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OGLE Collection of Galactic Cepheids*

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ABSTRACT

We present here a new major part of the OGLE Collection of Variable Stars – OGLE Collection of Galactic Cepheids. The new dataset was extracted from the Galaxy Variability Survey images – a dedicated large-scale survey of the Galactic disk and outer bulge conducted by the OGLE project since 2013.

The OGLE collection contains 2721 Cepheids of all types – classical, type II and anomalous. It more than doubles the number of known Galactic classical Cepheids. Due to the long-term monitoring and large number of epochs the selected sample is very pure, generally free from contaminating stars of other types often mimicking Cepheids. Its completeness is high at 90% level for classical Cepheids – tested using recent samples of Galactic Cepheids: ASAS-SN, ATLAS, Gaia DR2 and Wise catalog of variable stars. Our comparisons indicate that the completeness of the two latter datasets, Gaia DR2 and Wise catalog, is very low, at $<10\%$ level in the magnitude range of the OGLE GVS survey ($10.8 < I < 19.5$ mag). Both these samples are severely contaminated by non-Cepheids (the purity is 67% and 56%, respectively).

We also present several interesting objects found in the new OGLE Collection – multi-mode pulsators, first Galactic candidates for eclipsing systems containing Cepheid, a binary Cepheid candidate.

New OGLE Collection of Galactic Cepheids is available for the astronomical community from the OGLE Internet Archive in similar form as previous parts of the OGLE Collection of Variable Stars.

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

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

1. Introduction

Cepheid variables belong to the most important tools of modern astrophysics. These are pulsating giants and supergiants with periods from a fraction of a day to over 100 d. Their physical parameters, in particular the luminosity, are well-correlated with the pulsating period what makes these stars a very accurate tool for the distance determination. High luminosity of Cepheids allows one to measure precise distances in the local Universe up to several tens of Mpc. These stars are also very good empirical benchmarks of the stellar pulsation and evolution theories.

The term Cepheids does not describe a homogeneous group of pulsating stars. In fact, there are three groups of objects within this category with completely distinct properties and evolutionary status, namely classical Cepheids (CEP), type II Cepheids (T2CEP) and anomalous Cepheids (ACEP).

Classical Cepheids are young ($\approx 10-400$ Myr), Population I giants and supergiants evolving through the pulsation instability strip in the Hertzsprung–Russell diagram. Their pulsation periods are correlated not only with the luminosity but also with age (Bono *et al.* 2005, Anderson *et al.* 2016) making these stars a potential tool for studying the past of the systems in which they live in.

On the other hand, type II Cepheids are much older and less massive Population II giants which at certain evolutionary phases can cross the instability strip and reveal pulsations similar to those of classical Cepheids. Finally, the anomalous Cepheids are the most enigmatic group – pulsating giants less luminous than classical Cepheids showing Cepheid-like light curves. Their evolutionary status has not been firmly established yet. It is believed that pulsations in these stars are a result of evolution of either single low-mass, low-metallicity stars or a remnant of coalescence of a low-mass binary system.

Although the first Cepheids, η Aql and δ Cep, were discovered back in 18th century by Edward Pigott and John Goodricke, respectively, the scientific career of these stars started blooming more than a century ago when Henrietta Leavitt discovered multitude of such objects in the Small Magellanic Cloud (Leavitt 1908) and subsequently the famous Period-Luminosity relation was established (Leavitt and Pickering 1912).

Since then the number of known Cepheids gradually increased. The breakthrough occurred in the 1990s when variable stars became a precious by-product of the first large-scale sky surveys concentrating on the detection of gravitational microlensing events (MACHO – Alcock *et al.* 1995, EROS – Beaulieu *et al.* 1995, OGLE – Udalski *et al.* 1992). Long-term photometry of millions of stars allowed the detection of large samples of variables of all known classes, as well as new types of stellar variability (Pietrukowicz *et al.* 2017).

The Optical Gravitational Lensing Experiment (OGLE – Udalski, Szymański and Szymański 2015a) has played the leading role in the variable stars field since its start in 1992. During all phases of the OGLE survey, big samples of different types of variables were discovered, carefully classified, and then released to the astronomical community. They become the basis for a large number of further studies.

The OGLE Collection of Variable Stars (OCVS, Soszyński *et al.* 2018 and references therein) encapsulates various OGLE contributions, catalogs and data in the field of variable stars and is the largest collection of classified variables in modern astrophysics. Currently, it consists of almost a million of well characterized genuine periodic variable objects of different types.

OCVS contains large samples of Cepheids discovered by OGLE. The sample of Cepheids from the Magellanic System (the Large and Small Magellanic Clouds and the Magellanic Bridge) counts over 10 000 objects (Soszyński *et al.* 2017a, 2018). Such a rich collection allowed detailed studies of the structure of the Magellanic System in young population (Jacyszyn-Dobrzeniecka *et al.* 2016, Inno *et al.* 2016) and provided many unique objects like Cepheids in eclipsing systems (Udalski *et al.* 2015b) or multi-mode pulsators (Soszyński *et al.* 2015b, Smolec *et al.* 2018).

OCVS also contains Cepheids from the Galaxy. Over 1000 Cepheids of all classes were found in the OGLE fields in the Galactic bulge (Soszyński *et al.* 2017b). A small sample of Cepheids was also detected in the OGLE pilot study of the Galactic disk fields (Pietrukowicz *et al.* 2013).

Only about 900 Galactic classical Cepheids has been discovered so far (Pietrukowicz *et al.* 2013). The vast majority of them are bright nearby objects located closer than 4 kpc from the Sun. Thus, this sample is of little use for studying the general structure of the Milky Way – the basic application of classical Cepheids in the Galaxy. Keeping this in mind, the OGLE survey has launched in 2013 a new large-scale program – The Galaxy Variability Survey (GVS) – aiming at the variability detection and census of objects in the large sky area of over 3000 square degrees around the Galactic plane seen from the OGLE observing site (Las Campanas Observatory, Chile) and the outer Galactic bulge (Udalski *et al.* 2015a).

Although the GVS survey has not been completed yet, large areas of the observed sky are ready for exploration and the preliminary results have already been reported (Udalski 2017). Here we present the details of the OGLE search for Cepheids in the GVS fields. This is our first attempt to extract these important stars from over a billion of regularly observed objects in the GVS fields.

After a very careful analysis of the stability of multi-season light curves of the Cepheid candidates we finally classified 1339 objects as classical Cepheids, 316 as type II Cepheids and 25 as anomalous Cepheids. 1167 classical Cepheids presented here are new discoveries. Together with earlier OGLE Cepheid discoveries (Pietrukowicz *et al.* 2013, Hümmerich and Bernhard 2013, Soszyński *et al.* 2017b) the OGLE Galactic Cepheid Collection counts 1428 classical Cepheids. The number of type II Cepheids is 1240 (after including 924 objects from Soszyński *et al.* 2017b) and anomalous Cepheids – 53 (with 28 objects detected earlier: Soszyński *et al.* 2017ab). The total number of Galactic Cepheids in the OGLE Collection is currently 2721.

The new OGLE Collection more than doubled the number of known classical Cepheids in our Galaxy which reaches now 2476. What is more important, the photometric range of the GVS: $10.8 < I < 19.5$ mag allows for the first time a very detailed study of the Milky Way structure as seen in the young stellar population – up to the Galactic disk boundary (Skowron *et al.* 2018, Mróz *et al.* 2018).

The sample of Cepheids presented in this paper is limited to stars brighter than $I \approx 18$ mag. Also, our search for Cepheids in some of the fields is preliminary, because the number of collected epochs was below our standard limit of at least 100 epochs. Thus, we expect that there might be a number of missed Cepheids, in particular in the regions close to the Galactic plane that are the most obscured by the dust. We plan to update the OGLE sample of the Galactic Cepheids in the future when the next generation search is completed and observations of additional GVS fields are finished.

