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The OGLE Collection of Variable Stars. Anomalous Cepheids in the Magellanic Clouds*

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ABSTRACT

We present a collection of 250 anomalous Cepheids (ACs) discovered in the OGLE-IV fields toward the Large (LMC) and Small Magellanic Cloud (SMC). The LMC sample is an extension of the OGLE-III Catalog of ACs published in 2008, while the SMC sample contains the first known bona fide ACs in this galaxy. The total sample is composed of 141 ACs in the LMC and 109 ACs in the SMC. All these stars pulsate in single modes: fundamental (174 objects) or first overtone (76 objects). Additionally, we report the discovery of four ACs located in the foreground of the Magellanic Clouds. These are the first unambiguously identified fundamental-mode ACs known in the Galactic field.

We demonstrate that the coefficients ϕ_{21} and ϕ_{31} determined by the Fourier light curve decomposition are useful discriminators between classical Cepheids and ACs, at least in the LMC and in the field of the Milky Way. In the SMC, the light curve shapes and mean magnitudes of short-period classical Cepheids make them similar to ACs, which is a source of difficulties in the discrimination of both classes of pulsators. The presence of unidentified ACs in the catalogs of classical Cepheids may be partly responsible for the observed non-linearity of the period–luminosity relation observed for short-period Cepheids in the SMC. We compare spatial distributions of ACs, classical Cepheids and RR Lyr stars. We show that the distribution of ACs resembles that of old stars (RR Lyr variables), although in the LMC there are visible structures typical for young population (classical Cepheids): the bar and spiral arms. This may suggest that ACs are a mixture of relatively young stars and mergers of very old stars.

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

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

1. Introduction

Although anomalous Cepheids (ACs) have been observed and studied for over half a century, their origin is still a subject of debate. There is a consensus that ACs are metal-deficient core-helium-burning pulsating stars with masses 1–2 $M_\odot$ (*e.g.*, Bono *et al.* 1997, Caputo *et al.* 2004, Marconi *et al.* 2004). They occur in all dwarf galaxies that have been searched for variable stars and are remarkably rare in globular clusters. First representatives of ACs were discovered by Thackeray (1950) in the Sculptor dwarf and by Baade and Swope (1961) in the Draco dwarf galaxy. The term "anomalous Cepheids" was introduced by Zinn and Searle (1976), since the properties of these variables do not match neither those of classical nor type II Cepheids.

First unambiguously detected ACs in the Large Magellanic Cloud (LMC) were reported by Soszyński *et al.* (2008) on the basis of the photometric observations obtained during the third phase of the Optical Gravitational Lensing Experiment (OGLE-III). The OGLE sample consisted of 83 variables in the LMC (62 fundamental-mode and 21 first-overtone pulsators), which nearly doubled the total number of all ACs known at that time in the Universe.

The OGLE-III sample was used in several important researches. Fiorentino and Monelli (2012) estimated that masses of ACs in the LMC range from 0.8 $M_\odot$ to 1.8 $M_\odot$, with a mean value of 1.2 ± 0.2 $M_\odot$. They also compared the spatial distribution of ACs, classical Cepheids, type II Cepheids and RR Lyr stars, all originated from the OGLE-III Catalog of Variable Stars in the LMC. Their investigation could potentially answer the question how ACs were formed: are they intermediate-age stars (1–6 Gyr old) with exceptionally low metallicity (Demarque and Hirshfeld 1975, Norris and Zinn 1975) or are they coalesced old (>10 Gyr) binary stars (Renzini *et al.* 1977)? Fiorentino and Monelli (2012) found that the distribution of ACs is different from both: young stellar population represented by classical Cepheids and old stars indicated by RR Lyr stars and type II Cepheids. They concluded that a survey of the outskirts of the LMC would probably solve the problem of the ACs origin.

Recently, Ripepi *et al.* (2014) cross-correlated the OGLE catalog of ACs against the near-infrared K_s-band light curves collected by the VMC survey (Cioni *et al.* 2011) and derived period–luminosity (PL) relations for these pulsators. First application of the PL relations to ACs known in nearby dwarf galaxies revealed that they could be important distance indicators within the Local Group. OGLE ACs in the LMC provide currently the best pattern for the PL relations of this type of variables (*e.g.*, Osborn *et al.* 2012, Sipahi *et al.* 2013a, Cusano *et al.* 2013).

ACs in the LMC form a well separated group of pulsating stars, with PL relations located between classical and type II Cepheids. In contrast, we did not find such a well-defined group of ACs in the Small Magellanic Cloud (SMC). Soszyński *et al.* (2010) listed only six candidates for ACs (three fundamental-mode and three first-overtone pulsators) in the SMC. In this paper, we report the discovery of the first bona fide ACs in this galaxy. We found that the SMC ACs are very similar to classical Cepheids in the sense of their mean brightness and light curve morphology. We also extend the OGLE-III sample of ACs in the LMC by new identifications in the outer regions of this galaxy observed during the fourth phase of the OGLE project (OGLE-IV, Udalski *et al.* 2015).

2. Observational Data

Time-series *I* and *V*-band photometry of the Magellanic Clouds was obtained in the years 2010–2015 using the 32-chip mosaic CCD camera mounted at the focus of the 1.3-m Warsaw Telescope located at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution for Science. The OGLE-IV camera has a total field of view of 1.4 square degrees and pixel scale of $0\overset{\prime\prime}{.}26$. The OGLE-IV fields cover approximately 650 square degrees in both Clouds and a region between both galaxies, the so-called Magellanic Bridge. For each field we obtained from 90 (in sparse regions far from the centers of the Magellanic Clouds) to over 750 observing points (in the densest fields) in the Cousins *I*-band and from several to over 260 points in the Johnson *V*-band.

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

3. Identification and Classification of Anomalous Cepheids

The first step in the identification of ACs was a search for periods for all *I*-band light curves of stellar objects collected in the Magellanic System by the OGLE-IV survey. The frequency analysis for 75 million stars was performed using the FNPEAKS program[†] kindly provided by Z. Kołaczkowski. We tested frequencies from $0\ \mathrm{d}^{-1}$ to $24\ \mathrm{d}^{-1}$ with a spacing of $0.00005\ \mathrm{d}^{-1}$. Light curves with the largest signal to noise ratios of the detected periods and those which were located in the "Cepheid region" in the PL diagram (wide strip covering classical and type II Cepheids) were subjected to visual inspection.

