symbols present previously known Cepheids (Soszyński *et al.* 2017b, Udalski *et al.* 2018) and new detections, respectively.

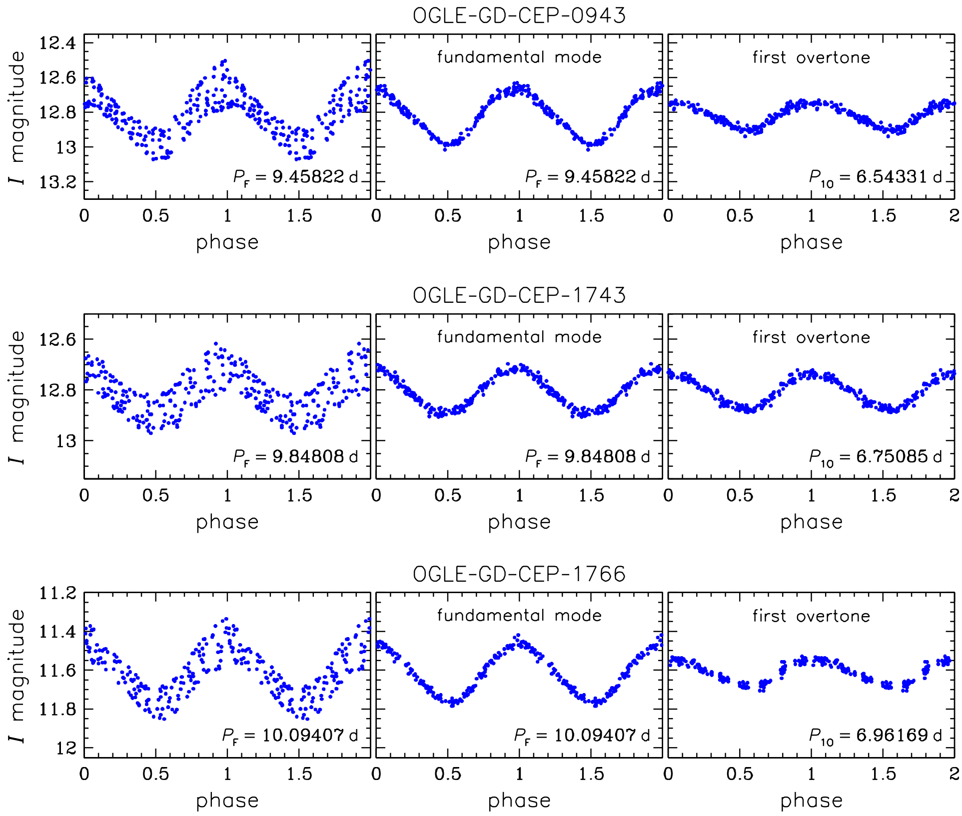

Fig. 3. Light curves of the longest-period double-mode F/1O classical Cepheids in the Milky Way. *Left panels* show original light curves folded with the fundamental-mode periods. *Middle* and *right panels* present light curves of the fundamental and first-overtone modes, respectively, prewhitened for the other radial modes and for the linear combination terms.

metallicity. Interestingly, the opposite relationship was found for RR Lyr stars: the incidence rates of double-mode RR Lyr stars are equal to 10%, 5%, and 0.5% for the SMC, LMC, and Galactic bulge samples, respectively (Soszyński *et al.* 2019c).

Fig. 2 presents the Petersen diagram (shorter to longer period ratios plotted against logarithmic longer periods) for multimode classical pulsators in the Milky Way. Our new detections are marked with red circles and triangles for double- and triple-mode variables, respectively.

First of all, we draw the reader's attention to the isolated sub-group of eight long-period double-mode F/1O classical Cepheids with the fundamental-mode periods in the range of 7.5–10 d and period ratios of about 0.69. The light curves of three the longest-period stars from this group are shown in Fig. 3. From this group, OGLE-GD-CEP-1766, with $P_{\rm F} = 10.0940$ d, is probably the longest-period beat Cepheid known in the Universe[§]. Two similar long-period double-mode F/1O

[§]Smolec (2017) found in the OCVS an even longer-period candidate for double-mode Cepheid – OGLE-SMC-CEP-0387 with $P_{\rm F} \approx 13.1$ d. However, the identification of the first-overtone mode in this star is very uncertain.