2. Observations

OGLE observations of Galactic Cepheids come from a large-scale survey, GVS, conducted since 2013 as one of the sub-surveys of the OGLE-IV phase. Photometric observations obtained with the 1.3-m Warsaw telescope equipped with the 32-CCD detector mosaic camera, located at Las Campanas Observatory, Chile (Observatory is operated by the Carnegie Institution for Science), started on January 17, 2013 and continue up to now. GVS consists of three parts: Galactic disk fields extending in Galactic longitude: $190^\circ < l < 345^\circ$ (GD fields), Galactic fields of $20^\circ < l < 60^\circ$ (DG fields) and the outer Galactic bulge defined as an area roughly: $-15^\circ < l < 20^\circ$, $-15^\circ < b < 15^\circ$ (BLG fields) – see Fig. 1. (RA,DEC) and (l, b) coordinates of all OGLE pointings in these sections of the sky can be found and downloaded from the OGLE Web page (*http://ogle.astrouw.edu.pl* Sky Coverage $\rightarrow$ OGLE-IV Fields tabs).

The central part of the Galactic bulge have been regularly monitored by OGLE since 1992 for gravitational microlensing phenomena. The results of the OGLE extensive search for Cepheids in the microlensing BLG fields were presented in Soszyński *et al.* (2017b). More than 1000 Cepheids of all types were discovered in these fields. In this paper we present results of our search for Cepheids in additional part of the BLG fields – those complementing the strip $-5^\circ < b < 5^\circ$ around the Galactic plane. These limits are a direct consequence that our priority was the detection of classical Cepheids which rarely lie outside such a strip. Although not all from these fields have reached the typical number of epochs requested by OGLE for our variability search (>100 observations), the vast majority of fields were close to that limit.

Observations of the OGLE GD fields reached about 100 epochs after 2016 season and the preliminary results for the OGLE search for Cepheids and RR Lyr-type stars were presented in Udalski (2017). Up to now about 150 observations of these

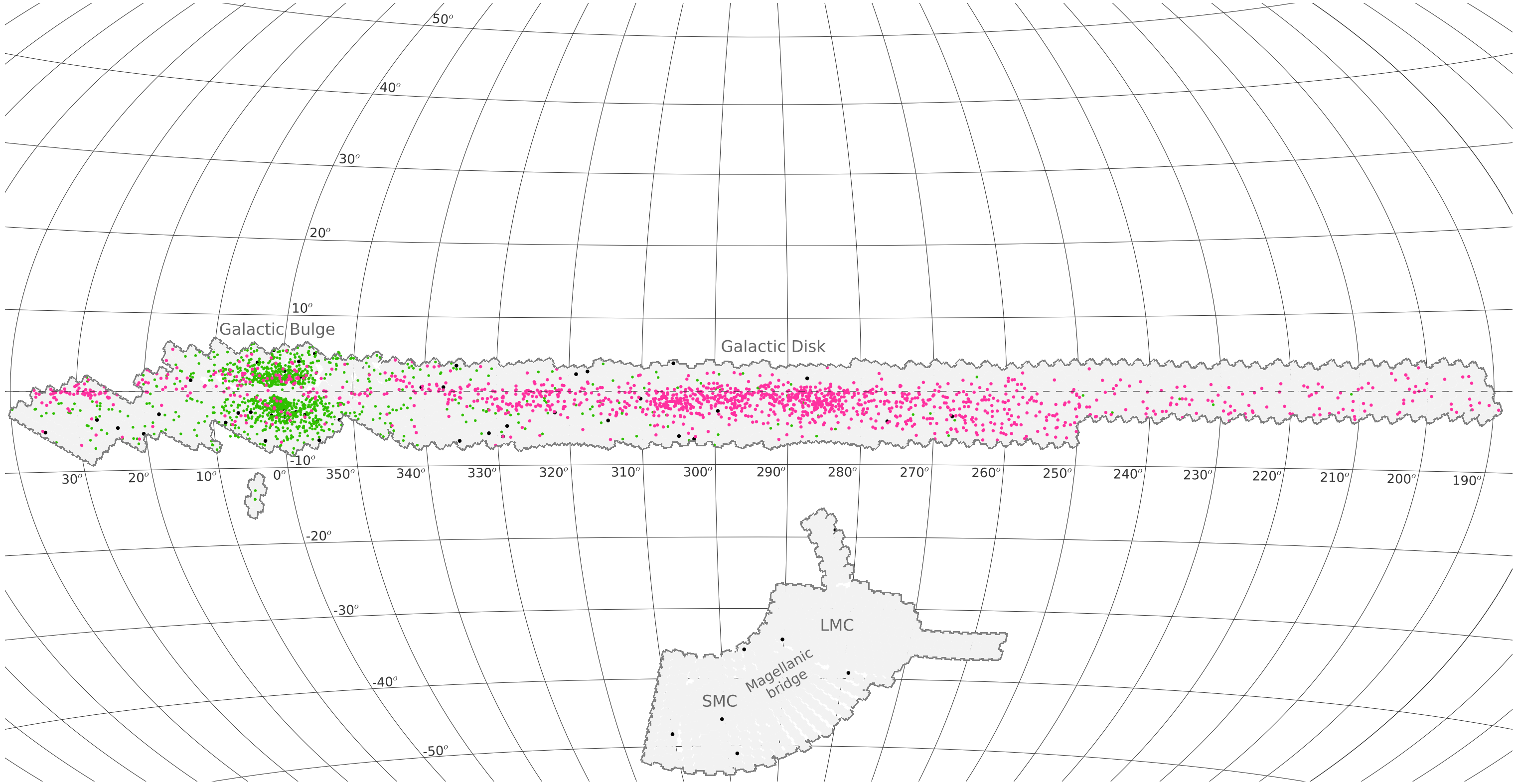

Fig. 1. Cepheids from the OGLE Collection of Variable Stars in the sky. Classical Cepheids – magenta dots, type II Cepheids – green dots, anomalous Cepheids – black dots.

fields spanning over five years were collected. Long span turned out to be crucial in our search for Cepheids to exclude large population of stars mimicking Cepheid light curves. In 2017 we extended coverage of the OGLE GD fields by adding pointings covering area $3^\circ < |b| < 6^\circ$ in a large range of Galactic longitudes of GD fields. Part of these GD extension fields has also been analyzed here.

The number of observations of the OGLE DG fields has reached the OGLE requirements after 2017 observing season. Thus, these fields were also included in our search for Galactic Cepheids.

All observations carried out in the GVS are relatively shallow with the exposure time of 25 s and 30 s in the *I* and *V*-band, respectively. During worse weather conditions the exposure times were sometimes extended to keep the signal at similar level. The majority of observations were taken in the *I*-band for variability studies and about 10 epochs were secured in the *V*-band for color information. The range of reliable photometry in the GVS is about $10.8 < I < 19.5$ mag.

OGLE *VI*-band photometry has been calibrated to the standard Johnson-Cousins system using observations of thousands secondary standards from the already calibrated OGLE-IV fields observed during the same nights as the target field. The procedures were similar to those described in Udalski *et al.* (2015a). The accuracy of the photometric zero points of the OGLE Galactic field databases is about 0.02 mag.

Astrometry of the OGLE Galactic fields was carried out in a similar way as for other OGLE-IV targets (Udalski *et al.* 2015a). 2MASS coordinate system (Skrutskie *et al.* 2006) was the base of the OGLE field astrometric solutions. The accuracy of transformations between the frame pixel grid (X,Y) and RA/DEC coordinates is about $0\farcs1$–$0\farcs3$ and the systematic errors of the 2MASS grid are of the order of $0\farcs1$.

3. Search for Periodic Variable Stars

Because the number of photometric data in the observed GVS fields still increases, we decided to carry out the first search for periodic variable stars on preselected sub-sample of stars. The natural and simplest criterion for preselection of a variable candidate is its detection by the OGLE photometric pipeline (Udalski 2003) on the difference images. The stars which leave measurable residua on difference images are certainly variable, thus they should be included in further analysis. While such a threshold selects true variable objects it also rejects fainter stars for which reasonable photometry can still be derived and variability, if large enough, can be detected. The typical limit of our preselection is $I \approx 18.0$ mag.