Variable stars were initially divided into three groups: pulsating, eclipsing, and other (usually of unknown type) variables. A more detailed classification of the first group was performed on the basis of the position of stars in the PL diagram and Fourier parameters fitted to the light curves. In general, ACs can be confused with RR Lyr stars, classical and type II Cepheids, although in the LMC they form a quite well separated group. Soszyński *et al.* (2008) demonstrated that ACs in the LMC delineate PL relations located between classical Cepheids and type II Cepheids/RR Lyr stars. In Fig. 1 we show that fundamental-mode ACs in the LMC

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

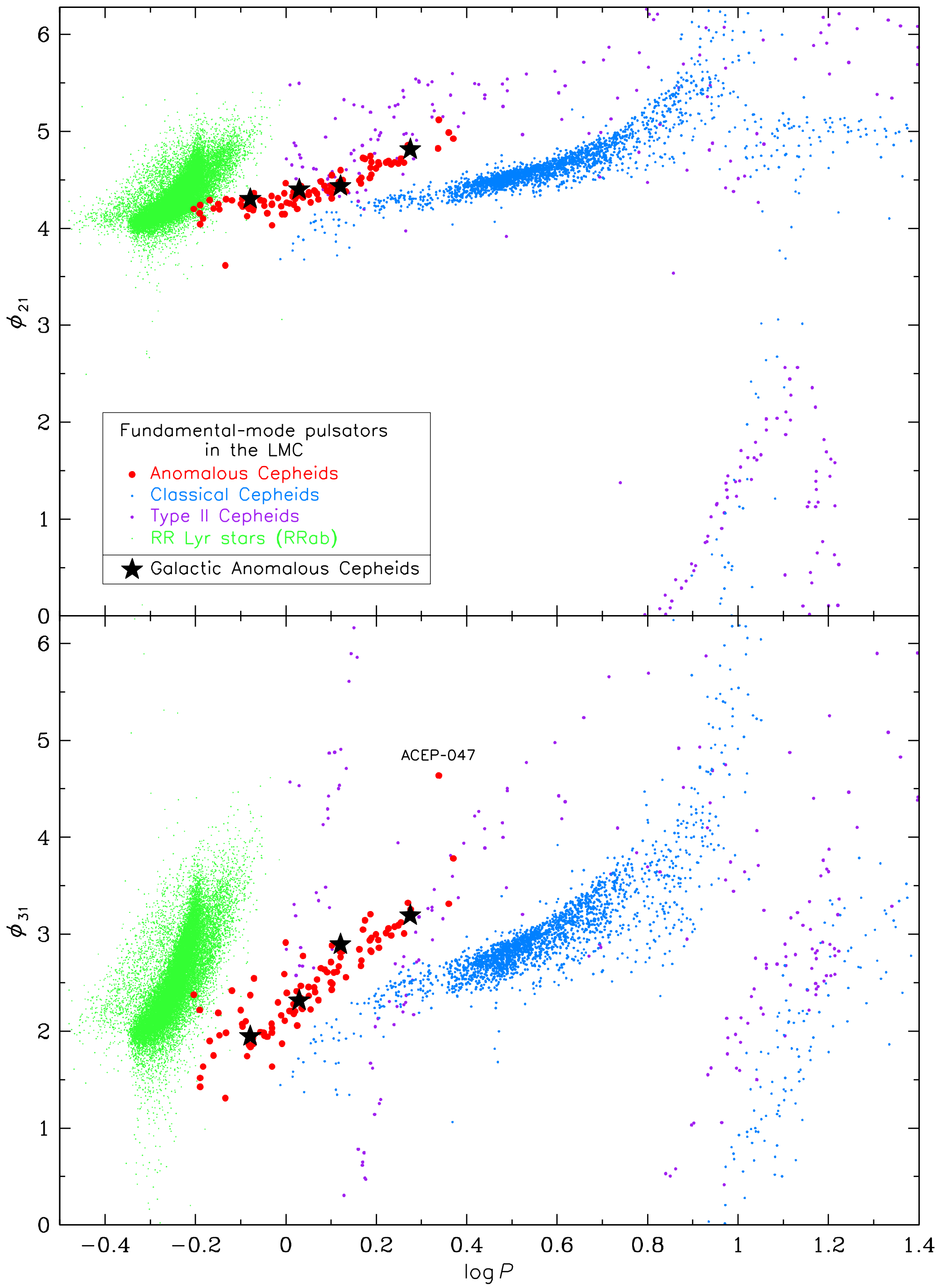

Fig. 1. Fourier coefficients ϕ_{21} and ϕ_{31} as a function of periods for the fundamental-mode Cepheids and RR Lyr stars detected in the OGLE fields toward the LMC. Red, blue, purple and green points indicate ACs, classical Cepheids, type II Cepheids, and RR Lyr stars, respectively. Four black star symbols show Galactic ACs found in the foreground of the Magellanic Clouds.

