ACTA ASTRONOMICA
Vol. **65** (2015) pp. 297–312

The OGLE Collection of Variable Stars. Classical Cepheids in the Magellanic System*

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Received November 22, 2015

ABSTRACT

We present here a nearly complete census of classical Cepheids in the Magellanic System. The sample extends the set of Cepheids published in the past by the Optical Gravitational Lensing Experiment (OGLE) to the outer regions of the Large (LMC) and Small Magellanic Cloud (SMC). The entire collection consists of 9535 Cepheids of which 4620 belong to the LMC and 4915 are members of the SMC. We provide the *I*- and *V*-band time-series photometry of the published Cepheids, their finding charts, and basic observational parameters.

Based on this unique OGLE sample of Cepheids we present updated period–luminosity relations for fundamental, first, and second mode of pulsations in the *I*- and *V*-bands and for the W_I extinction-free Wesenheit index. We also show the distribution of classical Cepheids in the Magellanic System.

The OGLE collection contains several classical Cepheids in the Magellanic Bridge – the region of interaction between the Magellanic Clouds. The discovery of classical Cepheids and their estimated ages confirm the presence of young stellar population between these galaxies.

Key words: *Cepheids – Magellanic Clouds – Catalogs*

1. Introduction

Classical Cepheids (also known as δ Cephei stars or type I Cepheids) are objects of particular interest for a variety of reasons. They are primary distance indicators within the Milky Way and to extragalactic systems up to the Virgo cluster.

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

These stars are also useful tracers of the young stellar population in our and other galaxies. Furthermore, classical Cepheids are excellent objects for constraining stellar pulsation and evolution models.

Cepheids in the Large (LMC) and Small Magellanic Cloud (SMC) played a special historical role, since the famous period–luminosity (PL) relation (also called the Leavitt law) was first noticed in these galaxies (Leavitt 1908). Nowadays, the LMC and SMC are also important targets for studying δ Cep stars because both galaxies contain the largest known collection of these pulsators among all stellar environments, including the Milky Way. The Optical Gravitational Lensing Experiment (OGLE) has regularly published large samples of classical Cepheids in the Magellanic Clouds discovered in consecutive phases of the survey since 1999 (*e.g.*, Udalski *et al.* 1999ab).

The latest samples of the OGLE classical Cepheids consisted of 3375 of these stars in the LMC (Soszyński *et al.* 2008) and 4630 in the SMC (Soszyński *et al.* 2010). These releases were followed by an avalanche of papers presenting various applications of the OGLE Cepheid data. The PL relations in a wide range of photometric passbands, from optical to infrared, were derived and studied based on the OGLE Cepheids (*e.g.*, Ngeow *et al.* 2009, 2010, 2012, Majaess *et al.* 2011, Storm *et al.* 2011, Ripepi *et al.* 2012, Macri *et al.* 2015), which led to precise measurements of the distances to the Magellanic Clouds (*e.g.*, Inno *et al.* 2013, Scowcroft *et al.* 2016, Ngeow *et al.* 2015) and three-dimensional geometric models of both galaxies (*e.g.*, Haschke *et al.* 2012ab, Moretti *et al.* 2014, Subramanian and Subramaniam 2015, Scowcroft *et al.* 2016). The morphology of the OGLE light curves of classical Cepheids were a subject of intensive comparative studies (*e.g.*, Deb and Singh 2009, Pejcha and Kochanek 2012, Klagyivik *et al.* 2013, Bhardwaj *et al.* 2015). The OGLE Cepheids were used as training sets for automatic classification systems (*e.g.*, Deb and Singh 2009, Long *et al.* 2012, Kim *et al.* 2014) and as a basis of the asteroseismic considerations (*e.g.*, Dziembowski and Smolec 2009, Moskalik and Kołaczkowski 2009, Smolec and Moskalik 2010, Dziembowski 2012). Cepheids in eclipsing binary systems discovered by OGLE allowed finding the solution of the mass discrepancy problem of Cepheids (*e.g.*, Pietrzyński *et al.* 2010, 2011, Gieren *et al.* 2014, Pilecki *et al.* 2015).

In this paper, we extend the OGLE-III samples of classical Cepheids in the Magellanic Clouds (Soszyński *et al.* 2008, 2010) by adding variables detected in the OGLE-IV fields covering the outskirts of both galaxies and the region between them, the so called Magellanic Bridge. The entire collection constitutes a nearly complete census of δ Cep stars in the Magellanic Clouds. We provide OGLE-IV light curves of the newly detected and previously known Cepheids, increasing the time span of the OGLE observations to over 18 years in the central regions of both galaxies.

The article is organized as follows. Section 2 briefly describes the OGLE-IV photometric data used in this investigation. Section 3 provides details on the

Cepheid identification and classification. In Section 4, we show the OGLE Cepheid collection itself. In Section 5, we estimate the completeness of our sample and compare it with other sets of Cepheids in the Magellanic Clouds. In Section 6, we present updated PL relations for fundamental, first-, and second-overtone pulsation modes in the W_I Wesenheit index and *VI* photometric bands. We also report there the discovery of several classical Cepheids in the Magellanic Bridge and discuss its consequences. The conclusions are summarized in Section 7.

2. Observations and Data Reduction

This study is based on the *I*- and *V*-band time-series photometry collected during the fourth phase of the OGLE survey (OGLE-IV) between March 2010 and July 2015. The project has been conducted with the 1.3-m Warsaw telescope at Las Campanas Observatory in Chile (the observatory is operated by the Carnegie Institution for Science). The telescope is equipped with a 32-CCD detector mosaic camera, covering approximately 1.4 square degrees on the sky with the scale of 0.26 arcsec/pixel. OGLE-IV is monitoring a total of about 650 square degrees in the LMC, SMC, and in the Magellanic Bridge which links the two galaxies. The number of point sources in the OGLE-IV databases is about 58 million in the LMC, 12 million in the SMC, and 5 million in the Magellanic Bridge.