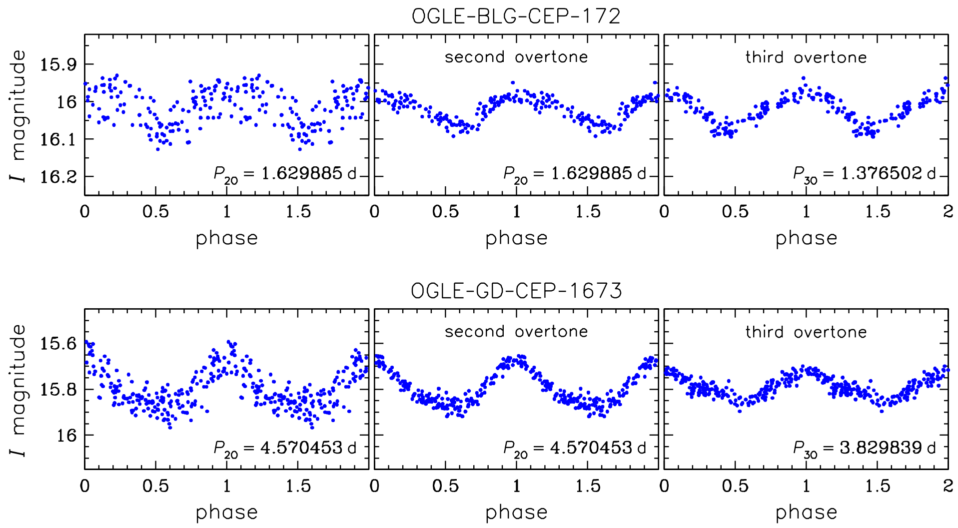

Fig. 4. Light curves of double-mode 2O/3O classical Cepheids in the Milky Way. *Left panels* show original light curves folded with the second-overtone periods. *Middle* and *right panels* present disentangled light curves of the second- and third-overtone modes, respectively.

Cepheids were discovered by Poleski (2013) in M31. The existence of such variables was theoretically predicted by Dziembowski and Kovács (1984) and Buchler (2009), who claimed that the F/1O bimodality in the vicinity of the $P_{\rm F} = 10$ d period is induced by the $P_{\rm F} = 2P_{\rm 2O}$ resonance. Indeed, at least some of our targets show strong $2f_{\rm F} + f_{\rm 1O}$ combination frequencies, which can be interpreted as $f_{\rm 2O} + f_{\rm 1O}$ frequencies.

Table 2

Double-mode 2O/3O classical Cepheids in the Milky Way

Identifier	R.A. [J2000.0]	Dec. [J2000.0]	$P_{\rm 2O}$ [d]	$P_{\rm 3O}$ [d]	$\langle I \rangle$ [mag]	$\langle V \rangle$ [mag]
OGLE-GD-CEP-1673	$10^{\rm h}43^{\rm m}58\overset{\rm s}{.}84$	$-59°34'28\overset{''}{.}0$	4.570453	3.829839	15.791	17.929
OGLE-BLG-CEP-172	$17^{\rm h}10^{\rm m}20\overset{\rm s}{.}43$	$-33°52'55\overset{''}{.}9$	1.629885	1.376502	16.008	–

Two other unique objects in our collection – OGLE-GD-CEP-1673 and OGLE-BLG-CEP-172 – are double-mode Cepheids pulsating in the second and third overtone modes. Table 2 lists their basic parameters, while their disentangled light curves are shown in Fig. 4. The period ratios (around 0.84) of our 2O/3O beat Cepheids place them at the top of the Petersen diagram (Fig. 2). So far, only one double-mode 2O/3O classical Cepheid was recognized: an LMC variable OGLE-LMC-CEP-3987 (Soszyński *et al.* 2015), however this object has much shorter periods ($P_{\rm 2O} \approx 0.5342$ d, $P_{\rm 3O} \approx 0.4483$ d) than our Galactic Cepheids. We believe that OGLE-GD-CEP-1673 and OGLE-BLG-CEP-172 will be important targets of asteroseismological research.