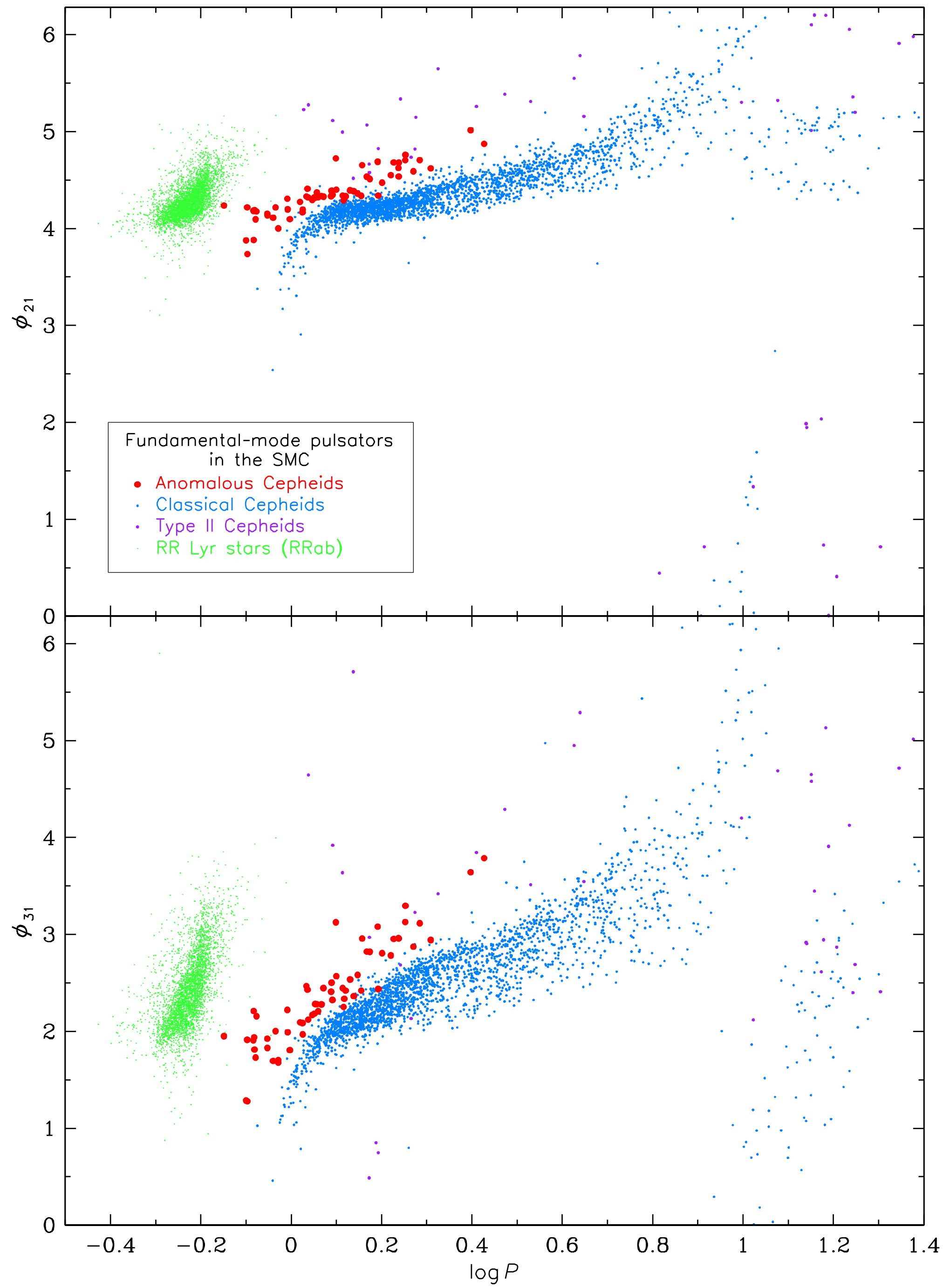

Fig. 2. Fourier coefficients ϕ_{21} and ϕ_{31} as a function of periods for the fundamental-mode Cepheids and RR Lyr stars detected in the OGLE fields toward the SMC. Different colors of points represent the same types of variable stars as in Fig. 1.

are characterized also by a distinct light curve morphology. Here ϕ_{21} and ϕ_{31} are phase differences of the Fourier cosine series fitted to the *I*-band light curves. It is clear that ACs (red points) can be well distinguished from classical Cepheids (blue points) only on the basis of their light curves.

The situation looks different in the SMC. Soszyński *et al.* (2010) noticed that there is no distinct group of pulsating stars between classical and type II Cepheids in the PL plane. However, it is known that fundamental-mode classical Cepheids in the SMC exhibit a break in the slope of the PL relation for a period of about 2.5 days (Bauer *et al.* 1999, Udalski *et al.* 1999), which may be also interpreted as an excess of faint Cepheids at the short-period end of the PL relation. We found that this excess is even more pronounced far from the SMC center, in the regions not observed by the OGLE-III project, but regularly monitored by the OGLE-IV survey.

A closer look at these faint Cepheids revealed that most of them have different light curves than regular classical Cepheids, although this difference is not so obvious as in the case of ACs and classical Cepheids in the LMC. Fig. 2 is analogous to Fig. 1, but presents variables in the SMC. Fundamental-mode Cepheids located distinctly below the mean PL relations of classical Cepheids and with ϕ_{21} and ϕ_{31} parameters larger than typical values for classical Cepheids were classified as ACs. A similar procedure was performed for first-overtone Cepheids, although their light curves exhibit larger diversity then their fundamental-mode counterparts, so our classification is more uncertain. Since ACs and classical Cepheids partly overlap in both – PL and period *vs.* Fourier coefficients – diagrams, our classification may be incorrect for individual stars, both fundamental-mode and overtone pulsators. On the other hand, there is no doubt that ACs, although morphologically similar to classical Cepheids, exist in the SMC, which is further confirmed by their radically different spatial distribution (see Section 6.2).

4. Catalog of Anomalous Cepheids in the Magellanic Clouds

The total sample of ACs in the Magellanic Clouds, including those detected in the OGLE-III survey (Soszyński *et al.* 2008), consists of 250 objects. The exact number of ACs belonging to the LMC and SMC cannot be given, because several pulsators were found in the Magellanic Bridge, approximately halfway between both galaxies. We allocated these Magellanic Bridge ACs to the LMC (two objects) or SMC (14 objects), according to their position in the sky and the position in the PL diagrams (which indicates their distance from us), but our assignments should be treated with caution. Thus, we identified 141 ACs in the LMC (101 fundamental-mode and 40 first-overtone pulsators) and 109 ACs in the SMC (73 fundamental-mode and 36 first-overtone). No double-mode ACs have been found with the exception of a first-overtone OGLE-LMC-ACEP-094 which exhibits an additional periodicity of about $P_{\rm X} \approx 0.364$ d (period ratio $P_{\rm X}/P_{1O} \approx 0.843$). The nature of the secondary period is unclear. We also detected four pulsating stars with light curves typical for fundamental-mode ACs, but much brighter than their counterparts in the Magellanic Clouds. These are likely Galactic ACs located in the foreground of these galaxies (Section 6.3).

The entire collection of ACs in the Magellanic Clouds can be downloaded from the OGLE Internet Archive:

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

for the LMC and SMC samples, respectively. Each AC has its unique identifier of the form OGLE-LMC-ACEP-NNN or OGLE-SMC-ACEP-NNN (where NNN is a three-digit sequential number), compatible with the identifiers used in the OGLE-III catalog (Soszyński *et al.* 2008).

In the LMC, ACs numbered from OGLE-LMC-ACEP-001 to OGLE-LMC-ACEP-083 were discovered and cataloged by Soszyński *et al.* (2008). In the current version of the catalog we removed two objects: OGLE-LMC-ACEP-022 and OGLE-LMC-ACEP-083, since we reclassified them as RR Lyr stars. On the other hand, a star previously classified as a type II Cepheid (OGLE-LMC-T2CEP-114) were moved to the collection of ACs in the LMC. Newly detected ACs in the LMC have identifiers between OGLE-LMC-ACEP-084 and OGLE-LMC-ACEP-143 and are organized by increasing right ascension.

Ripepi *et al.* (2014) suggested that three variables with periods longer than 2 d (OGLE-LMC-ACEP-014, 033, and 047), classified by Soszyński *et al.* (2008) as ACs in the LMC, are rather BL Her stars (type II Cepheids). We carefully inspected their light curves and we maintain our classification for OGLE-LMC-ACEP-014 and 033. The light curves of BL Her stars with periods above 2 d have completely different morphology (compare in Fig. 3 typical light curves of classical, anomalous and type II Cepheids with periods of about 2.3 d). Also the mean luminosity of these two ACs, although slightly lower than suggested by the linear fit to the PL relation for fundamental-mode ACs, is by at least 0.7 mag higher than expected for type II Cepheids of the same periods.