Such a preselection does not basically affect Galactic Cepheids, although a large number of fainter RR Lyr stars may be missing. All objects that are detected in the OGLE GVS (altogether about 1.5 billion) will be searched for variability in the next generation final analysis.

In the case of the GD fields the requested number of detections on the difference images was set to ten. In the GD extended and DG fields we required at least seven detections and in the BLG fields 5–7 detections depending on the number of collected epochs.

After the preselection, 1 794 420 variable candidates were left for further analysis. In the next step all these objects were subject of the period analysis. We carried out the period search using two algorithms – Fourier based analysis – FNPEAKS by Z. Kołaczkowski†, and Analysis of Variance (Schwarzenberg-Czerny 1989). We decided to use both methods because of relatively limited number of epochs and similar sidereal time of observations (so that the dataset was prone to aliasing). In the case of discrepant results from both algorithms the real periodicity was selected after careful visual check of the variable candidate.

To filter-out non-Cepheid candidates the Fourier series were fitted to light curves of the periodic variable candidates which passed the previous step. As usual in the OCVS we fitted cosine Fourier series up to the fifth order and calculated the amplitude ratios R_{21}, R_{31} and phase shifts ϕ_{21}, ϕ_{31} (Simon and Lee 1981). For preselection of Cepheid candidates we defined large areas on R_{21} *vs.* $\log P$ and ϕ_{21} *vs.* $\log P$ surfaces additionally limiting $\log P$:

$$-0.58 < \log P < 1.7,$$
$$0.03 < R_{21} < 0.8,$$
$$\phi_{21} < 2.5 \quad \text{for} \quad 0.9\ \text{d} < \log P < 1.2\ \text{d}.$$

These regions embed with large margins the area occupied by Cepheids and other important pulsating stars – RR Lyr – in the diagrams based on the OGLE Magellanic Cloud samples containing thousands of these objects (*e.g.*, Soszyński *et al.* 2008a – Fig. 5).

In the GVS regions located close to the Galactic bulge, namely OGLE DG and BLG (shallow) fields, where the RR Lyr stars significantly outnumber short period Cepheids, we decided to put stronger constraint on the range of searched periods:

$$0.0 < \log P < 1.7.$$

Short period Cepheids can be easily misclassified with RR Lyr stars. By limiting our search to $P > 1.0$ d we get rid of practically all RR Lyr contaminants. Our sample of Galactic Cepheids will be complemented with the potentially missing short period Cepheids in these areas when the OGLE search for RR Lyr is completed.

Objects that passed this cut were than subjected to the first pass visual inspection to filter out obvious non-pulsating stars. It has been quickly realized that the number of non-Cepheid variables in the preselected sample is huge. The main contaminants included eclipsing and ellipsoidal stars, long period variables (LPVs) and spotted stars which may very well mimic the pulsating light curves. Preliminary

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

results of our search for Galactic Cepheids after this step were presented in Udalski (2017).

Precise filtering out of the contaminants in our Cepheid sample was not trivial. Eclipsing stars can be removed relatively easy, when the number of collected epochs is large enough and coverage of eclipses is sufficient. On the other hand, light curves of LPVs and spotted stars are usually unstable in the time scale of months to years. Thus, it is crucial to have coverage spanning a few years to filter out these types of non-Cepheids. This is the reason why we decided to collect one additional season of observations after the preliminary OGLE Cepheid sample was selected (Udalski 2017).

One of the main selection criterion in the final cleaning of the preliminary OGLE sample was the stability of the long term light curve. We did it extremely carefully to avoid removing multi-periodic Cepheids which also present variable shape of light curves. Each case which resembled a beat Cepheid was analyzed individually.

The next important selection criterion was position of a Cepheid candidate on the color–magnitude diagram (CMD). This test is very useful in distant galaxies like the Magellanic Clouds where all objects are at roughly similar distance. Cepheids populate well defined region of the instability strip on the CMD and the selection of candidates is, thus, straightforward. In the case of the Galactic CMDs the situation is much more complicated because stars (and Cepheids) are located at different distances from hundreds of parsecs to kiloparsecs. Additionally, large interstellar extinction near the Galactic plane can significantly dim and redden Galactic objects. The typical CMDs of the Galactic disk fields look like those presented in Szymański *et al.* (2010) – the main characteristic feature is a clear strip of Galactic main sequence stars slanted to redder color at fainter magnitudes due to increasing reddening. The second much weaker feature is a redder parallel sequence formed by red clump giants at different distances.

By checking the position of a Cepheid candidate on the CMD of the field, one can easily find if this object is a main sequence star. If so it cannot be a Cepheid even if the light curve has a pulsating-star shape. Ellipsoidal stars mimicking overtone Cepheids, eclipsing close binary systems, blue cataclysmic variables, spotted α^2 CVn stars can be removed using this criterion.

Additional and independent verification of the candidates was carried out based on Fourier parameters of the Fourier light curve decomposition. Soszyński *et al.* (2017a) showed that this can be a very useful tool for classification of different classes of Cepheids (CEP, ACEP, T2CEP) because they populate different sequences on appropriate diagrams. Such diagrams are also useful tools for rejecting non-Cepheids. We used the following Fourier parameters: R_{21}, ϕ_{21}, R_{31}, ϕ_{31} as a function of $\log P$ for classification of the Galactic Cepheid candidates. Template diagrams were constructed based on precise OGLE light curves of thousands of Cepheids from the Large Magellanic Cloud (Soszyński *et al.* 2008a).

The sample of OGLE Galactic Cepheids after applying all the above mentioned selection cuts was finally visually inspected by three very experienced astronomers (IS, PP, AU). In this final vetting step we rejected several uncertain candidates and left on the final list only the Cepheids accepted by the vetting team.

In total the OGLE sample of Galactic Cepheids presented in this paper contains 2721 objects.

4. OGLE Collection of Galactic Cepheids

The structure of the new part of the OCVS – the Galactic Cepheids – is identical to the former parts, in particular the OGLE Collection of Cepheids in the Magellanic System (Soszyński *et al.* 2015a, 2017a, 2018). The entire collection of the OGLE Galactic Cepheids is available from the OGLE WWW Page and OGLE FTP Internet Archive:

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

We continue to use the standard OGLE naming convention for detected Cepheids: OGLE-GD-CEP-NNNN, OGLE-GD-T2CEP-NNNN for Cepheids located in the OGLE Galactic disk fields. The first twenty numbers for classical Cepheids have already been occupied by the OGLE-III Cepheids discovered by Pietrukowicz *et al.* (2013) in a pilot survey of the Galactic disk based on the OGLE-III observations. Not all of them can be confirmed as *bona fide* Cepheids in the OGLE-IV data (Section 5), nevertheless we keep the numbering for historical reasons. We start the list of OGLE-IV Galactic classical Cepheids from '0021'. Although none of the type II Cepheid candidates presented by Pietrukowicz *et al.* (2013) survived after OGLE-IV verification (Section 5) we keep numbering here as well. Therefore, we start the OGLE-IV Collection of this class from OGLE-GD-T2CEP-0007.

Although the Galactic bulge is a crucial part of our Galaxy, it is kept as a separate entity in the OGLE Collection. Therefore, we decided to add all the new OGLE-IV Cepheid detections in the OGLE outer Galactic bulge fields (designated with prefix BLG) to the already existing OGLE BLG collections of classical and type II Cepheids. The numeration of presented in this paper Cepheids will start from OGLE-CEP-BLG-101, and OGLE-T2CEP-BLG-0932 for classical, and type II Cepheids, respectively. We add one more significant digit for the latter Cepheid class as the original three-digit field was close to overflow.

In the case of Galactic anomalous Cepheids the first seven OGLE objects were detected in the Galactic halo in the direction of the Magellanic Clouds (Soszyński *et* *al.* 2017a). The next twenty in the Galactic bulge (Soszyński *et al.* 2017b) and, very recently, one more in the direction of the Magellanic Bridge. All of them have designations OGLE-GAL-ACEP-NNN. For compatibility, we add all new detections of anomalous Cepheids in both: the OGLE-IV Galactic disk (GD, DG) and outer Galactic bulge (BLG) fields to this list, starting from OGLE-GAL-ACEP-029.