Most of the observations (from about 100 to over 750, depending on the field) were secured through the Cousins *I*-band filter, the remaining data points (from several to 260) were obtained in the Johnson *V*-band. Data reduction of the OGLE images was performed using the standard OGLE photometric data pipeline (Udalski *et al.* 2015), based on the Difference Image Analysis technique (Alard and Lupton 1998, Woźniak 2000). Detailed description of the instrumentation, photometric reductions and astrometric calibrations of the OGLE observations is provided in Udalski *et al.* (2015).

3. Selection and Classification of Classical Cepheids

An extensive search for variable stars was preceded by a period search performed for all point sources observed by the OGLE-IV survey in the Magellanic Clouds. The Fourier periodogram was calculated for each *I*-band light curve with at least 30 observing points. We used the FNPEAKS code[†] written by Z. Kołaczkowski. Having the primary periods, their signal-to-noise ratios, amplitudes of variability, mean magnitudes, and parameters of the Fourier decomposition of the light curves we conducted a semi-manual search for variable stars. We visually inspected the light curves with the largest signal-to-noise ratios and stars located within a wide strip in the PL diagram covering all types of Cepheids and RR Lyrae type stars.

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

The detected variable stars were initially classified as pulsators, eclipsing binaries, and other variables.

The first group was then divided into classical Cepheids, anomalous Cepheids, type II Cepheids, RR Lyrae stars, δ Scuti stars, and long-period variables. The most important criteria used in this classification were the light curve shapes quantified by their Fourier parameters, position of the stars in the PL diagrams, and the period ratios (for multi-periodic variables). For example, Soszyński *et al.* (2015) showed that Fourier parameters ϕ_{21} and ϕ_{31} are useful tools to distinguish between classical and anomalous Cepheids. Because δ Sct stars and overtone classical Cepheids form a continuous relationship in the PL diagram, we adopted a boundary period of 0.23 d to separate both groups. In ambiguous cases we carefully inspected the light curves, checked other properties of the stars, before deciding on the final classification. Nevertheless, one should be aware that for a limited number of individual objects our classification may be incorrect. We mark doubtful stars in the remark file of the catalog.

Table 1

Reclassified stars from the OGLE-III catalogs of classical Cepheids in the Magellanic Clouds

Identifier	New classification	Identifier	New classification
OGLE-LMC-CEP-0320	RR Lyr	OGLE-SMC-CEP-1636	Anom. Cepheid
OGLE-LMC-CEP-0665	Other	OGLE-SMC-CEP-1650	Anom. Cepheid
OGLE-LMC-CEP-1277	RR Lyr (RRd)	OGLE-SMC-CEP-1826	Anom. Cepheid
OGLE-LMC-CEP-3063	Eclipsing	OGLE-SMC-CEP-2089	Anom. Cepheid
OGLE-SMC-CEP-0008	Anom. Cepheid	OGLE-SMC-CEP-2169	Anom. Cepheid
OGLE-SMC-CEP-0080	Anom. Cepheid	OGLE-SMC-CEP-2210	Anom. Cepheid
OGLE-SMC-CEP-0167	Anom. Cepheid	OGLE-SMC-CEP-2343	Anom. Cepheid
OGLE-SMC-CEP-0174	Anom. Cepheid	OGLE-SMC-CEP-2485	Anom. Cepheid
OGLE-SMC-CEP-0220	Anom. Cepheid	OGLE-SMC-CEP-2659	Anom. Cepheid
OGLE-SMC-CEP-0252	Anom. Cepheid	OGLE-SMC-CEP-2714	Anom. Cepheid
OGLE-SMC-CEP-0269	Anom. Cepheid	OGLE-SMC-CEP-2740	Anom. Cepheid
OGLE-SMC-CEP-0326	Anom. Cepheid	OGLE-SMC-CEP-2834	RR Lyr
OGLE-SMC-CEP-0354	Anom. Cepheid	OGLE-SMC-CEP-2862	Anom. Cepheid
OGLE-SMC-CEP-0366	Anom. Cepheid	OGLE-SMC-CEP-3136	Anom. Cepheid
OGLE-SMC-CEP-0475	Anom. Cepheid	OGLE-SMC-CEP-3540	Anom. Cepheid
OGLE-SMC-CEP-0532	Anom. Cepheid	OGLE-SMC-CEP-3698	Anom. Cepheid
OGLE-SMC-CEP-0677	Anom. Cepheid	OGLE-SMC-CEP-3814	Anom. Cepheid
OGLE-SMC-CEP-1078	Anom. Cepheid	OGLE-SMC-CEP-3957	Anom. Cepheid
OGLE-SMC-CEP-1082	Anom. Cepheid	OGLE-SMC-CEP-4369	Anom. Cepheid
OGLE-SMC-CEP-1129	Anom. Cepheid	OGLE-SMC-CEP-4391	Anom. Cepheid
OGLE-SMC-CEP-1241	Anom. Cepheid	OGLE-SMC-CEP-4582	Anom. Cepheid
OGLE-SMC-CEP-1355	Anom. Cepheid	OGLE-SMC-CEP-4608	Anom. Cepheid
OGLE-SMC-CEP-1476	Anom. Cepheid	OGLE-SMC-CEP-4621	Anom. Cepheid