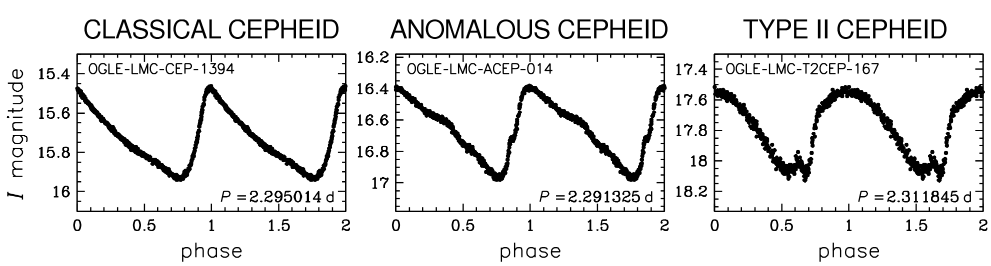

Fig. 3. Typical *I*-band light curves of classical Cepheids, ACs, and type II Cepheids (BL Her stars) with periods of about 2.3 d in the LMC.

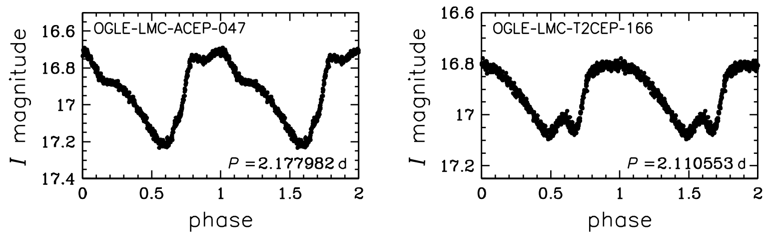

Fig. 4. *Left panel*: *I*-band light curve of OGLE-LMC-ACEP-047 – a Cepheid intermediate between ACs and BL Her stars. *Right panel*: *I*-band light curve of a blended BL Her star OGLE-LMC-T2CEP-166.

The third of the Cepheids reclassified by Ripepi *et al.* (2014) – OGLE-LMC-ACEP-047 – is an exceptional case of a pulsating star intermediate between anomalous and type II Cepheids. In the PL diagram it is located halfway between the relations of both types of Cepheids. Its light curve (left panel of Fig. 4) also differs from those of ACs or BL Her stars (Fig. 3), since OGLE-LMC-ACEP-047 has a distinct bump on the descending branch near the light maximum. This feature affects the ϕ_{31} Fourier coefficient, which shift this star outside the region occupied by typical ACs and BL Her stars (Fig. 1). Thus, we do not confirm that OGLE-LMC-ACEP-047 is a typical BL Her star and we temporarily leave it on the list of ACs, although we point out that this star deserves special attention in the future.

In turn, Fiorentino and Monelli (2012) reclassified one of the OGLE type II Cepheids in the LMC (namely OGLE-LMC-T2CEP-166) as an AC. Indeed, this star is brighter than other type II Cepheids with the same periods and falls among ACs in the PL diagram, but the light curve of OGLE-LMC-T2CEP-166 (right panel of Fig. 4) undoubtedly indicates that this star is a type II Cepheid. Its higher luminosity and decreased amplitude of light variations (if expressed in magnitudes) is most likely associated with the blending by an unresolved star.

In the SMC, we did not hitherto published a separate catalog of ACs, although six candidates for ACs were listed by Soszyński *et al.* (2010). All these objects are included in the present collection. Our final sample contains a total of 41 pulsating stars from the SMC classified by Soszyński *et al.* (2010) as classical Cepheids and now reclassified as ACs. We provide their previous designations in the remarks file of the catalog.

In the FTP site we provide OGLE-IV multi-epoch photometry in the *I* and *V* filters, finding charts, and basic observational parameters of each AC: coordinates, periods, intensity mean magnitudes in the *I*- and *V*-bands, *I*-band peak-to-peak amplitudes, and Fourier coefficients R_{21}, ϕ_{21}, R_{31}, and ϕ_{31} derived for 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. Note that ACs in the central regions of the LMC and SMC were also observed during the OGLE-II (1997–2000) and/or OGLE-III (2001–2009) surveys, and these light curves were published by Soszyński *et al.* (2008, 2010). We suggest to merge both datasets if one plans to study long-term behavior of ACs in the Magellanic Clouds.

Several ACs discovered by Soszyński *et al.* (2008) do not have OGLE-IV observations, because they fell in the gaps between the CCD chips of the mosaic camera. For these stars we provide their parameters from the OGLE-III catalog.

5. Completeness of the Sample

Some stars in our sample have two entries in the OGLE-IV database, because they fell in the overlapping regions of two neighboring fields. In such cases, we publish only one light curve, usually that with the larger number of data points. These double detections can be used to test the completeness of our collection of ACs in the Magellanic Clouds. We *a posteriori* checked that 27 of the 250 ACs should be detected twice, in the overlapping parts of the adjacent fields, so we had an opportunity to identify 54 counterparts. We independently detected 53 of them. The only missing light curve consists of only 20 observing points and was not searched for periodicity in the first step of our procedure. Thus, it seems that the completeness of our sample is very high, close to 100%.

One should be aware that the very high level of completeness refers to the regions covered by the OGLE fields. The sky coverage outside the central regions of both Magellanic Clouds has some gaps resulting from the observing strategy. Moreover, in the OGLE-IV mosaic camera there are technical gaps between CCD detectors, which decrease an effective area of the OGLE-IV fields by about 6%. Of course, these restrictions do not affect central regions of the Clouds, which were observed during the OGLE-II and OGLE-III projects. In these areas we expect the largest level of completeness, since it was searched for variable stars in the past (*e.g.,* Soszyński *et al.* 2008, 2010).

We cross-matched our collection of ACs with the extragalactic part of the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995). We found nine counterparts, usually classified as RR Lyr stars or classical Cepheids. Only one object – CV101 = OGLE-SMC-ACEP-048 discovered by Landi Dessy (1959) – is classified in the GCVS as a BL Boo star (an alternative name for ACs). It is interesting that GCVS lists as many as 41 stars in the SMC classified as BL Boo stars. These objects were discovered half a century ago by Landi Dessy (1959), Tifft (1963), Wesselink and Shuttleworth (1965), and Graham (1975). All but one of these stars were observed by OGLE and only CV101 is a real AC. From the remaining 39 stars designated as BLBOO in the GCVS over 75% turned out to be classical Cepheids in the SMC. In many cases the pulsation periods provided in the GCVS are daily aliases of the real periods. Several of the misclassified variables are Galactic RR Lyrae stars in the foreground of the SMC, one star (HV 12132) is an eclipsing binary system, and one object (HV 12912) seems to be a constant star in the OGLE database. HV12153 suggested by Duncan *et al.* (1993) to be an AC turned out to be a typical first-overtone classical Cepheid.