Type II and Anomalous Cepheids

In contrast to classical Cepheids, double-mode type II Cepheids are extremely rare objects. Smolec *et al.* (2018) identified the first two BL Her variables with the fundamental and first-overtone modes simultaneously excited. Shortly after, Udalski *et al.* (2018) reported the discovery of two other stars belonging to the same class. The four known beat type II Cepheids constitute a very homogeneous group: their fundamental-mode periods $P_{\rm F}$ range from 1.04 to 1.26 d, their period ratios $P_{\rm 1O}/P_{\rm F}$ are in the range of 0.7033–0.7051, the peak-to-peak *I*-band amplitudes of the fundamental-mode light curves are equal to about 0.4 mag and are several times larger than the amplitudes of the first-overtone mode. Finally, the light curve shape is also remarkably similar in these four stars.

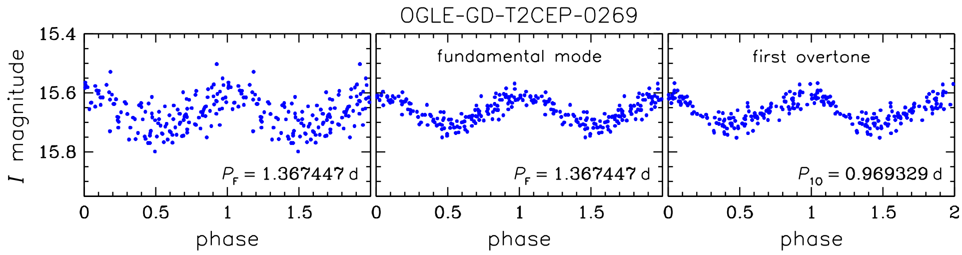

Fig. 5. Light curve of a newly detected double-mode F/1O type II Cepheid OGLE-GD-T2CEP-0269. *Left panel* shows original light curves folded with the fundamental-mode period. *Middle* and *right panels* present disentangled light curves of the fundamental and first-overtone modes, respectively.

Table 3

Double-mode type II Cepheids (BL Her stars) in the Milky Way

Identifier	R.A. [J2000.0]	Dec. [J2000.0]	$P_{\rm F}$ [d]	$P_{\rm 1O}$ [d]	$\langle I \rangle$ [mag]	$\langle V \rangle$ [mag]
OGLE-GD-T2CEP-0045	$13^{\rm h}27^{\rm m}58.^{\rm s}53$	$-67^\circ25'01.''5$	1.086491	0.764100	13.899	14.857
OGLE-GD-T2CEP-0269	$16^{\rm h}50^{\rm m}18.^{\rm s}84$	$-41^\circ51'12.''8$	1.367447	0.969329	15.666	17.624
OGLE-BLG-T2CEP-0209	$17^{\rm h}57^{\rm m}11.^{\rm s}87$	$-28^\circ51'49.''5$	1.181284	0.832978	15.445	17.279
OGLE-BLG-T2CEP-0749	$17^{\rm h}50^{\rm m}05.^{\rm s}11$	$-32^\circ16'17.''2$	1.041577	0.734419	17.529	20.852
OGLE-BLG-T2CEP-1041	$18^{\rm h}12^{\rm m}35.^{\rm s}05$	$-15^\circ31'16.''0$	1.256607	0.885549	15.718	–

In this work, we supplement the list of double-mode BL Her stars with one more object: OGLE-GD-T2CEP-0269. The pulsation periods of this star ($P_{\rm F} = 1.36745$ d, $P_{\rm 1O}/P_{\rm F} = 0.7089$) are slightly longer than the periods of other beat type II Cepheids, but the position of OGLE-GD-T2CEP-0269 in the Petersen diagram (Fig. 2) indicates that it is a plausible member of the same class of double-mode pulsators. Fig. 5 shows disentangled light curves of OGLE-GD-T2CEP-0269. The amplitudes of the two modes are nearly equal to each other, which distinguishes our new detection from the other double-mode BL Her stars. Table 3 summarizes all known double-mode type II Cepheids in the Milky Way.