The data provided in the OCVS for OGLE-IV Galactic Cepheids include astrometry (RA/DEC J2000.0), mean magnitudes in the *I* and *V*-bands, pulsation period, epoch of the maximum of light, *I*-band amplitude and Fourier parameters from the Fourier light curve decomposition. After rejecting obvious outlying points, the pulsation periods have been tuned up using the TATRY program (Schwarzenberg-Czerny 1996). For details see README file in the appropriate sub-archives of the OCVS.

In total the search presented in this paper provided 1680 objects: 1339 classical Cepheids, 316 type II Cepheids (154 BL Her type, 143 W Vir type, including four peculiar W Vir type, Soszyński *et al.* 2008b, and 19 RV Tau type) and 25 anomalous Cepheids. The separation in pulsation period between different groups of type II Cepheids was the same as in other parts of the OGLE Collection – shorter than 4 d for BL Her, shorter than 20 d for W Vir Cepheids.

Fig. 1 presents the sky map in the Galactic coordinates with the positions of the OGLE Cepheids: CEP, T2CEP and ACEP marked with different colors.

5. Completeness of the OGLE Cepheid Sample

OGLE Collection of Galactic Cepheids supplemented with OGLE microlensing fields detections (Soszyński *et al.* 2017b) contains 2721 stars – classical, type II and anomalous Cepheids. Because the vast majority of Galactic classical Cepheids are bright objects with $I < 18$ mag, the completeness of the OGLE Collection for this type of pulsators is high. We expect that our preselection of objects which was the first step of our search for Cepheids only marginally affects completeness of the OGLE sample (only the very highly reddened objects near the Galactic plane and Galactic center may be obscured so much that they are below our preselection threshold; a $P = 3$ d Cepheid at $d \approx 20$ kpc from the Sun should be detectable even at the extinction of $A_I \approx 4$ mag). Due to technical reasons, the OGLE footprint of the Galactic fields in the sky contains non-covered regions reaching 5–7% of the area (gaps between CCD detectors of the OGLE-IV camera). Thus, even the full completeness of the OGLE observed fields means $\approx 94\%$ absolute completeness.

In the case of classical Cepheids we estimate that the completeness of the OGLE Collection is at $\approx 90\%$ level. For type II Cepheids of BL Her and W Vir type the completeness is still high – about 80–90%. We note here that only single RV Tau type stars are included to the OGLE sample at this moment because presented here search has not been focused on such objects. In the case of anomalous Cepheids the completeness is difficult to assess. Generally these stars are fainter and harder to distinguish from other Cepheid types and RR Lyr stars (*cf.* Soszyński *et al.* 2017b). Thus, our completeness may be lower.

High completeness of the OGLE Collection of Galactic Cepheids can be verified by comparison with other Cepheid detections from the literature. On the other hand, we can assess purity of other surveys which have recently claimed the discovery of significant number of Galactic Cepheids. In this latter case we may compare Cepheid candidates with all objects in the full range of the OGLE-IV databases (even the faintest – down to $I \approx 19.5$ mag) as the position of each candidate is known. However, when assessing the OGLE search completeness we only use those stars which are currently in the OGLE Collection and which should pass our preselection cut (thus, be brighter than $I \approx 18$ mag).

For years there have been two major sources of Galactic Cepheids in the literature: the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995) and the All Sky Automated Survey (ASAS) catalog (Pojmański 2002). Unfortunately, the majority of Cepheids listed in these sources are nearby objects ($d < 4$ kpc) – bright and mostly saturated in the OGLE GVS observations. The original GCVS sample is also non-homogeneous and, sometimes, hard to verify because objects listed there came often from old observations obtained with out-of-date techniques.

After presentation of the preliminary sample of the OGLE Galactic Cepheid Collection (Udalski 2017) a few new datasets of variable stars containing Galactic Cepheid candidates have been published. Below, we compare the content of all these datasets with the OGLE Collection of Galactic Cepheids.

5.1. GCVS and OGLE Collection of Galactic Cepheids

For comparisons with the GCVS we have used objects included in the list of Galactic classical Cepheids prepared by Pietrukowicz *et al.* (2013, Section 6). This list is based on the original GCVS list (Artyukhina *et al.* 1995) with upgrades in the following years (Samus *et al.* 2017). Objects from GCVS have been additionally verified and often reclassified *vs.* the original GCVS classification based on modern data and AAVSO VSX Catalog.

Current version of the Pietrukowicz *et al.* (2013) list contains 713 classical Cepheids defined as GCVS objects (they have GCVS as main ID).

328 of these classical GCVS Cepheids are located in the OGLE sky coverage footprint. As expected the majority of them (224) are saturated in OGLE images. 12 fall in uncovered part of the OGLE area. 90 classical GCVS Cepheids were detected in the OGLE data and confirmed as genuine Cepheids. One could not be verified because it is located very close to a bright saturated star.

5.2. ASAS Survey and OGLE Collection of Galactic Cepheids

The ASAS survey has detected and classified a large number of bright variables considerably increasing the number of known bright Cepheids. This survey collected large number of epochs, thus, the classification of variables is rather sound and homogeneous. Unfortunately, the ASAS and OGLE surveys overlap only in a very limited magnitude range – faint end of ASAS and bright end of the OGLE GVS. Similarly to the GCVS case – many ASAS detections are saturated in OGLE images.

105 ASAS classical Cepheids are listed by Pietrukowicz *et al.* (2013). 60 are located in the OGLE footprint. 22 were detected and confirmed by OGLE. The remaining 36 are saturated and two fell into non-observed area of the fields.

5.3. OGLE-III Pilot Survey and OGLE Collection of Galactic Cepheids

The most convenient and comparable in quality dataset of Cepheids suitable for checking the completeness of the present search is the OGLE Galactic disk pilot study by Pietrukowicz *et al.* (2013). Unfortunately, this survey focused on the OGLE-III transiting planet search, covered only 7.12 square degrees. On the other hand, the pointings were in the stellar rich Galactic fields and the exposures were much longer than those of the OGLE-IV GVS. Pietrukowicz *et al.* (2013) found 20 classical Cepheids and six candidates for type II Cepheids in these OGLE-III fields.

All classical Cepheids, except one, OGLE-GD-CEP-0020, which fell in the uncovered part of the field, were independently detected in the OGLE-IV GVS. However, OGLE-GD-CEP-0013 turned out to have completely different shape of the light curve compared with a decade earlier observations during OGLE-III phase. Variable shape of the light curve indicates that this is rather a spotted star than a Cepheid. Therefore OGLE-GD-CEP-0013 has been retracted from the list of OGLE Cepheids. The remaining 18 OGLE-III classical Cepheids have been confirmed implying high, $>90\%$ completeness of the OGLE-IV Galactic Cepheid Collection.

On the other hand, the light curves of all six candidates for type II Cepheids show in the OGLE-IV GVS data different and variable shapes compared to the original OGLE-III ones (Pietrukowicz *et al.* 2013). This clearly indicates that these objects are also rather spotted stars than genuine type II Cepheids. Therefore, we also rejected them from the OGLE-IV Collection.

5.4. ASAS-SN Survey and OGLE Collection of Galactic Cepheids

ASAS-SN project has released a variable star catalog based on its all-sky photometry (Jayasinghe *et al.* 2018). The range of this search for variables is relatively shallow ($V<17$ mag). However, the number of collected epochs is large which makes classification significantly easier. Classification is obtained using automatic machine learning algorithms.

ASAS-SN catalog contains 315 objects classified as classical or type II Cepheids. 66 stars are located in the footprint of the OGLE-IV GVS. However, two are overexposed in the OGLE images, two are located in the gaps between the OGLE subfields, six have too few observing points to be analyzed in this OGLE search (they are located close to the field edge). The remaining 56 ASAS-SN objects can be verified using OGLE photometry. Five are misclassified by ASAS-SN (non-Cepheids) and one (ASAS-SN J081259.7-442549) was overlooked by OGLE due to bad period value (1-d alias with resulting $P < 1$ d, thus, not included here). The remaining 50 common stars are genuine Cepheids. This comparison of the OGLE Collection indicates its high completeness in the range covered by ASAS-SN.