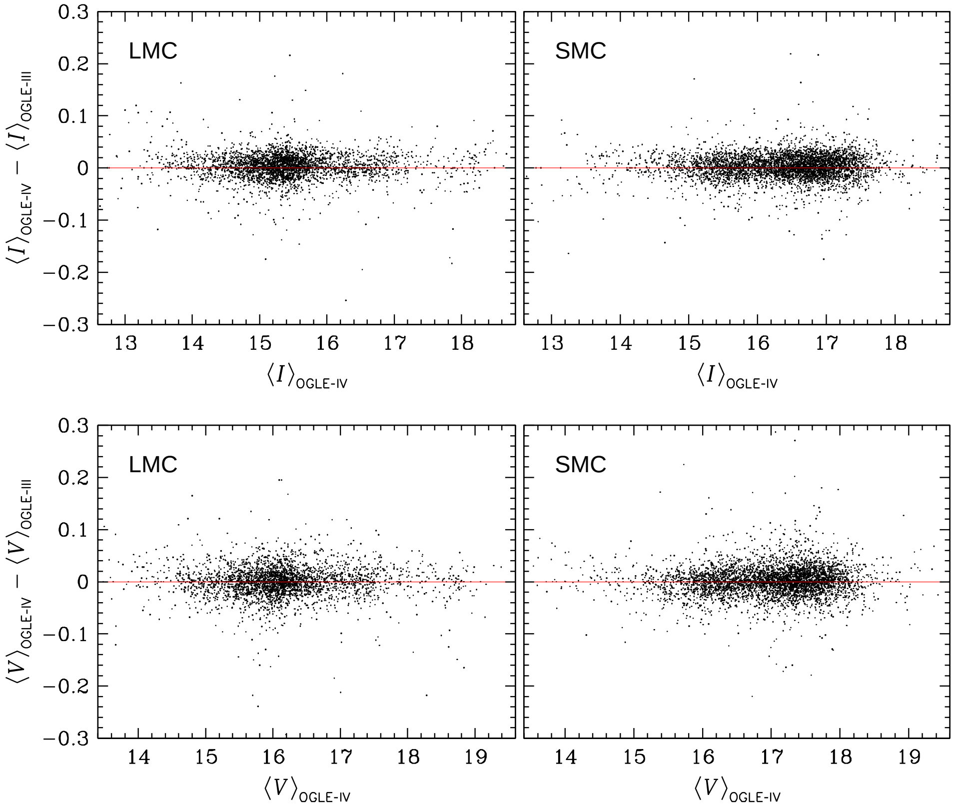

Fig. 1. Comparison between OGLE-III and OGLE-IV *I*-band (*upper panels*) and *V*-band (*lower panels*) mean magnitudes of classical Cepheids in the LMC (*left panels*) and SMC (*right panels*).

We also examined OGLE-IV light curves of Cepheids discovered during the OGLE-II and OGLE-III phases of the project and cataloged by Soszyński *et al.* (2008, 2010). Forty six objects were reclassified as other types of variable stars and they were removed from the OGLE collection of classical Cepheids in the Magellanic System. A list of these stars is given in Table 1. The vast majority of them are variables in the SMC which were reclassified by Soszyński *et al.* (2015) as anomalous Cepheids. Classical and anomalous Cepheids in the SMC share very similar light curve morphology that can be associated with the low metallicity of the stars in this galaxy. Further several candidates for classical Cepheids in the OGLE-III collection have very dubious classification, but they were left on the list, since we cannot rule out the possibility that they are real Cepheids with unusual properties.

Periods, mean magnitudes, amplitudes, and other parameters of the Cepheids known from the previous stages of the OGLE project were recalculated using the OGLE-IV light curves accumulated in the years 2010–2015. The OGLE-III and OGLE-IV photometry were obtained with different instrumental configurations, in particular with different filters and CCD detectors, but both datasets were transformed to the standard photometric system with the systematic uncertainties of the calibration zero point up to 0.02 mag. In Fig. 1, we compare the OGLE-III and OGLE-IV mean magnitudes of Cepheids in the *I*- and *V*-filters. The agreement between both data sets is very good. The mean difference between magnitudes measured from the OGLE-IV and OGLE-III photometry is smaller than 0.003 mag in both filters and in both galaxies. The standard deviation is smaller than 0.03 mag. Outliers in Fig. 1 can be explained by crowding and blending by unresolved stars.

4. Classical Cepheids in the Magellanic Clouds

The OGLE collection of classical Cepheids in the Magellanic Clouds comprises 9535 objects (4620 in the LMC and 4915 in the SMC), of which 5168 pulsate solely in the fundamental mode (F), 3530 are single-mode first-overtone pulsators (1O), 117 oscillate purely in the second overtone (2O), 711 stars are double-mode Cepheids, and nine – triple-mode Cepheids. The data on all these objects are available through the OGLE anonymous FTP sites or *via* the OGLE web interface:

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

OGLE FTP sites are organized as follows. The files named `ident.dat` contain the full lists of classical Cepheids in both galaxies. For each star we provide its identifier, J2000 equatorial coordinates, mode(s) of pulsation, fields and internal numbers in the OGLE-IV, OGLE-III, and OGLE-II photometric databases (if available) and the cross-matches with the extragalactic part of the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995). The identifiers of the Cepheids are the same as in the OGLE-III catalogs – OGLE-LMC-CEP-NNNN and OGLE-SMC-CEP-NNNN – where NNNN is a four-digit number. The newly detected Cepheids have numbers larger than 3375 and 4630 in the LMC and SMC, respectively, and are organized by increasing right ascension.