6. Discussion

6.1. Period–Luminosity Relations

ACs, as other types of pulsating stars, obey PL laws. The OGLE collection of ACs in the Magellanic Cloud offers an opportunity to study in detail these relations, since both galaxies host rich samples of various pulsating stars and other distance indicators. Baade and Swope (1961) first suggested that ACs may obey a PL law different than classical and type II Cepheids. This hypothesis was confirmed by van Agt (1967) and Swope (1968). Then, the PL relations for ACs were studied, among others, by Pritzl *et al.* (2002), Marconi *et al.* (2004), and Ripepi *et al.* (2014).

Table 1

Period–luminosity relations for pulsating stars in the Magellanic Clouds

Type of pulsators	Mode	Galaxy	a	σ_a	b	σ_b
		$W_I = a \log P + b$				
Anomalous Cepheids	F	LMC	−3.05	0.11	16.59	0.02
Anomalous Cepheids	1O	LMC	−3.38	0.19	16.03	0.04
Classical Cepheids	F	LMC	−3.32	0.01	15.89	0.01
Classical Cepheids	1O	LMC	−3.43	0.01	15.39	0.01
Type II Cepheids	F	LMC	−2.53	0.02	17.35	0.02
RR Lyr stars	F	LMC	−3.06	0.02	17.15	0.01
Anomalous Cepheids	F	SMC	−2.85	0.15	17.01	0.03
Anomalous Cepheids	1O	SMC	−3.69	0.28	16.64	0.05
Classical Cepheids	F	SMC	−3.46	0.02	16.56	0.01
Classical Cepheids	1O	SMC	−3.57	0.02	16.03	0.01
Type II Cepheids	F	SMC	−2.32	0.08	17.64	0.06
RR Lyr stars	F	SMC	−3.35	0.06	17.50	0.02
		$I = a \log P + b$				
Anomalous Cepheids	F	LMC	−2.94	0.15	17.52	0.02
Anomalous Cepheids	1O	LMC	−3.31	0.22	16.83	0.05
Classical Cepheids	F	LMC	−2.91	0.02	16.82	0.01
Classical Cepheids	1O	LMC	−3.30	0.02	16.38	0.01
Type II Cepheids	F	LMC	−2.00	0.04	18.20	0.03
RR Lyr stars	F	LMC	−1.89	0.02	18.33	0.01
Anomalous Cepheids	F	SMC	−2.63	0.15	17.83	0.03
Anomalous Cepheids	1O	SMC	−3.78	0.34	17.31	0.06
Classical Cepheids	F	SMC	−3.12	0.02	17.43	0.01
Classical Cepheids	1O	SMC	−3.31	0.03	16.84	0.01
Type II Cepheids	F	SMC	−1.96	0.12	18.51	0.09
RR Lyr stars	F	SMC	−2.12	0.06	18.63	0.02

Figs. 5 and 6 show period *vs.* Wesenheit index (upper panels) and period *vs.* I-band magnitude for Cepheids and RR Lyr stars in the LMC and SMC, respectively. Wesenheit index is an extinction insensitive quantity, defined as $W_I = I - 1.55(V -$

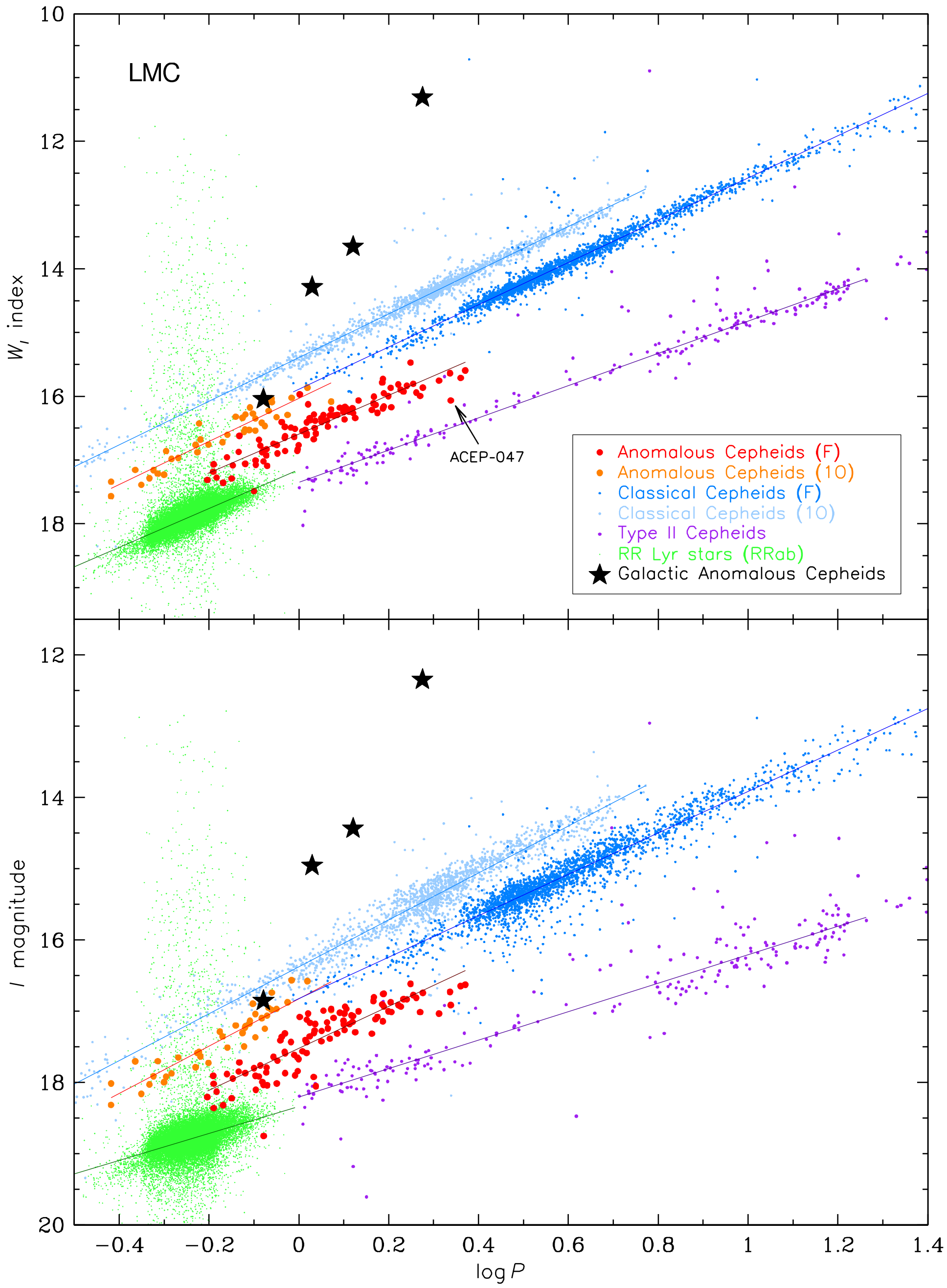

Fig. 5. Period–luminosity diagrams for ACs (red and orange points), classical Cepheids (blue points), type II Cepheids (purple points) and RR Lyr stars (green points) in the LMC. Four black star symbols show Galactic ACs in the foreground of the Magellanic Clouds. *Upper panel* shows the $\log P - W_I$ relations, where $W_I = I - 1.55(V-I)$ is an extinction-free Wesenheit index. *Lower panel* shows the $\log P - I$ relations, where I are apparent mean magnitudes of the stars.