5.5. ATLAS Survey and OGLE Collection of Galactic Cepheids

The Asteroid Terrestrial-impact Last Alert System survey (ATLAS, Tonry *et al.* 2018) designed for finding near-Earth asteroids (NEAs) has collected during the past years a large set of images of the sky north of declination $\delta = -30^\circ$ suitable also for analysis of stellar variability. In April 2018 a huge catalog containing about 450 000 of variable object candidates based on photometry collected during the ATLAS survey was published. Additionally, the whole set of individual measurements containing over 100 epochs for each individual object was released (Heinze *et al.* 2018).

Because the automatic classification approach used by the authors of the ATLAS catalog does not meet the OGLE strict criteria of variability analysis we decided to independently classify the ATLAS Cepheid candidates. We downloaded light curves of all stars preliminary designed as pulsating (all types) in the ATLAS catalog and many more objects where Cepheid candidates could be hidden. Altogether we analyzed over 3000 ATLAS light curves, independently in two filters used. They were run through the OGLE data pipeline – identical as used for objects from the OGLE Collection. Because we were mostly interested in classical Cepheids for the Galactic structure studies we concentrated on selection of only this type of ATLAS Cepheids neglecting other classes.

438 classical Cepheids were found during our search of the ATLAS data. We compared the list of these objects with Cepheids from the OGLE Collection and lists of other known classical Cepheids. 170 objects are the new discoveries – Cepheids undetected by previous searches.

101 out of 438 ATLAS classical Cepheids are located in the OGLE footprint. 89 could be verified using OGLE databases (the remaining objects are either overexposed in OGLE images or fall into gaps between OGLE camera detectors). 87 Cepheids were already found by OGLE during the search presented in this paper. Two missing objects are certainly classical Cepheids but the number of collected epochs by OGLE was too low for passing preselection and period determination steps. Comparison of ATLAS data and OGLE collection indicates again that the completeness of the OGLE collection is almost perfect.

5.6. Gaia DR2 Cepheids and OGLE Collection of Galactic Cepheids

At the end of April 2018 the Gaia satellite team made available its second data release, DR2, including, among others a set of variable stars detected and characterized by the Gaia pipeline (Holl *et al.* 2018). Gaia DR2 includes a sample of

Cepheids of all types (classical, type II and anomalous) and the main, most reliable set of Gaia Cepheid candidates – SOS Cep&RRL (Clementini *et al.* 2018) – contains 9575 stars claimed as Cepheids. The vast majority of them are located in the Magellanic System. Virtually all of them have already been included in the OGLE Collection of this region of the sky (see the comparison in Udalski *et al.* 2016 and Soszyński *et al.* 2018). Large number of OGLE Cepheids were used by Holl *et al.* (2018) to train the Gaia DR2 automatic classifiers.

The remaining part of the Gaia DR2 Cepheid candidates is located all over the sky. The photometric ranges of the Gaia photometry and the OGLE survey are comparable. Thus, the huge OGLE footprint of the GVS fields presented in this paper (≈ 1800 square degrees) enables direct comparison of the datasets and verification of the quality of the Gaia DR2 Cepheid sample in the sky regions where the vast majority of Galactic classical Cepheids reside (Galactic disk). On the other hand, the completeness of the presented here collection of OGLE Galactic Cepheids can be checked based on independent Gaia DR2 set.

559 Gaia objects from the DR2 SOS Cepheid set are located in the footprint of the OGLE Galactic fields observed so far, *i.e.*, the central Galactic bulge fields observed for microlensing and already searched for Cepheids (Soszyński *et al.* 2017b) as well as Galactic disk and outer Galactic bulge fields presented in this paper. Not all of them can be verified as Gaia also observes brighter stars which are saturated in the OGLE images. Altogether 344 Gaia objects can be cross-identified with stars in the OGLE databases and verified with the OGLE most recent photometry. The remaining Gaia objects are either too bright for the OGLE camera (thus saturated) or fall in the unobserved gaps between the OGLE mosaic camera CCD detectors.

Out of these 344 Gaia objects 231 can be confirmed by OGLE photometry as *bona fide* Cepheids. The purity of the Gaia DR2 Cepheid sample in the Galactic disk region of the sky is, then, about 67%. The remaining Gaia objects which are certainly non-Cepheids are in the vast majority eclipsing stars (32%) and spotted stars (22%) but also LPVs and sometimes even non-variable objects.

The OGLE search presented in this paper yielded 223 Cepheids out of 231 Gaia DR2 verified ones, *i.e.*, 97%. The missing objects are located usually at the edge of detectors. Thus, the number of their observations at the moment when our search for Cepheids started was too small either to pass the preselection criterion or to derive the correct period. In the case of one missing object (GAIA 5521400228203695232) the period was so close to 1 d that finding this double mode Cepheid from the ground would be a miracle.

The total number of all types Cepheids in the OGLE Collection (anomalous, classical, type II but excluding RV Tau which have not been carefully searched by OGLE yet) is 2538 (45 anomalous – not counting eight Galactic ACEPs located in the direction of the Magellanic System, 1428 classical, 1065 type II – BL Her and W Vir). They are fainter than $I \approx 10.8$ mag, *i.e.*, in the most interesting magnitude range for many new applications and discoveries.

Provided statistics indicate that the completeness of the Gaia DR2 Cepheid sample *vs.* the OGLE Collection in the Galactic disk and bulge sky regions is very low – only at the $231/2538 = 9.1\%$ level. In part this may be caused by low number of epochs collected by Gaia up to the DR2 dataset and the high stellar density of the fields. These statistics may improve with further Gaia data releases.

5.7. WISE Catalog of Variables and OGLE Collection of Galactic Cepheids

Another relatively large catalog of variable stars containing the Galactic Cepheid candidates was published in July 2018 by Chen *et al.* (2018). This catalog is based on all sky mid-infrared photometry collected during the WISE satellite mission. The authors analyze and classify the infrared light curves of individual objects. This catalog includes 1312 objects classified as Cepheids and a number of Cepheid-like objects.

We downloaded the data for Cepheid and Cepheid-like classifications from the WISE catalog (Chen *et al.* 2018). The sample consists of 1772 objects. 509 of them are located in the OGLE footprint. It is well known that the classification of pulsating stars is difficult in the infrared bands and often leads to misclassifications. Therefore, we have first verified purity of the WISE catalog. We cross-identified WISE Cepheid candidates with objects from the OGLE databases.

434 Cepheid candidates from the WISE catalog can be verified in our optical OGLE databases. The remaining objects are overexposed in the OGLE images, are located in the gaps between OGLE camera CCDs or are too faint ($I > 20$ mag) in the optical range for verification – likely due to high extinction. Moreover, in many cases the periods listed in the WISE catalog are wrong up to several percent (in 25% cases of the real Cepheids). Thus, we have calculated proper periods for each of the candidates based on the OGLE optical data. Wrong periods may be a result of specific pattern of WISE satellite observations.

244 WISE objects out of 434 having OGLE counterparts can be verified as genuine Cepheids. Thus, the purity of the sample is at the $244/434 = 56\%$ level, *i.e.*, every second object is not a Cepheid. The largest group of misclassified objects are eclipsing variables (32% of the sample). Some objects are LPVs or simply non-variables.

During the OGLE search presented in this paper 231 Cepheids from the WISE verified list were found. Five were missed because of too small number of epochs or wrong period determination and eight uncertain Cepheid candidates have not passed the OGLE preselection procedure because they are too faint (> 18) mag due to high interstellar extinction close to the Galactic plane (while being detectable in the infrared). Thus, the completeness of the OGLE collection estimated with the verified WISE Cepheids remains at the $231/236 = 97.9\%$ level. The eight missing faint Cepheid candidates on the whole OGLE footprint indicate that the number of faint Cepheids overlooked in our present search should be less than $\approx 5\%$.