Files `cep*.dat` contain observational parameters of various types of classical Cepheids: their mean magnitudes in the *I*- and *V*-bands, pulsation periods, epochs of the maximum light, peak-to-peak *I*-band amplitudes, and Fourier parameters derived from the *I*-band light curves. The pulsation periods were refined with the TATRY code (Schwarzenberg-Czerny 1996) using OGLE-IV observations obtained between 2010 and 2015. To study the long-term behavior of Cepheids in the Magellanic Clouds, we recommend to merge the OGLE-IV light curves with the photometry obtained during the previous phases of the OGLE survey and published by Soszyński *et al.* (2008, 2010). One should take into account that smaller or larger differences between mean magnitudes and amplitudes for individual objects are possible (see Section 3). A limited number of Cepheids published by Soszyński *et al.* (2008, 2010) do not have OGLE-IV measurements, because they fell into the gaps between the CCD detectors of the OGLE-IV mosaic camera. For these stars we provide their parameters from the OGLE-III Cepheid data release.

Files containing OGLE-IV time-series photometry in the *I*- and *V*-bands are stored in the directory phot. Finding charts can be found in the directory fcharts. These are $60'' \times 60''$ subframes of the *I*-band reference images, oriented with North at the top and East to the left. Additional information on some Cepheids (uncertain classification, eclipsing or ellipsoidal variability, secondary periods, etc.) are given in the file remarks.txt.

Most of the classical Cepheids detected in the Magellanic Bridge (see Section 6.3) were included in the SMC sample, since it is widely believed that gas present in the Bridge was drawn out of the SMC through tidal forces during a close encounter of the two galaxies, which took place about 250 Myr ago (Mathewson 1985, Muller *et al.* 2004).

5. Completeness of the Sample

The completeness of the OGLE Collection of classical Cepheids in the Magellanic System is the highest in the area covered by the OGLE-II and OGLE-III fields because these regions were independently searched for variable stars in the past (Udalski *et al.* 1999ab, Soszyński *et al.* 2008, 2010). The central 40 square degrees in the LMC and 14 square degrees in the SMC contain most of the classical Cepheids in these galaxies. The completeness of the OGLE sample outside these regions is limited by the gaps between the OGLE-IV fields and between the CCD detectors of the mosaic camera. We estimate that currently about 7% of stars may be missed in the outer regions of the Clouds due to the gaps in our coverage. It has to be, however, noted that we plan to conduct additional search for classical Cepheids in these currently uncovered area using a new set of reference images which practically fully fill all the gaps between CCD detectors. After this minor update planned for 2016, the OGLE collection of classical Cepheids should contain practically all classical Cepheids from the Magellanic System.

The completeness of the sample in the area covered by the OGLE observations may be calculated based on the stars with double entries in the database. Neighboring OGLE-IV fields overlap (*cf.* Udalski *et al.* 2015) and some Cepheids have been detected twice, independently in both fields. Please note, however, that the final version of our collection contains only one light curve per star – usually the one with larger number of epochs.

We found that 897 classical Cepheids are located in the overlapping regions of the neighboring fields. Taking into account light curves with at least 100 observing points, we obtained 854 pairs, so we had a chance to identify 1708 counterparts.

We independently detected 1698 of them, which gives the general completeness of our sample larger than 99%. Six of the missing Cepheids have nearly sinusoidal light curves and were initially classified as ellipsoidal variables, two objects have exceptionally large noise due to the proximity of bright stars, and two Cepheids have periods close to 1 or 2 days which affected the Fourier series fits to their light curves.

We also compared our collection with other samples of Cepheids in the Magellanic Clouds. The MACHO catalog of Cepheids in the LMC (Alcock *et al.* 1999) consists of 1800 objects. Our collection does not contain 11 of these stars, of which three are located beyond the OGLE fields and eight are misclassified by the MACHO project non-pulsating stars: eclipsing or spotted variables.

Kim *et al.* (2014) released a list of 117 234 candidates for periodic variable stars in the LMC based on EROS-2 microlensing survey observations. The sources were categorized into several variability types using an automatic random forest method. The EROS-2 set contains variable stars not observed by the previous stages of the OGLE survey, of which 638 sources were classified by Kim *et al.* (2014) as Cepheids and 178 stars – as type II Cepheids. We checked all these objects (classified as CEPH_F, CEPH_1O, CEPH_Other, T2CEPH_N). The preliminary version of our collection overlooked a surprisingly large number of 376 Cepheid candidates from the EROS-2 catalog, of which 350 stars were monitored by the OGLE survey (most of the remaining stars fell into the gaps between the CCD detectors).

We carefully investigated the OGLE light curves of these sources and found four additional classical Cepheids. Three of them were missed because of a small number of observing points in the OGLE database and one was an overtone Cepheid with the photometry affected by blending. We supplemented our collection with these four Cepheids. The remaining 346 EROS-2 candidates for Cepheids turned out to be eclipsing binaries, ellipsoidal variables, spotted stars, RR Lyraes or other types of variable stars. This result demonstrate the weakness of the automated methods of the variable star classification.

We also confronted our collection with a list of 299 candidates for new Cepheids in the SMC recently announced by the VMC near-infrared survey (Moretti *et al.* 2015). We successfully identified OGLE-IV light curves for 278 of these stars and we confirm that 35 of them are real Cepheids (33 classical and two anomalous Cepheids). Most of the remaining objects from the VMC list turned out to be constant or nearly constant stars. Nine of the Cepheids released by Moretti *et al.* (2015) were included in the GCVS (Artyukhina *et al.* 1995). This example clearly indicates that only a full variability survey with a sufficient number of observing epochs (at least around one hundred) may provide data for reliable characterization and classification of variable objects.