Finally, we also identified the first known triple-mode anomalous Cepheid – OGLE-GAL-ACEP-091. Its thorough analysis will be presented in a forthcoming paper.

5.2. Single-Mode First-Overtone Type II Cepheids

Until recently, all known type II Cepheids were pure fundamental-mode pulsators. The two double-mode BL Her stars discovered by Smolec *et al.* (2018) were the first known type II Cepheids with the first-overtone mode excited. Soon after, Soszyński *et al.* (2019a) reported the discovery of two stars in the LMC that are strong candidates to be single-mode first-overtone type II Cepheids. Soszyński's *et al.* (2019a) classification is based mostly on the position of these stars in the period–luminosity diagram and their characteristic light curve morphology. Unfortunately, the former criterion cannot be easily applied to Cepheids in the Milky Way, because distances to individual targets are not *a priori* known. Thus, it is impossible to place these stars in the period–absolute luminosity diagram. Taking this limitation into consideration, we performed a search for Galactic overtone type II Cepheids based on their light curve characteristics.

The two candidates for overtone BL Her stars in the LMC – OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291 – pulsate with periods of about 0.93 d and 0.82 d, respectively. Their light curves (see Fig. 2 in Soszyński *et al.* 2019a) are characterized by round minima (the feature typical for overtone pulsators) and sharp maxima. Although overtone classical, anomalous and type II Cepheids have relatively similar light curves, a careful analysis of the Fourier parameters ϕ_{21}, ϕ_{31}, R_{21}, R_{31} can make it possible to distinguish these three types of classical pulsators.

We restricted our collection of Cepheids in the Milky Way to single-mode pulsators with periods in the range 0.7–1 d, and we conducted a search for light curves with round minima and sharp maxima – resembling those of OGLE-LMC-T2CEP-290 and OGLE-LMC-T2CEP-291. The result of our search is displayed in Fig. 6, showing the light curves of three convincing candidates for the Galactic first-overtone BL Her stars. Their basic parameters (identifiers, J2000.0 equatorial coordinates, periods, mean magnitudes in the I and V bands, and I-band amplitudes) are listed in Table 4. We emphasize that our candidates for first-overtone type II Cepheids in the Milky Way are not as certain as the two candidates found by Soszyński *et al.* (2019a) in the LMC, because we currently cannot verify their positions on the period–luminosity diagram.

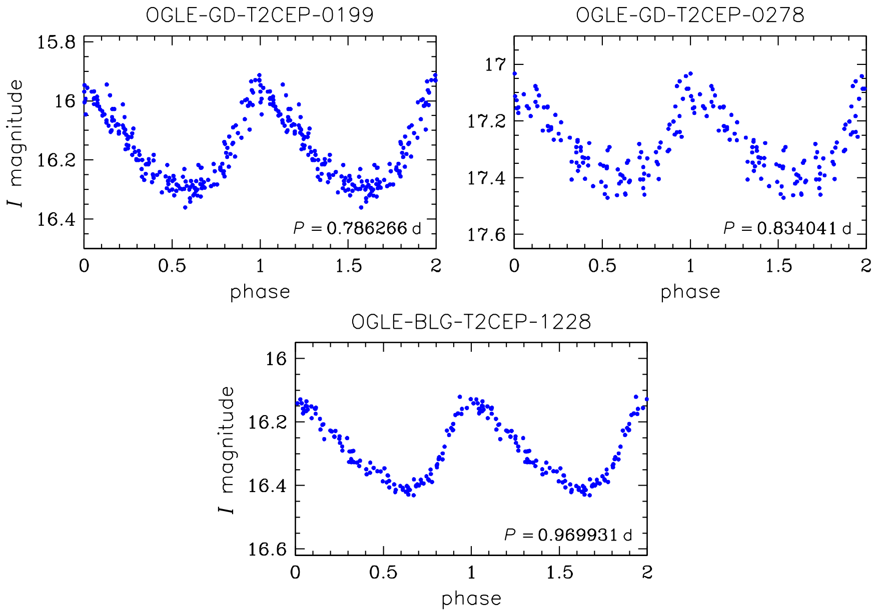

Fig. 6. Light curves of candidates for single-mode first-overtone type II Cepheids (BL Her stars) in the Milky Way.