Because the WISE catalog is all sky collection of variables and in the infrared the majority of Galactic Cepheids should be detectable (*cf.* Skowron *et al.* 2018) we may estimate the completeness of the WISE catalog. As already mentioned (Section 5.6) the number of all types of Cepheids in the OGLE Collection footprint is 2538. Thus, including the WISE faint Cepheid candidates, the completeness of the WISE catalog is at the $244/(2538+10) = 9.6\%$ level – again very low compared to the OGLE Collection.

5.8. Ground Infrared Surveys and OGLE Collection of Galactic Cepheids

Our analysis of the detections of infrared Cepheids based on the comparison of the WISE and OGLE data confirms that the solely infrared detections can be significantly contaminated by other variables. On the other hand, using the infrared bands is tempting as one can probe the Galactic plane and Galactic center regions – not available for optical bands. Matsunaga *et al.* (2016) and Dékány *et al.* (2015) reported the discovery of several tens of classical Cepheids in the optically obscured regions of the Galactic bulge, based on the IRSF/Sirius (Nagashima *et al.* 1999) and VVV (Minniti *et al.* 2010) surveys, respectively. We tried to cross-identify those objects in the OGLE *I*-band images. We succeeded only in two cases – stars #6 and #7 on the Matsunaga *et al.* (2016) list (#7 = VVV-29 on the Dékány *et al.* 2015 list). OGLE optical photometry confirms the Cepheid status and period of the star #6 (OGLE-BLG-CEP-121). Its *I*-band magnitude is, however, fainter than our preselection limit, so this variable has not been found during the present search. On the other hand, the star #7 cannot be confirmed as a periodic variable in spite of its reasonable OGLE photometry. This is another example that the infrared detections should be treated with care.

Three more infrared Cepheid candidates were detected by Tanioka *et al.* (2017) in the Galactic disk close to the Galaxy center. Only one object can be verified with the OGLE optical photometry – Lp30A. OGLE data confirm Cepheid classification and this star is designated as OGLE-GD-CEP-1238 in the OGLE Collection.

Five additional infrared Galactic disk Cepheids were presented by Inno *et al.* (2019). While the two brightest objects (ID-1 and ID-4) are known Cepheids from the OGLE Collection – OGLE-GD-CEP-1017 and OGLE-GD-CEP-1021, the remaining three are very faint in the optical *I*-band. Additionally, one of the candidates (ID-2) – bright in the infrared – is blended with much brighter optical companion, thus practically non-verificable in the optical band. One of the two remaining candidates (ID-5) reveals noisy Cepheid-like light curve in the OGLE data. The last one does not show any trace of periodic optical variability, although we cannot exclude it is hidden in the observing noise as the star is very faint in the *I*-band.

5.9. Other Detections and OGLE Collection of Galactic Cepheids

To complete this Section we note that the discovery of 11 new Cepheids and 88 Cepheid candidates in the Galactic bulge was reported by Kains *et al.* (2019). We were able to identify and verify 95 stars. None of these objects can be confirmed as a Cepheid based on the OGLE extensive and precise photometry. Most of them are periodic but rather spotted, ellipsoidal or eclipsing than pulsating variables.

5.10. Summary of Comparisons

Summarizing, all these tests clearly indicate that the sample of Galactic Cepheids presented in this paper has high completeness, purity and quality. It significantly increases the number of known classical and other type Cepheids and opens new possibility for studies of our Galaxy and better understanding of properties of these very important standard candles.

Please note that the single Cepheids overlooked during our OGLE search but within its magnitude range and found during the above verifications with other datasets have been added to the OGLE Collection of Galactic Cepheids for completeness. It is also worth noting that the OGLE photometry of misclassifed Cepheid candidates described in Section 5 can be found in the OGLE Collection of Galactic Cepheids archive.

6. OGLE List of Galactic Classical Cepheids

Because the classical Cepheids are one of the main tools for studying the Galactic structure we completed a list of all known and verified with modern observations Galactic Cepheids, trying to keep it as reliable as possible. This list was originally presented by Pietrukowicz *et al.* (2013) and its electronic version became available from the OGLE *ftp* site. With a flurry of new discoveries of new Galactic Cepheids the major update of the list and its structure was necessary.

A new version of the list of Galactic classical Cepheids is available from the OGLE *ftp* archive:

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

Additionally, we prepared a Web page containing the same information and some visualizations. It is available from the main OGLE Web site:

http://ogle.astrouw.edu.pl

Please cite Pietrukowicz *et al.* (2013) paper when using the list in publications.

The original list was supplemented with the new OGLE discoveries as well as confirmed detections from other surveys. To keep the purity as high as possible we do not include in this list Cepheid candidates which cannot be verified (except for IR Cepheid candidates in the Galactic center). Stellar contamination in the Galactic fields is so high that only sound detections enter the list. Currently, the list counts 2476 objects. Cross-identification with other surveys is also provided. Updates of the list will be done regularly.

7. Basic Statistics of the OGLE Collection

OGLE Collection of Galactic Cepheids contains now 2721 Cepheids from the Milky Way. 87 classical, 924 type II and 28 anomalous Cepheids have been already reported in Soszyński *et al.* (2017ab). The remaining OGLE objects are reported in detail in this paper for the first time. A part of them have already been detected earlier. Our Collection will be updated when observations of additional OGLE-IV Galactic fields are completed.

Having so large sample of 1428 OGLE classical Cepheids from the Galaxy we may compare basic parameters of Cepheids in different environments. Virtually all classical Cepheids in the Magellanic System have been found during the OGLE monitoring (Soszyński *et al.* 2017a). Young stars from the Large Magellanic Cloud (LMC) have on average a half of metallicity of the Milky Way young stars. The metallicity of the Small Magellanic Cloud (SMC) young population is by an additional factor of two lower than that of the LMC objects. Thus, direct comparison of these samples provides empirical data on how properties of Cepheids depend on the chemical composition of galaxies they live in.

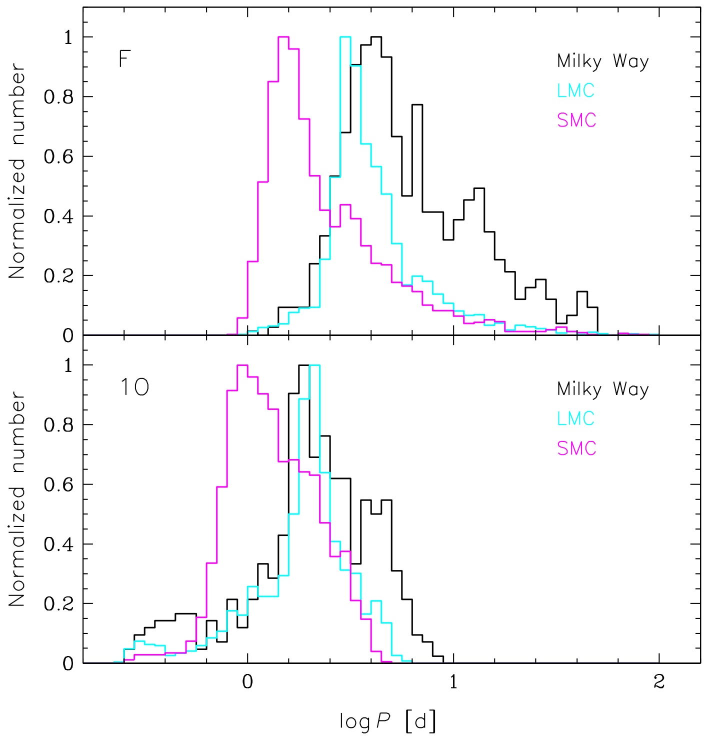

Fig. 2. Distribution of periods of classical Cepheids from the OGLE Collection of Galactic Cepheids. Similar distributions of periods for Cepheids from the Magellanic System are shown for comparison: cyan for the LMC and magenta for the SMC. *Upper panel* – fundamental-mode Cepheids, *lower panel* – first-overtone Cepheids.

Fig. 2 presents distribution of periods for classical Cepheids of fundamental pulsation mode (upper panel) and the first overtone mode (lower panel) for stars from the Milky Way and, for comparison, from the Magellanic System (Soszyński *et al.* 2015a). The shift of the pulsation period distribution in environments of different metallicities is clearly seen in both pulsation modes. Periods are longer in more metal abundant environments.