6. Discussion

6.1. Period–Luminosity Relations

The PL relations for Cepheids (also known as the Leavitt Law) were discovered in the SMC (Leavitt 1908) and the Magellanic Clouds still play a dominant role in the studies of this phenomenon (*e.g.,* Ngeow *et al.* 2009, 2010, 2012, Majaess *et al.* 2011, Storm *et al.* 2011, Macri *et al.* 2015). The PL diagrams in the apparent I and V magnitudes and in the extinction-free Wesenheit index, defined as $W_I = I - 1.55(V - I)$, are shown in Figs. 2 and 3. In Table 2, we summarize the linear

Table 2

Period–Luminosity Relations for Classical Cepheids in the Magellanic Clouds

Mode of pulsation	Galaxy	$W_I = \alpha \log P + \beta$		
		α	β	σ
F	LMC	-3.314 ± 0.008	15.888 ± 0.005	0.077
1O	LMC	-3.431 ± 0.007	15.393 ± 0.002	0.081
2O	LMC	-3.548 ± 0.027	15.025 ± 0.008	0.087
3O	LMC	-4.000 ± 0.134	14.486 ± 0.077	0.071
F	SMC	-3.460 ± 0.011	16.493 ± 0.005	0.155
1O	SMC	-3.548 ± 0.017	15.961 ± 0.004	0.169
2O	SMC	-3.651 ± 0.098	15.545 ± 0.025	0.154

Mode of pulsation	Galaxy	$I = \alpha \log P + \beta$		
		α	β	σ
F	LMC	-2.911 ± 0.014	16.822 ± 0.009	0.146
1O	LMC	-3.260 ± 0.013	16.362 ± 0.004	0.162
2O	LMC	-3.438 ± 0.048	15.940 ± 0.014	0.158
3O	LMC	-3.829 ± 0.197	15.370 ± 0.113	0.104
F	SMC	-3.115 ± 0.015	17.401 ± 0.007	0.215
1O	SMC	-3.299 ± 0.023	16.818 ± 0.005	0.222
2O	SMC	-3.600 ± 0.135	16.350 ± 0.034	0.213

Mode of pulsation	Galaxy	$V = \alpha \log P + \beta$		
		α	β	σ
F	LMC	-2.690 ± 0.018	17.438 ± 0.012	0.208
1O	LMC	-3.142 ± 0.018	16.979 ± 0.006	0.227
2O	LMC	-3.333 ± 0.062	16.531 ± 0.018	0.202
3O	LMC	-3.719 ± 0.257	15.941 ± 0.147	0.135
F	SMC	-2.898 ± 0.018	17.984 ± 0.008	0.266
1O	SMC	-3.155 ± 0.028	17.368 ± 0.007	0.271
2O	SMC	-3.544 ± 0.170	16.870 ± 0.043	0.267