T a b l e 4

Candidates for single-mode first-overtone type II Cepheids (BL Her stars).

Identifier	R.A. [J2000.0]	Dec. [J2000.0]	P_{1O} [d]	$\langle I\rangle$ [mag]	$\langle V\rangle$ [mag]	$A(I)$ [mag]
OGLE-GD-T2CEP-0199	$11^h54^m27\overset{s}{.}70$	$-65^\circ13'49\overset{''}{.}5$	0.786266	16.154	18.433	0.332
OGLE-GD-T2CEP-0278	$18^h29^m08\overset{s}{.}06$	$-05^\circ28'27\overset{''}{.}9$	0.834041	17.264	–	0.311
OGLE-BLG-T2CEP-1228	$17^h42^m20\overset{s}{.}75$	$-20^\circ36'34\overset{''}{.}4$	0.969931	16.285	–	0.274

Our candidates for overtone type II Cepheids are relatively faint in the shallow GVS, which makes their time series quite noisy (Fig. 6). Nevertheless, we have determined the Fourier coefficients and peak-to-peak amplitudes of their light curves and plotted these parameters against the pulsation periods in Fig. 7. For comparison, the same quantities derived for the first-overtone classical pulsators (RRc stars, classical Cepheids, anomalous Cepheids, and type II Cepheids) in the LMC are shown in these diagrams. Note that our three candidates for Galactic overtone type II Cepheids have Fourier parameters very similar to the parameters of their siblings in the LMC. At the same time, their Fourier parameters differ from the parameters of overtone anomalous Cepheids with similar periods and have larger amplitudes than the bulk of overtone classical Cepheids with similar periods. Fur-