8. Multi-periodic Objects

OGLE Collection of Galactic Cepheids contains many new multi-periodic objects. The most prominent are Cepheids pulsating in more than one radial mode. Altogether the OGLE Collection contains 107 multi-mode Cepheids pulsating either in the fundamental and first overtone or first and second overtone modes. Six

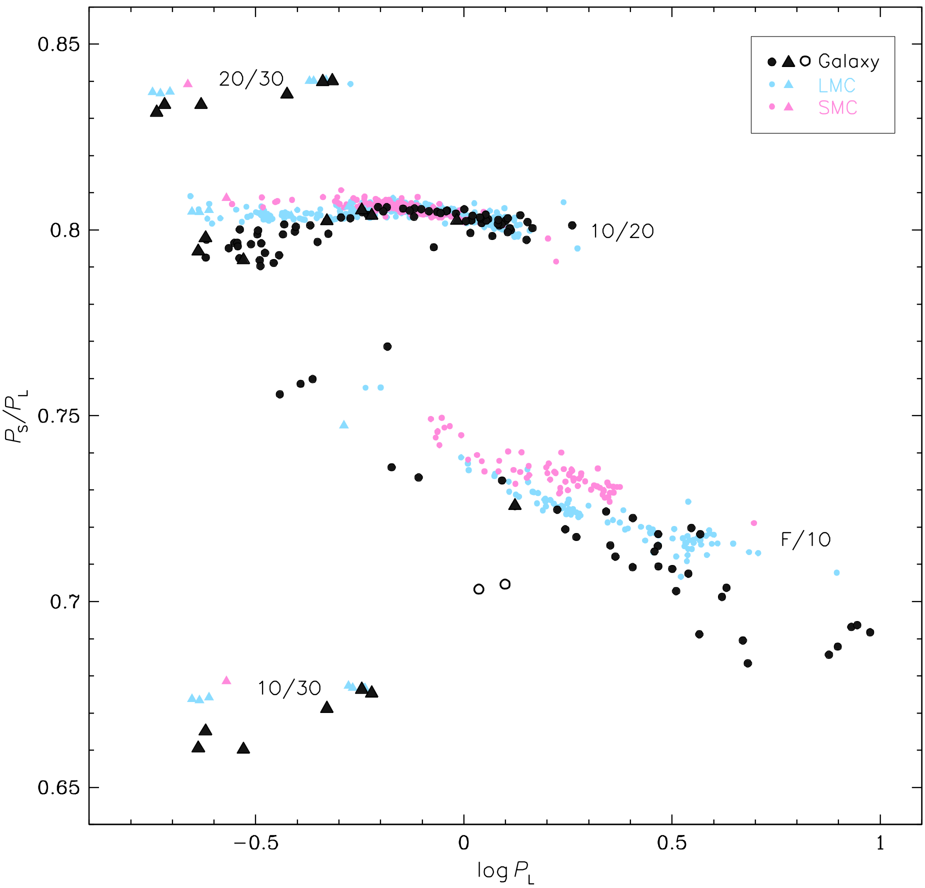

Fig. 3. Petersen diagram for multi-mode classical Cepheids. Black dots and triangles show multi-mode Cepheids from the OGLE Collection of Galactic Cepheids while cyan and magenta signs show multi-mode Cepheids from the LMC and SMC, respectively. Two open black circles mark position of two new multi-mode type II Cepheids.

additional objects are triple-mode Cepheids pulsating simultaneously in the first, second and third overtones. Three of these unique objects have already been presented in the previous paper (Soszyński *et al.* 2017b). Additional three – OGLE-GD-CEP-0360, OGLE-GD-CEP-0555 and OGLE-GD-CEP-0643 – have been found during the GVS. Moreover, we have also found one triple-mode Cepheid pulsating in the fundamental mode and the first and second overtones – OGLE-GD-CEP-1011. Fig. 3 shows the Petersen diagram presenting the ratio of the shorter to longer pulsation periods *vs.* logarithm of the longer period for the multi-mode Galactic classical Cepheids from the OGLE Collection (black dots). For comparison, similar data are plotted for classical Cepheids from the LMC (cyan dots) and SMC (magenta dots). One can notice that the characteristic sequences in the Petersen diagram for double-mode stars from different environments are somewhat shifted one *vs.* another indicating again some dependence of pulsation properties on metallicity of Cepheids.

When preparing the diagram we noted that two short period multi-mode Cepheids originally classified as classical ones are evident outliers from the sequence of F/1O multi-mode classical Cepheids (Fig. 3). With the pulsation periods close to one day and the period ratio of 0.70 they closely resemble the first two multi-periodic type II Cepheids of BL Her type found recently by Smolec *et al.* (2018). Moreover, their light curves are almost identical with those prototypes (Fig. 4). Thus, we finally reclassify these two Cepheids as T2CEP type: OGLE-GD-T2CEP-0045 and OGLE-BLG-T2CEP-1041 increasing the sample of multi-periodic BL Her stars to four.

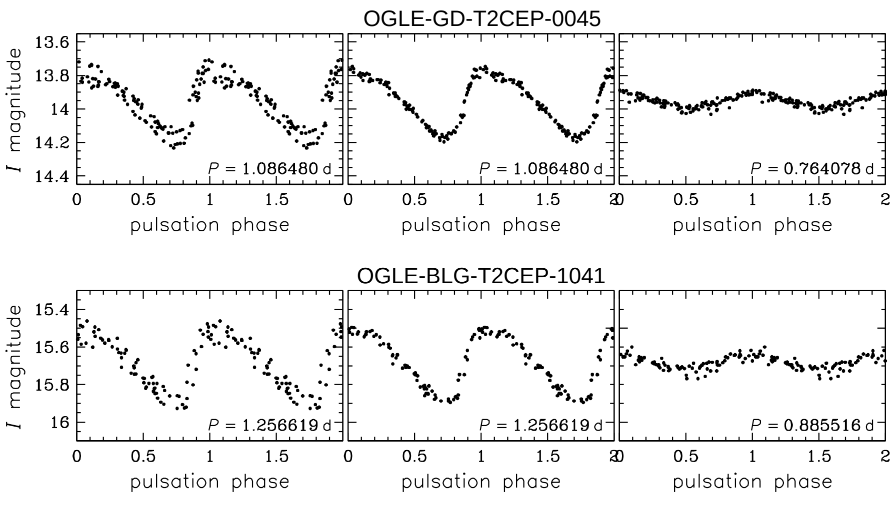

Fig. 4. Light curves of OGLE-GD-T2CEP-0045 and OGLE-BLG-T2CEP-1041 – new candidates for double mode type II Cepheids. *Left panel* shows the original data folded with the fundamental mode period. *Middle* and *right panels* present separated pulsations in the fundamental mode and first overtone, respectively.

It is very likely that the OGLE Collection contains a sample of multi-mode Cepheids in which the additional modes are non-radial. Many such objects have been discovered, for example, in the LMC sample (Soszyński *et al.* 2015b, Smolec 2017). However, the search for such objects is out of the scope of this paper and we leave it for follow-up studies.

9. Binary Candidates

One of the large successes of the OGLE search for Cepheids in the Magellanic Clouds was the discovery of several Cepheids in binary eclipsing systems (Soszyński *et al.* 2008a, Udalski *et al.* 2015b). With the spectroscopic follow-up observations obtained by the Araucaria project, the first, spectacular measurement of the Cepheid mass with the accuracy of 1% was possible (Pietrzyński *et al.* 2010). This pioneering measurement provided an empirical solution of the long-standing discrepancy between the predicted Cepheid masses by theories of stellar pulsation and evolution – differing by $>20\%$.

Since then, several more classical Cepheids in eclipsing systems were found. Part of them have already been followed-up spectroscopically by the Araucaria project (Pilecki *et al.* 2018a). The current status of the OGLE Cepheids in eclipsing systems can be found in Udalski *et al.* (2015b).