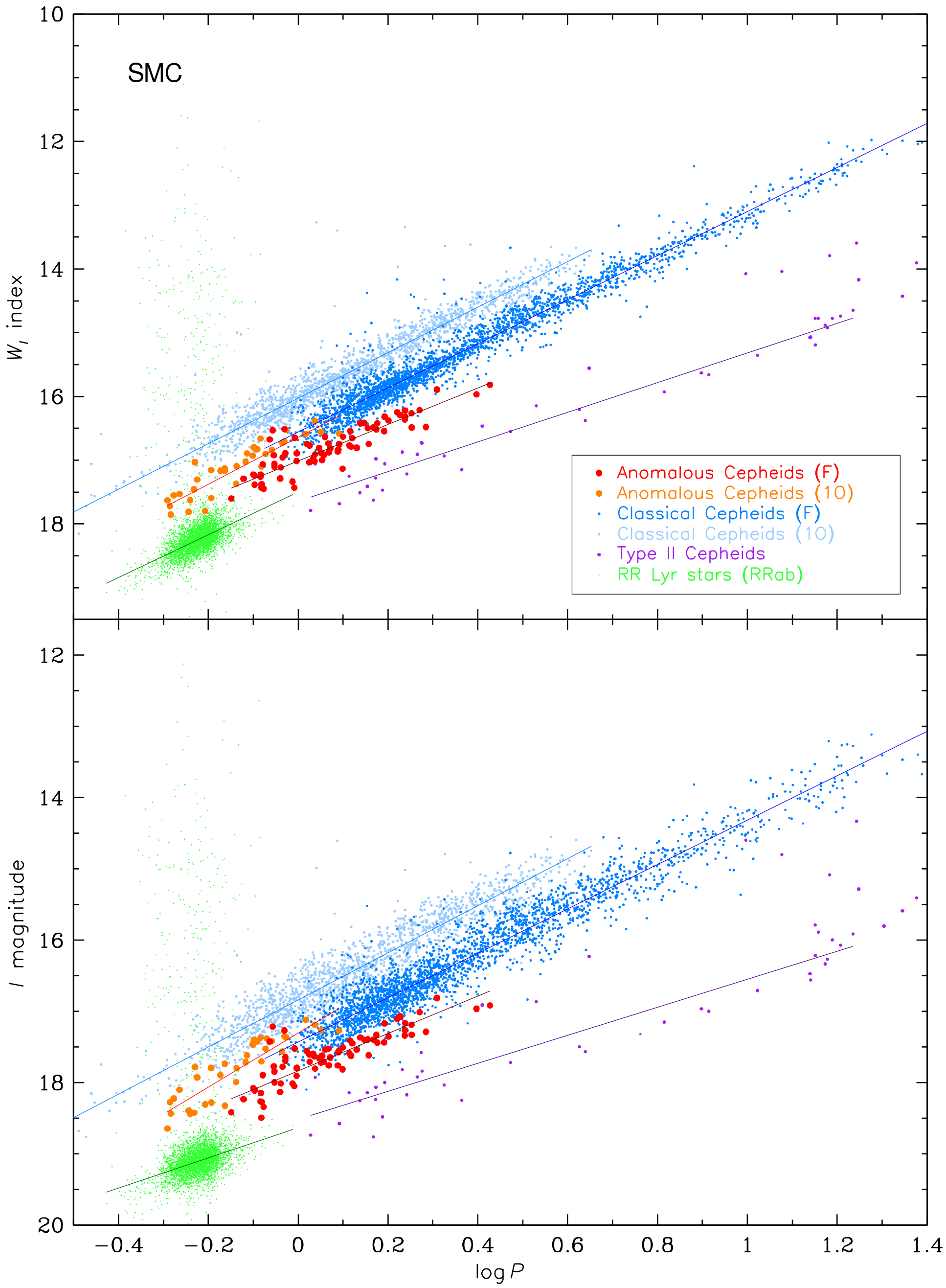

Fig. 6. Period–luminosity diagrams for Cepheids and RR Lyr stars in the SMC. Symbols are the same as in Fig. 5.

I). As can be seen, ACs pulsating in the fundamental and first-overtone modes follow the PL relations located below their classical counterparts. In the LMC, anomalous and classical Cepheids are well separated in the PL planes, while in the SMC both types of pulsators seem to partly overlap, which was a source of difficulties in the identifications of ACs in this environment.

The overlap of anomalous and classical Cepheids in the PL diagrams may be partly explained by the large line-of-sight depth of the SMC, which broadens the PL relations. However, the mean PL relations of ACs and classical Cepheids seem to have inconsistent zero points in both galaxies. We fitted the linear PL relations for ACs, classical Cepheids, type II Cepheids (BL Her and W Vir stars) and RRab stars using a standard least square method with 3σ clipping. Slopes and zero points of the fits are summarized in Table 1. The fits are also shown in Figs. 5 and 6. We may compare mean luminosities of various types of Cepheids and RR Lyr stars at the pulsation period of $P = 1$ d ($\log P = 0$), because all studied types of pulsators have representatives with periods around this value. In the LMC, fundamental-mode ACs are by 0.70 ± 0.02 mag fainter than fundamental-mode classical Cepheids, while in the SMC this difference is only 0.45 ± 0.03 mag (in the period–W_I plane, but similar values can be found in the PL diagrams in the I-band). Similar discrepancy is also visible when we compare classical Cepheids and RR Lyr stars or type II Cepheids, which suggests that ACs belong to the old population. The effect of different zero points of the PL relations in the LMC and SMC is not visible for the first-overtone Cepheids, but it cannot be excluded that the overtone ACs in the SMC are affected by the selection effect – the brightest ones still remain on the list of classical Cepheids.

Assuming that young and old stars in the SMC are on average at the same distance from us, the proximity of anomalous and classical Cepheids in the SMC has consequences for the calibration of Cepheids as distance indicators. Either classical Cepheids in the SMC are fainter than in the LMC, or ACs in the SMC are brighter than in the LMC. It is also possible than both conjectures are true.