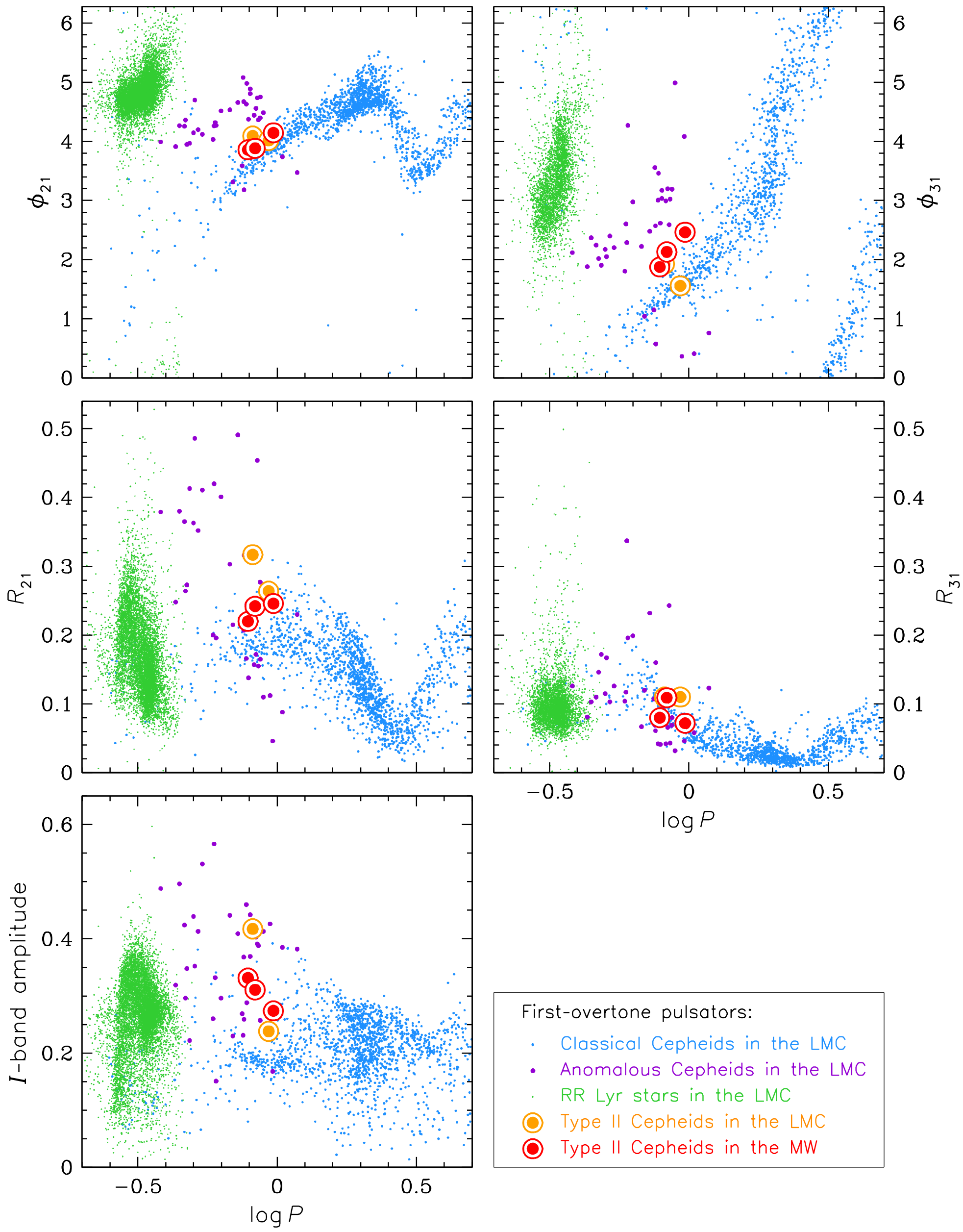

Fig. 7. Fourier coefficients ϕ_{21}, ϕ_{31}, R_{21}, R_{31}, and I-band peak-to-peak amplitudes as a function of periods for Cepheids and RR Lyr stars pulsating in the first-overtone mode. Blue, violet, and green points indicate classical Cepheids, anomalous Cepheids, and RRc stars in the LMC, respectively. Orange circles represent two first-overtone type II Cepheids identified by Soszyński *et al.* (2019a) in the LMC. Red circles mark three candidates for first-overtone type II Cepheids in the Milky Way.

ther studies, including a dedicated spectroscopic observations, should shed more light on the nature of our candidates for overtone BL Her stars.

5.3. Cepheids in Eclipsing Binary Systems

Eclipsing binary systems with pulsating components are very rare, but important astrophysical targets. Such objects give us an opportunity to directly and very precisely measure stellar parameters like masses, absolute luminosities, and radii. Several classical Cepheids in eclipsing binary systems have been discovered in the Magellanic Clouds (*e.g.*, Udalski *et al.* 2015b). These objects have been the subject of extensive studies by the Araucaria project (*e.g.*, Pietrzyński *et al.* 2010). Until recently, no candidates for the eclipsing classical Cepheid were known in our Galaxy.

Udalski *et al.* (2018) reported the discovery of two Galactic classical Cepheids with additional eclipsing modulations. However, in this paper we reclassify one of these stars (OGLE-GD-CEP-0069) as a peculiar W Vir star and we move this object to the collection of type II Cepheids (its new designation is OGLE-GD-T2CEP-0178). It is known that a large fraction of peculiar W Vir stars (Soszyński *et al.* 2008) are members of binary systems – it can be even supposed that the binarity is necessary for the occurrence of pulsations in these variables. The morphology of both, pulsation and eclipsing, light curve components of OGLE-GD-T2CEP-0178 are more compatible with the variability of a peculiar W Vir star in an eclipsing binary system (*cf.* Fig. 5 in Soszyński *et al.* 2018) than with a classical Cepheid.

In turn, OGLE-GD-CEP-0465 – the other pulsator revealing simultaneous eclipsing variability presented by Udalski *et al.* (2018) – is a certain fundamental-mode classical Cepheid. This is currently the only known Galactic classical Cepheid which can be a member of an eclipsing system. Spectroscopic observations of this object should answer the question whether this is a binary system hosting δ Cep star or rather the Cepheid and eclipsing variable are physically unrelated blend observed by chance along the same line-of-sight.