Our search for Galactic Cepheids yields three very interesting binary systems. The first one, OGLE-GD-CEP-0069, contains an overtone classical Cepheid. Its pulsation period is 3.832704 ± 0.0001069 d. It is a member of a wide eclipsing system with the orbital period of 81.64 d. Different width of eclipses may indicate a presence of a disk in the system similar as in a W Vir star OGLE-LMC-T2CEP-211 (Pilecki *et al.* 2018b).

OGLE-GD-CEP-0465, is another eclipsing system containing a classical Cepheid as one of the components, however, pulsating in fundamental mode. The pulsation period is 6.605564 ± 0.000059 d while the orbital period equals to 193.83 d. Fig. 5 presents the light curves of OGLE-GD-CEP-0069 and OGLE-GD-CEP-0465 showing the variability folded with the pulsation period and eclipsing light curve after removal of pulsations. Both these objects remain very promising candidates for the first eclipsing Cepheid systems in the Galaxy. However, their status must be confirmed spectroscopically to exclude a by-chance coincidence of two independent variables. This is unlikely in the rather empty stellar fields where these stars reside.

The third object – OGLE-GD-CEP-0291 – reveals light variations of a Cepheid shape with two different periods: $P_1 = 3.398938 \pm 0.000018$ d and $P_2 = 3.667764 \pm 0.000024$ d. Thus, it is very likely that this object is a binary system containing two Cepheids pulsating in the fundamental mode. Another possibility is a by-chance blend of two unrelated Cepheids. However, this possibility seems to be unlikely – also in this case the stellar density of the field is not too high. Spectroscopic

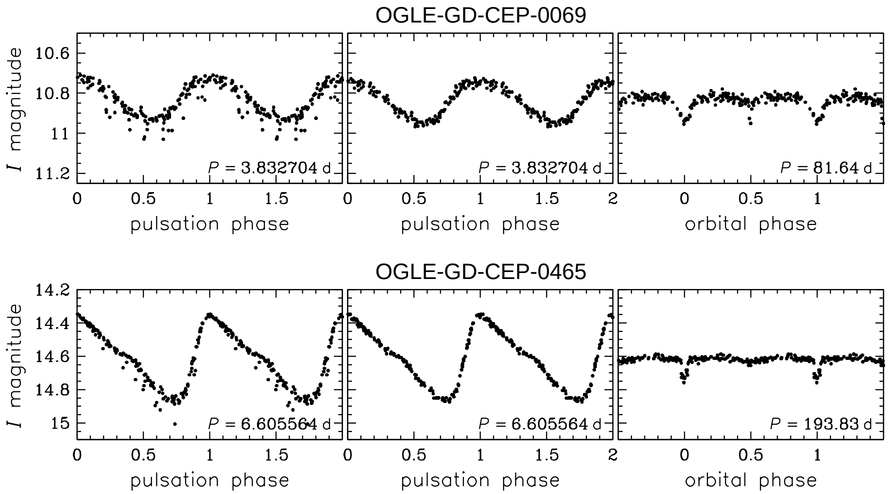

Fig. 5. OGLE-GD-CEP-0069 *(top panel)* and OGLE-GD-CEP-0465 *(bottom panel)* – new candidates for eclipsing binary systems with a classical Cepheid as one of the components. *Left panel* shows the original data folded with the pulsation period. *Middle panel* presents the pulsation light curve and the *right panel* – eclipsing light curve.

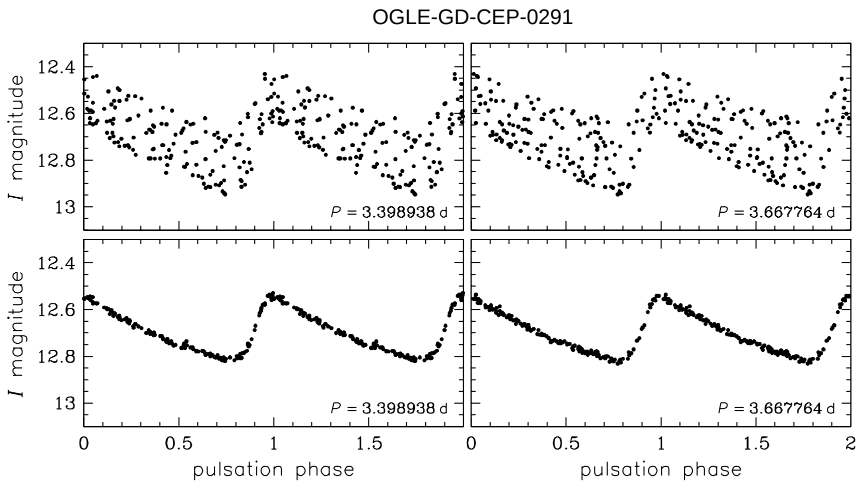

Fig. 6. OGLE-GD-CEP-0291 – candidate for a binary system containing two classical Cepheids. *Top panel* shows the original data folded with the pulsation period of each of the components. *Lower panel* presents the pulsation light curve after subtracting other variability.

follow-up will provide the status of this interesting object. Fig. 6 shows the light curves of individual components of the system.

It is worth noticing that similar binary systems containing two Cepheids were found in the LMC (Alcock *et al.* 1995, Udalski *et al.* 1999, Soszyński *et al.* 2008a). In one of these systems, OGLE-LMC-CEP-1718, Soszyński *et al.* (2008a) found eclipses and with follow-up spectroscopy from the Araucaria project the system was solved by Gieren *et al.* (2014). Unfortunately, our Galactic system does not reveal eclipses what indicates that the inclination must be lower.

10. Discussion

OGLE Collection of Galactic Cepheids constitutes a new major OGLE dataset of variable stars. After the OGLE Collection of Cepheids in the Magellanic System (Soszyński *et al.* 2015a, 2017a) this is the next important step in studies of these very important objects of modern astrophysics.

The OGLE Collection more than doubles the number of known Galactic classical Cepheids and considerably increases the number of other types of these pulsators. The OGLE sample is very complete and not contaminated by other variables. Additionally, precise and calibrated *VI* photometry makes the OGLE dataset ideal for many scientific projects.

OGLE new Cepheids are located in a considerably larger volume of the Milky Way, up to 20 kpc from the center, and cover practically the entire disk. Based on this unique sample it has already been possible to prepare a 3-D picture of the Galaxy in young population as traced by Cepheids (Skowron *et al.* 2018). This analysis showed the structure of the Galactic disk like its warp, seen for the first time with individual stars having accurate distance determination. One may also notice several clear overdensities in the distribution of classical Cepheids in our Galaxy which only roughly correspond to the present spiral arm pattern. However, these overdensities can be modeled as a result of the past star formation episodes in defined regions of the spiral arms and smeared up to now by the Galactic and arm rotation (Skowron *et al.* 2018).

The OGLE Cepheids can also be excellent tracers of the Galactic rotation. With the proper motions and radial velocities from the Gaia mission (Gaia Collaboration *et al.* 2018) Mróz *et al.* (2018) have already presented the rotation curve of the Milky Way reaching distances much farther from the center than available for now. This study shows that the rotation curve is basically flat up to the Galactic disk boundary. It can still be improved when more radial velocities and proper motions of a significant part of the OGLE Cepheids located far from the Galactic center become available.

OGLE Galactic Cepheids Collection can also be a new gold mine for studies of properties of these pulsating stars. It provides new opportunities for searching for additional low level pulsations. Many interesting additional discoveries were done after releasing the previous parts of the OGLE Cepheid Collection.

The OGLE Galactic Cepheid Collection released with this paper is an open project. It will be updated in the future when additional fields monitored during the GVS are ready for variable objects search and additional samples of Galactic Cepheids are detected. Because classical Cepheids are highly concentrated toward the Galactic plane and the most abundant regions containing them are presented here, we do not expect a large increase of the total number of new OGLE classical Cepheids in the subsequent updates of our Collection. However, the number of other type Cepheids may significantly increase, especially in the fields of the outer Galactic bulge.

Additional update will occur when the search for faint Cepheids which did not pass our preselection cut is finished. The ultimate goal of this OGLE sub-project is to collect the vast majority of the Galactic Cepheids observable from the Las Campanas Observatory.

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