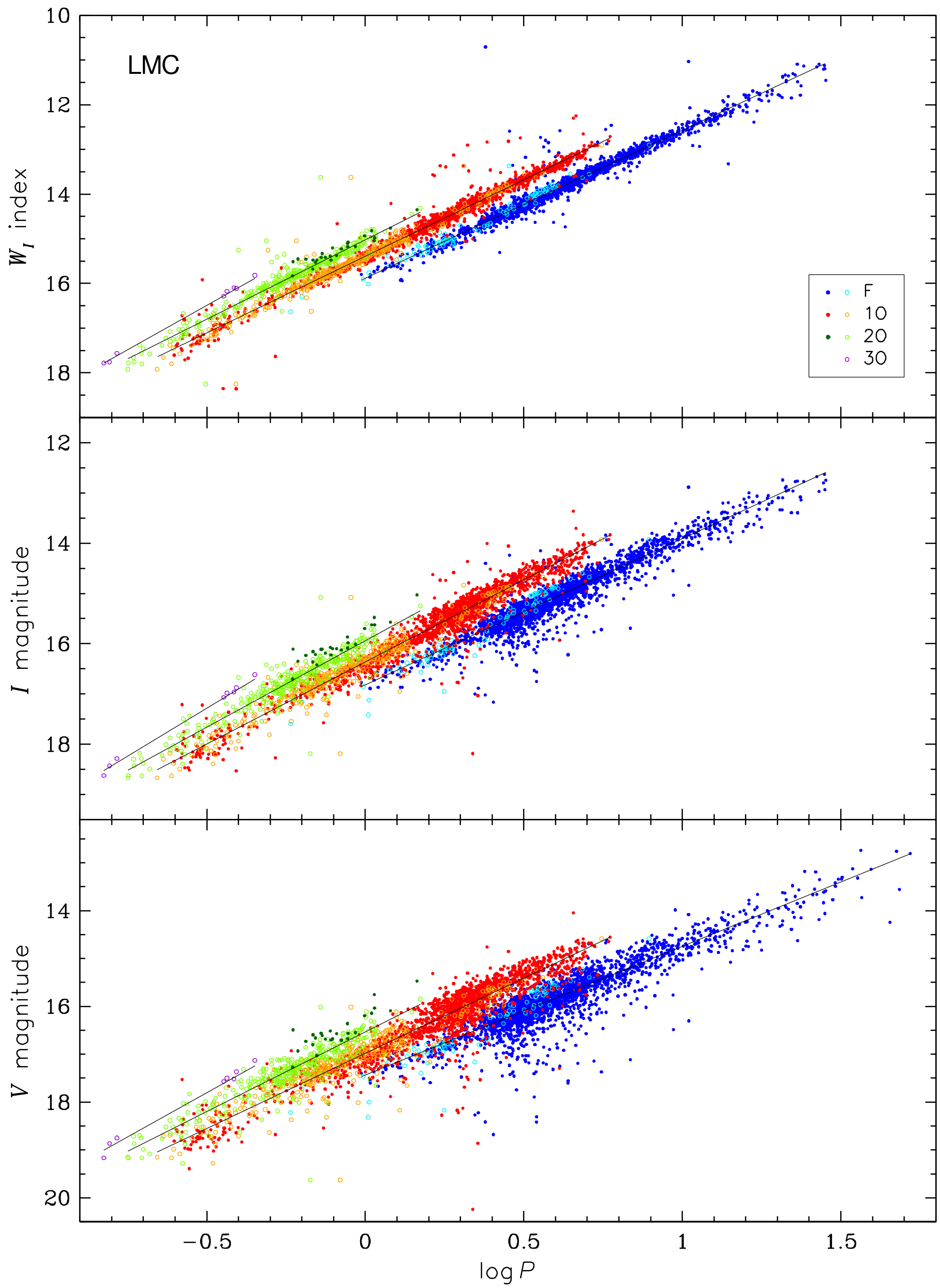

Fig. 2. Period–luminosity diagrams for classical Cepheids in the LMC. Blue, red, and dark-green solid circles mark F, 1O, and 2O single-mode Cepheids, respectively. Cyan, orange, light-green and violet empty circles represent, respectively, F, 1O, 2O, and 3O modes in multi-mode Cepheids. Black lines show the linear least-square fits to the PL relations.

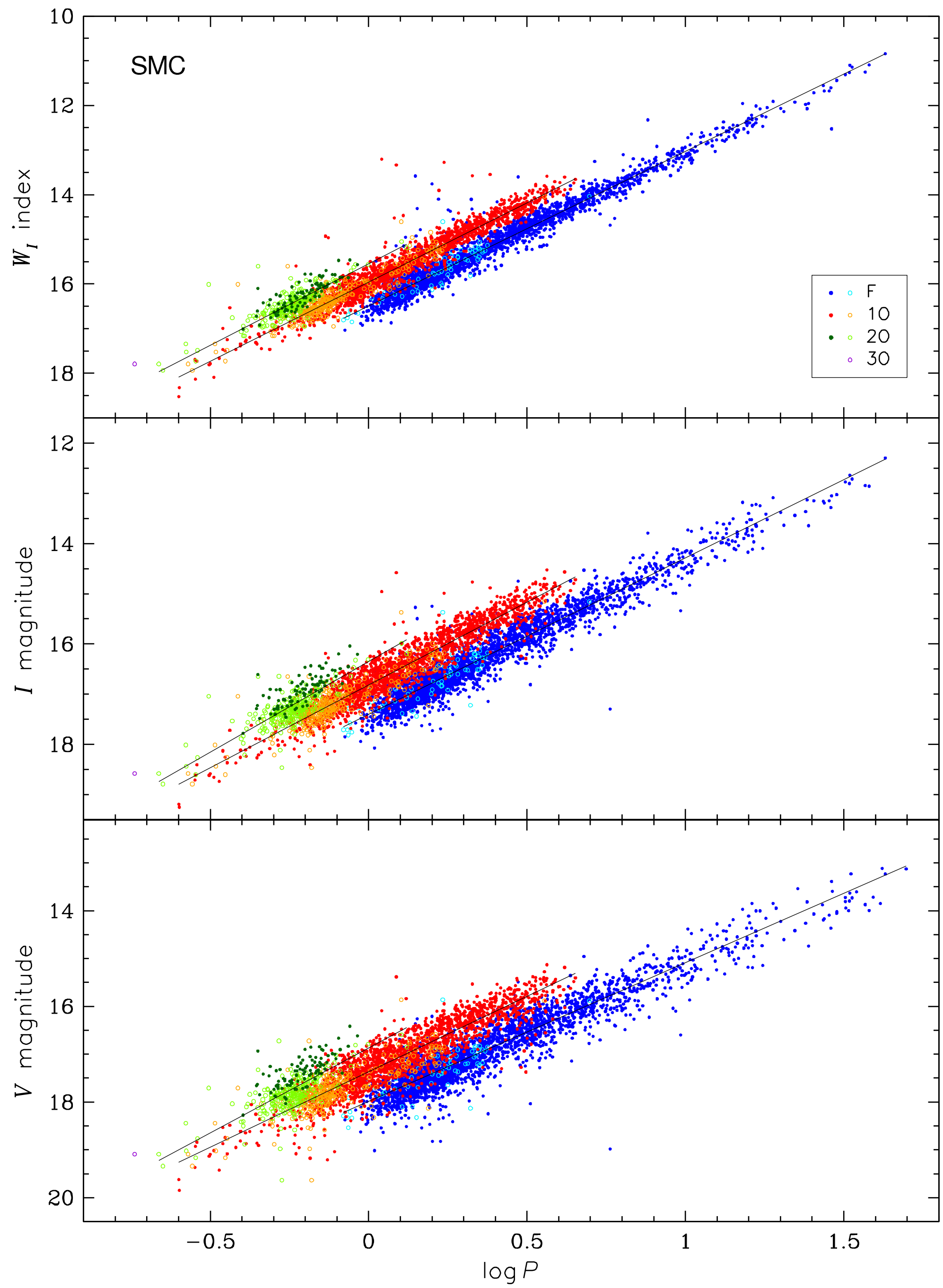

Fig. 3. Period–luminosity diagrams for classical Cepheids in the SMC. Color symbols represent the same modes of pulsation as in Fig. 2.

fits to the PL relations presented in Figs. 2 and 3. We used the least square method with an iterative 3σ clipping. In our procedure, we used all the Cepheids pulsating in a given mode (including multi-mode pulsators), despite the fact that some of the relations might not be strictly linear (*e.g.*, Ngeow *et al.* 2009).

6.2. Spatial Distribution of Classical Cepheids in the Magellanic System

Classical Cepheids are simultaneously distance indicators and tracers of the young stellar population. Thus, they play a unique role in studying the three-dimensional structures of galaxies (*e.g.*, Haschke *et al.* 2012ab, Moretti *et al.* 2014, Subramanian and Subramaniam 2015, Scowcroft *et al.* 2016). We believe that the OGLE-IV collection of δ Cep stars in the Magellanic Clouds will be crucial for understanding the dynamical history of both galaxies. In Fig. 4, we plot the two-dimensional distributions of classical Cepheids in the Magellanic System, separately for the fundamental-mode and first-overtone pulsators (together with the multi-mode variables). It is clear that both classes of Cepheids have a different spatial distribution, in particular in the LMC, which implies different history of their formation.