Note that the reclassification of several dozen short-period classical Cepheids as ACs changed the appearance of the PL diagram for Cepheids in the SMC. The break in the slope observed for the fundamental-mode classical Cepheids at a period of about 2.5 d ($\log P = 0.4$, Bauer *et al.* 1999, Udalski *et al.* 1999) is not so distinct when ACs were separated, although it is still visible. Whatever the cause of this non-linearity (see Bauer *et al.* 1999 for the discussion of possible explanations of such behavior of Cepheids), this effect additionally hampers the detection of ACs in the SMC, since short-period classical Cepheids approach ACs in the PL plane.

6.2. Spatial Distribution of Anomalous Cepheids in the Magellanic Clouds

Study of spatial distribution of various stars is a powerful tool to discriminate between old, intermediate and young stellar populations. Fiorentino and Monelli (2012) suggested that a survey for ACs in the outer regions of the LMC may solve the problem of their origin. OGLE-IV covers outskirts of the Magellanic Clouds, including the Magellanic Bridge – a region located between them.

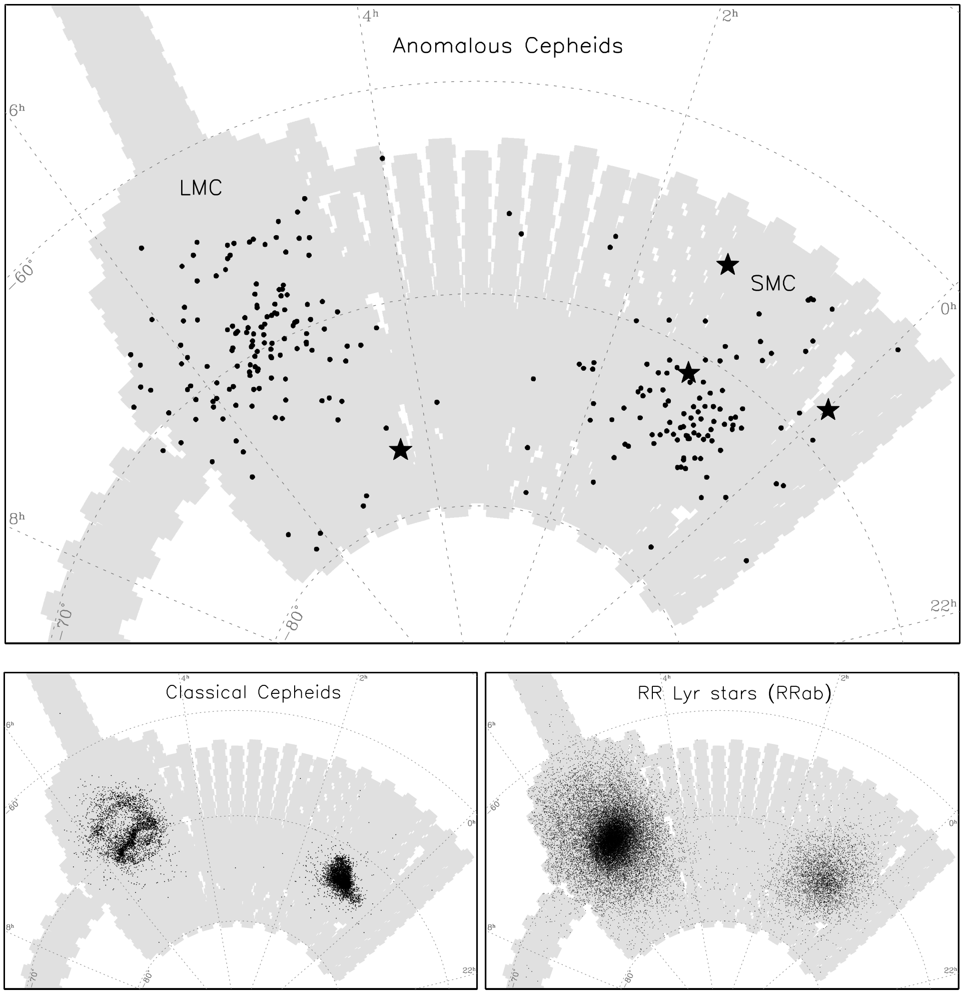

Fig. 7. Spatial distribution of ACs (*upper panel*), classical Cepheids (*lower left panel*), and RRab stars (*lower right panel*) in the Magellanic System. Star symbols show Galactic ACs in the foreground of the Magellanic Clouds. The gray area shows the sky coverage of the OGLE fields.

In the upper panel of Fig. 7 we present the positions of our sample of 250 ACs in the Magellanic System. In the lower panels of Fig. 7 we plot the positions of classical Cepheids (tracers of the young stellar population) and fundamental-mode RR Lyr stars (representatives of the old population) found in the same OGLE fields toward the Magellanic Clouds. Our collection of classical Cepheids in the Clouds contains in total 9513 objects. Our current sample of RRab stars (fundamental-mode RR Lyr stars) detected in the OGLE fields toward the Magellanic Clouds consists of 32 483 objects. In this study we used RRab stars only, since their light curves have very characteristic shapes and we expect the largest completeness and the least contamination in this sample. To reject RR Lyr variables belonging to the Milky Way halo, we removed objects more than 0.6 mag brighter or fainter than the mean fit to the PL relation. In our last cut we removed RR Lyr stars that likely belong to globular clusters in both Clouds. Our final sample counts 30 331 RRab stars in the LMC and SMC.

The difference between spatial distributions of the young and old stellar population is clearly visible in the lower panels of Fig. 7. Against this background, the distribution of ACs is ambiguous. In the LMC ACs seem to trace the bar and spiral arms of this galaxy, like classical Cepheids, although there is an excess of objects far from the LMC center, in particular in the southern direction. In the SMC, ACs seem to follow very broad spatial distribution, similarly to the RR Lyr stars. Several ACs can be found even in the Magellanic Bridge, at halfway between Clouds.

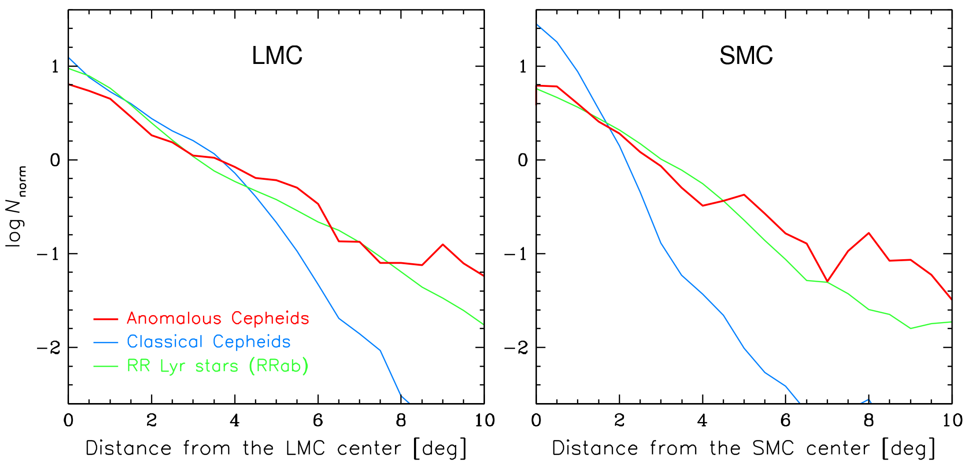

Fig. 8. One-dimensional distributions of ACs (red lines), classical Cepheids (blue lines), and RRab stars (green lines) plotted against angular distance from the LMC (*left panel*) and SMC center (*right panel*). The number of classical Cepheids and RR Lyr stars were normalized to the number of ACs within 10 degrees from the galactic centers.