In this paper, we supplement the short list of Galactic Cepheids in eclipsing binary systems with two new objects of that type: OGLE-GD-T2CEP-0185 and OGLE-BLG-T2CEP-1237. Both stars are classified as peculiar W Vir stars, although their pulsation periods are shorter than 5 d (which we adopted as a transition between BL Her and W Vir stars). The disentangled light curves of both objects are presented in Fig. 8. In the case of OGLE-GD-T2CEP-0185, different widths of the primary and secondary eclipses indicate the presence of a disk in the system. The same effect is visible, among others, in OGLE-GD-T2CEP-0178 and OGLE-LMC-T2CEP-211, the latter examined in detail by Pilecki *et al.* (2018). The shape of the eclipsing component of OGLE-BLG-T2CEP-1237 indicates that it is a close binary system. It is worth noting that additional frequencies that are linear combinations of the pulsation and orbital periods are visible in the pre-whitened light curve of this object. This feature proves that the pulsating star is a real member of

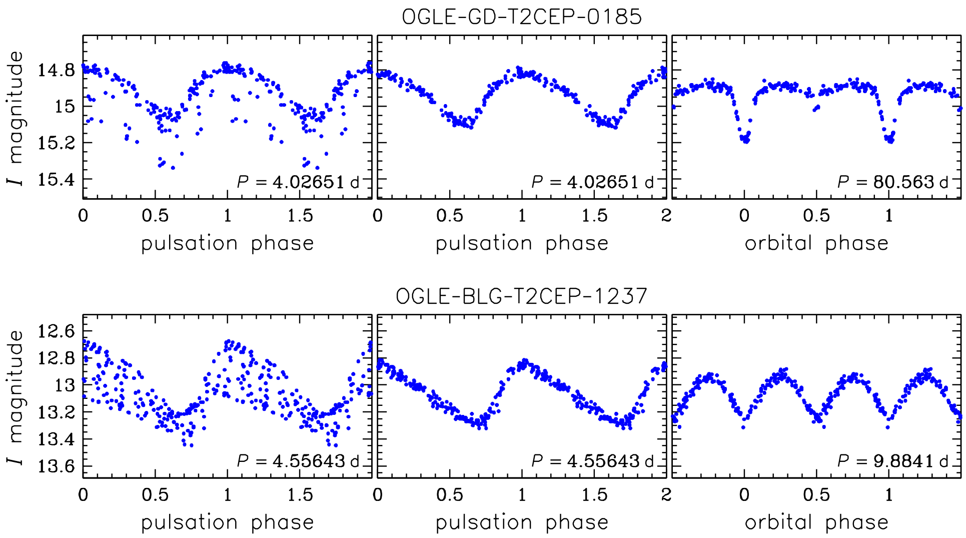

Fig. 8. Light curves of newly detected type II Cepheids with additional eclipsing variability. *Left panels* show original light curves folded with the pulsation periods. *Middle* and *right panels* present pulsation and eclipsing light curves, respectively, after subtracting the other component.

the system. Such combination of frequencies reflect complex oscillations of stars which are distorted by tidal interactions from their companions.

Table 5 lists all known Galactic Cepheids revealing eclipsing modulation.

Table 5

Milky Way Cepheids showing additional eclipsing variability

Identifier	R.A. [J2000.0]	Dec. [J2000.0]	$P_{\rm puls}$ [d]	$P_{\rm ecl}$ [d]	$\langle I \rangle$ [mag]	$\langle V \rangle$ [mag]
Classical Cepheid						
OGLE-GD-CEP-0465	$10^{\rm h}14^{\rm m}30\overset{\rm s}{.}19$	$-59°13'36\overset{''}{.}3$	6.605641	193.83	14.411	17.127
Type II Cepheids						
OGLE-GD-T2CEP-0178	$06^{\rm h}48^{\rm m}58\overset{\rm s}{.}05$	$-00°37'30\overset{''}{.}8$	3.833057	81.640	10.855	11.832
OGLE-GD-T2CEP-0185	$08^{\rm h}16^{\rm m}54\overset{\rm s}{.}77$	$-46°09'44\overset{''}{.}6$	4.026511	80.563	14.931	16.229
OGLE-BLG-T2CEP-0674	$17^{\rm h}45^{\rm m}00\overset{\rm s}{.}28$	$-27°15'08\overset{''}{.}3$	6.985900	714	16.739	21.395
OGLE-BLG-T2CEP-1237	$17^{\rm h}47^{\rm m}01\overset{\rm s}{.}12$	$-24°23'31\overset{''}{.}1$	4.556427	9.8841	13.058	15.249