Well defined and tight OGLE period–luminosity relations of classical Cepheids derived in Section 6.1 provide an important tool for the determination of distances to individual Cepheids, adding the third dimension to the 2-D maps presented in Fig. 4. Such 3-D maps based on complete sample of the OGLE collection of Cepheids will constitute a unique picture of the Magellanic System enabling detailed modeling of their structure as seen *via* young stellar population. Results of this study will be presented in the forthcoming paper.

6.3. Classical Cepheids in the Outskirts of the Magellanic Clouds

Several variable stars with Cepheid characteristics found in the OGLE-IV data are located surprisingly far from the centers of the LMC and SMC in the region called the Magellanic Bridge. This is a stream of gas and stars distributed between these galaxies.

Careful analysis of the shape of the light curves of this sub-sample indicated that some of these objects have characteristics similar to anomalous Cepheids. Thus, they were included to the OGLE set of anomalous Cepheids (Soszyński *et al.* 2015). Their presence in the Magellanic Bridge is not surprising because the distribution of anomalous Cepheids clearly shows that these stars are often located in the halo of the Magellanic Clouds, far from their centers (*cf.* Fig. 7, Soszyński *et al.* 2015).

The remaining detected objects are genuine classical Cepheids. At least five of them are located in the Magellanic Bridge. These are the first such type variable stars discovered in this very important region of the sky. The presence of classical Cepheids there independently confirms the existence of young stellar component. This component of the Magellanic Bridge was first discovered by Irwin *et al.* (1985,

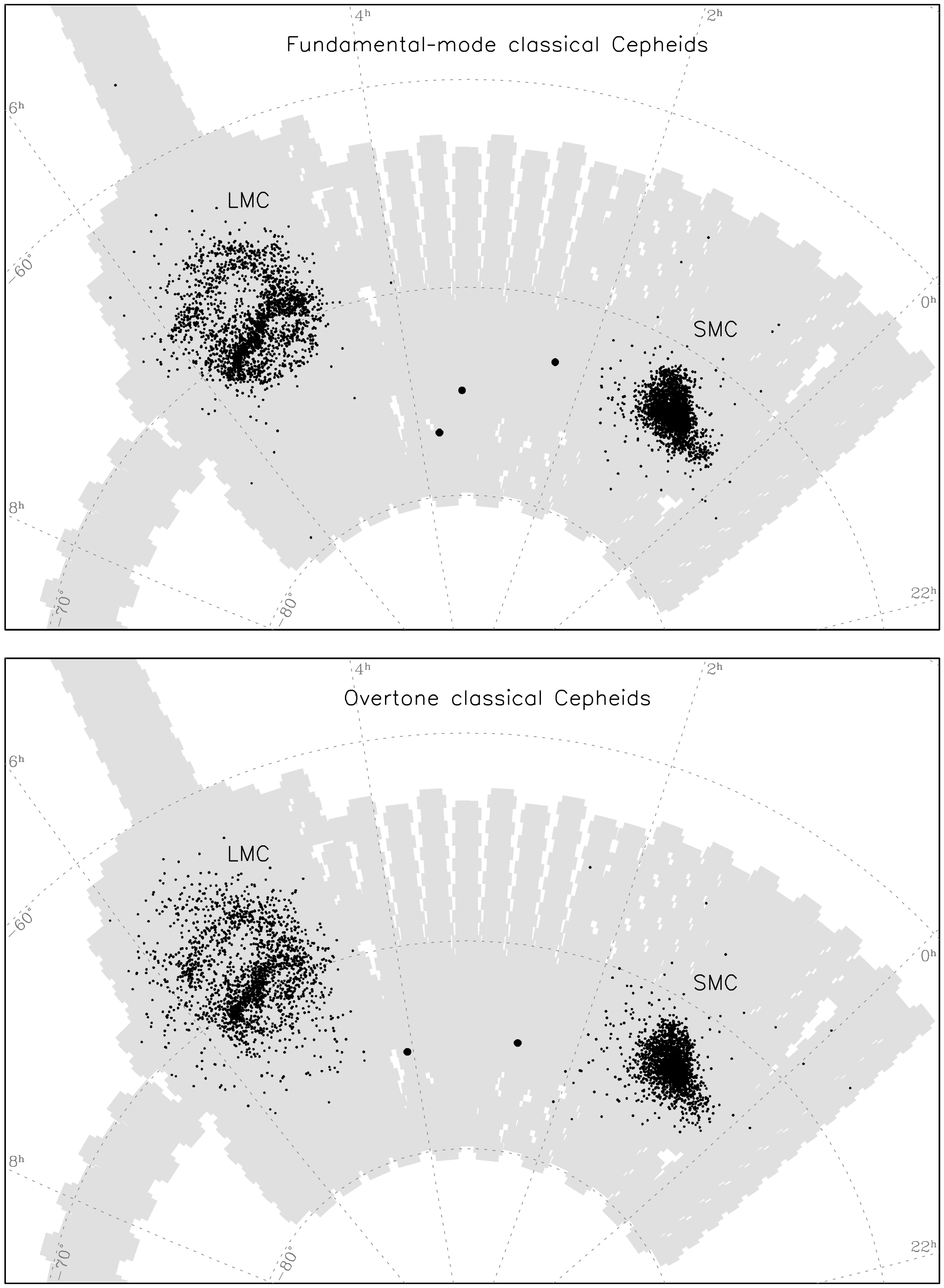

Fig. 4. Spatial distribution of classical Cepheids in the Magellanic System. *Upper panel* shows the positions of single-mode fundamental-mode Cepheids. *Lower panel* presents single- and multi-mode overtone pulsators. The gray area shows the sky coverage of the OGLE fields. Larger dots mark classical Cepheids in the Magellanic Bridge.