5.4. *Cepheids in Globular Clusters*

We matched our collection of Galactic Cepheids with the catalog of globular clusters in the Milky Way compiled by Harris (2010). We searched for stars located in the sky not farther than one tidal radius from the center of a cluster. Our collection contains exactly 60 Galactic type II Cepheids which could potentially be members of 25 globular clusters. The list of these stars is provided in the file gc.dat in the FTP site of the collection. Of course, some of these stars are probably not physically associated with the clusters – their positional coincidence are accidental. However, the discrimination between cluster members and field variables is beyond the scope of this paper. The most Cepheid-rich globular clusters in our fields are Terzan 1, NGC 6273 (M19), and NGC 6266 (M62), containing, respectively, seven, six, and five type II Cepheids within the tidal radii of these clusters.

We cross-matched our list of 60 type II Cepheids with the updated version¶ of the catalog of variable stars in the Galactic globular clusters (Clement *et al.* 2001) and we successfully identified 36 objects. The other 24 type II Cepheids are candidates for new cluster members. This group includes three Cepheids in Terzan 6 (the first variable stars known in this cluster), three additional Cepheids in Terzan 1, and the first known Cepheids in the globular clusters NGC 6355, NGC 6540, NGC 6749, Terzan 9, and Djorg 2.

Anomalous Cepheids are extremely rare in globular clusters. The Clement *et al.* (2001) catalog contains only five such objects, including BL Bootis (V19 in NGC 5466) – the prototype of a class of anomalous Cepheids. Our collection includes three anomalous Cepheids (all of them are first-overtone pulsators) positionally coincident with globular clusters. One of these stars (OGLE-GAL-ACEP-082 = NGC 6304 V4) has already been classified in the OCVS as an RR Lyr star (OGLE-BLG-RRLYR-00225). In this investigation, we change this classification following the suggestion of De Lee *et al.* (2006), who noticed a characteristic light curve shape of this star. The two remaining anomalous Cepheids located within tidal radii of globular clusters are new discoveries. OGLE-GAL-ACEP-100 seems to be a member of NGC 6541, considering its brightness compared to the brightness of RR Lyr stars in the same cluster. In turn, OGLE-GAL-ACEP-105 is too bright to be a member of NGC 6638 – we assume that this is a field anomalous Cepheid located by chance in the area outlined by the cluster radius.

On the other hand, our data clearly show that the variable star V12 in globular cluster NGC 6333 (M9) is a type II Cepheid (OGLE-BLG-T2CEP-1158), contrary to the classification of this object as an anomalous Cepheid suggested by Arellano Ferro *et al.* (2013). The light curve shape of V12, its Fourier parameters, and its brightness in relation to the brightness of RR Lyr stars in this cluster undoubtedly indicate that this object belongs to the BL Her class.

Finally, our collection contains four stars classified as classical Cepheids in the regions outlined by the tidal radii of globular clusters: OGLE-BLG-CEP-034 in NGC 6355, OGLE-BLG-CEP-068 in Pal 6, OGLE-BLG-CEP-098 in NGC 6569, and OGLE-GD-CEP-1244 in GLIMPSE01. The cluster membership status of these variables will be a matter of further research.

¶*http://www.astro.utoronto.ca/~cclement/read.html*

6. Conclusions

We presented a sample of 742 additional Galactic Cepheids found in the OGLE GVS fields. Nearly 70% objects from this sample are new discoveries. We also supplemented photometric time series of the previously published Cepheids and removed some misclassified objects. This is a final release of the OGLE Collection of Galactic Cepheids.

The huge OGLE photometric database is invariably a source of important astrophysical discoveries. In this paper we presented, among others, the longest-period beat Cepheid, the first known Galactic double-mode 2O/3O classical Cepheids, candidates for single-mode first-overtone type II Cepheids, and new eclipsing binary systems with pulsating components.

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