1990) in a few regions between the Magellanic Clouds. Recently, Skowron *et al.* (2014) presented extensive density maps of various stellar populations in the entire Magellanic Bridge based on the OGLE-IV observations. They showed that the young stellar population forms a continuous stream connecting both Magellanic Clouds.

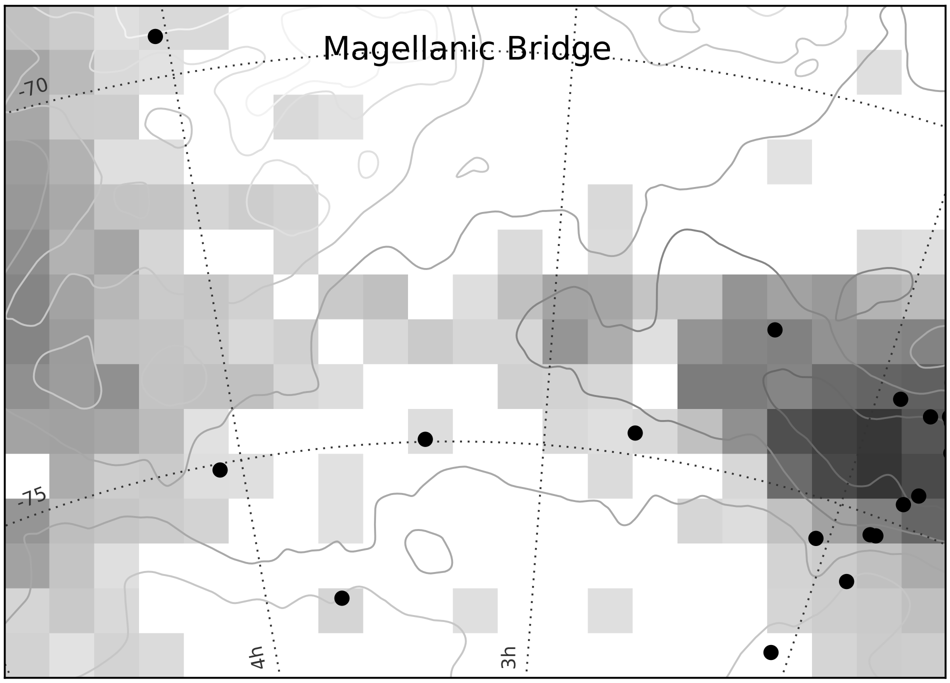

Fig. 5. Spatial distribution of classical Cepheids in the Magellanic Bridge area (black points). Background shaded map shows a spatial density map of the young population stars from Skowron *et al.* (2014). Grey contours mark neutral hydrogen emission from Kalberla *et al.* (2005).

Fig. 5 presents location of the Magellanic Bridge classical Cepheids on the map of the distribution of the young stellar population in the Magellanic Bridge. Positions of the five classical Cepheids in the Magellanic Bridge coincide roughly with this stream although they are mostly located at its southern side. We estimated the ages of these Cepheids using period–age relations provided by Bono *et al.* (2005). The ages range from 27 Myr (for OGLE-SMC-CEP-4953 = HV 11211) to 280 Myr (for OGLE-SMC-CEP-4956). This agrees with the scenarios of the past interaction between the Clouds which took place about 250 Myr ago. Rough estimate of distances to the Magellanic Bridge Cepheids based on their position in the LMC W_I index PL diagram indicates that objects located on the SMC side of the Bridge are at the distance of the eastern wing of the SMC (55–60 kpc) while two objects closer to the LMC are roughly at the LMC distance of 40–50 kpc. Surprisingly, two objects in the middle of the Magellanic Bridge (OGLE-SMC-CEP-4956, OGLE-

SMC-CEP-4957) are much farther than both galaxies – at a distance of 68–72 kpc. This indicates that the 3-D distribution of matter in the Magellanic Bridge may be much more complex than simple expectation from the recent encounter interaction of both Clouds.

7. Conclusions

We presented the most complete and least contaminated collection of classical Cepheids in the Magellanic System. Compared to the past OGLE-III Cepheid data release (Soszyński *et al.* 2008, 2010), we increased the sizes of our samples by 1249 and 327 Cepheids in the LMC and SMC, respectively. Thus, we compiled a nearly complete census of these stars in the Magellanic Clouds. We showed the distribution of classical Cepheids in the Magellanic System and discovered the first classical Cepheids in the Magellanic Bridge that confirm the presence and date the young stellar population in this important region of the interaction between the Magellanic Clouds.

The final OGLE collection of classical Cepheids should contribute to many extensive astrophysical studies: better understanding of stellar evolution and pulsation, modeling structure and dynamics of the Magellanic Clouds, analysis of the extragalactic distance scale, and to many cosmological applications.

Acknowledgements. We would like to thank Prof. M. Kubiak, OGLE project co-founder, for his contribution to the collection of the OGLE photometric data over the past years. We are grateful to Z. Kołaczkowski and A. Schwarzenberg-Czerny for providing software used in this study.

This work has been supported by the Polish Ministry of Science and Higher Education through the program "Ideas Plus" award No. IdP2012 000162. The OGLE project has received funding from the Polish National Science Centre grant MAESTRO no. 2014/14/A/ST9/00121 to AU. DS is supported by the Polish National Science Center (NCN) under the grant no. 2013/11/D/ST9/03445.

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