We derived one-dimensional density distributions of ACs, classical Cepheids and RRab stars in both Clouds. We counted the number of pulsators in one-degree-wide circular rings around the centers of the LMC ($\alpha_{\rm LMC} = 5^{\rm h}23\overset{\rm m}{.}6$, $\delta_{\rm LMC} = -69°45'$) and SMC ($\alpha_{\rm SMC} = 0^{\rm h}52\overset{\rm m}{.}7$, $\delta_{\rm SMC} = -72°50'$) and rescaled the numbers of classical Cepheids and RR Lyr stars to the number of ACs within 10 degrees from the galactic centers. Taking into account the incomplete sky coverage of the OGLE fields, we derived the number of stars per square degree in each ring. These numbers in the logarithmic scale are plotted in Fig. 8 against the projected angular distances from the centers of the LMC and SMC.

In both galaxies, the radial distribution of ACs resembles that of RR Lyr stars. It is particularly evident in the SMC, where classical Cepheids are much more concentrated in the center of this galaxy than the old stellar population. In both Clouds, there is an excess of ACs with respect to RR Lyr stars for angular distances larger than 7 degrees from the centers. This suggests that at least part of the ACs in the Magellanic Clouds are very old stars, what implies their binary origin. On the other hand, the traces of the bar and spiral arm visible in the distribution of ACs in the LMC may indicate much younger population. The most likely explanation is that ACs in the Magellanic Clouds represent a mixture of two formation channels: the evolution of coalescent binaries and the evolution of single, intermediate-age, metal-poor stars.

6.3. Galactic Anomalous Cepheids in the Foreground of the Magellanic Clouds

Four pulsating stars found in the OGLE fields toward the Magellanic Clouds are much brighter than expected for fundamental-mode Cepheids from these galaxies (Fig. 5), but have light curves typical for ACs (Fig. 9). The Fourier coefficients ϕ_{21} and ϕ_{31} of the decomposed light curves place them among fundamental-mode ACs in the Magellanic Clouds (Fig. 1). Given that the Magellanic Clouds are far from the plane of the Milky Way (so we do not expect to find Galactic classical Cepheids in these regions), we can safely assume that these four objects are ACs belonging to our Galaxy. Until now, the only known confirmed AC in the Galactic field was a first-overtone pulsator XZ Ceti (Szabados *et al.* 2007). The OGLE variables are the first known unambiguously detected fundamental-mode ACs found in the field of the Milky Way. Their basic observational parameters are summarized in Table 2. Individual distances to these stars were derived from the $\log P - W_I$ relation of the LMC ACs, assuming the distance to the LMC of 49.97 kpc (Pietrzyński *et al.* 2013).

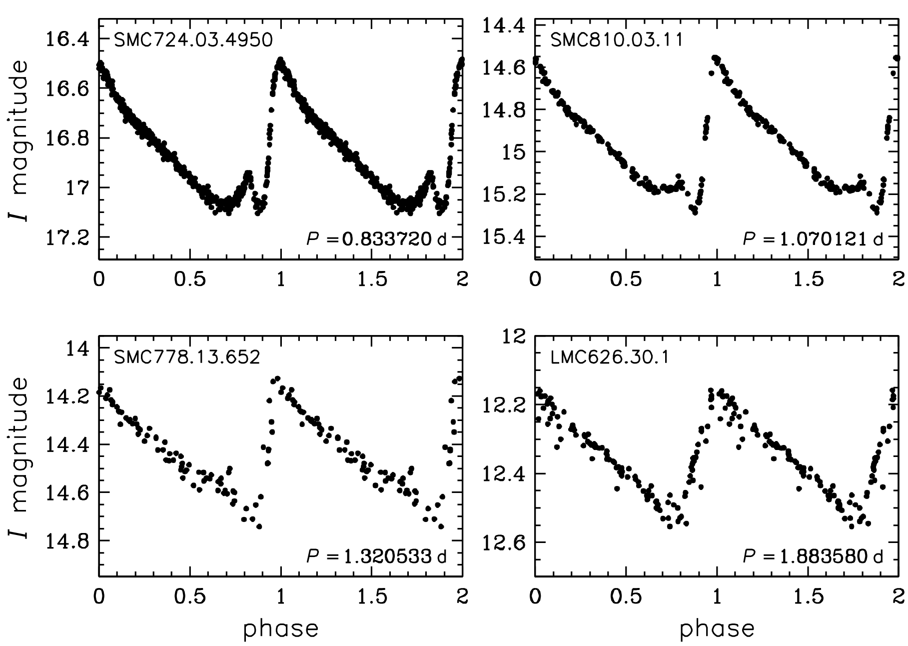

Fig. 9. *I*-band light curves of four Galactic ACs in the foreground of the Magellanic Clouds.

Table 2

Galactic anomalous Cepheids in the foreground of the Magellanic Clouds

Identifier	Pulsation mode	P [d]	$\langle I \rangle$ [mag]	$\langle V \rangle$ [mag]	R.A. [J2000.0]	Dec. [J2000.0]	Distance [kpc]
SMC724.03.4950	F	0.8337199	16.850	17.373	$01^{h}10^{m}57.^{s}51$	$-71^{\circ}01'57.''6$	34.7
SMC810.03.11	F	1.0701211	14.955	15.387	$01^{h}20^{m}14.^{s}74$	$-65^{\circ}42'38.''3$	18.0
SMC778.13.652	F	1.3205328	14.443	14.939	$23^{h}59^{m}14.^{s}51$	$-68^{\circ}13'56.''6$	15.3
LMC626.30.1	F	1.8835803	12.344	13.015	$04^{h}23^{m}51.^{s}47$	$-76^{\circ}54'42.''8$	6.5

Recently, Sipahi *et al.* (2013ab) measured masses of two pulsating stars that are components of eclipsing binary systems. Their relatively small masses – 1.64 $M_{\odot}$ and 1.46 $M_{\odot}$ – led the authors to the conclusion that both pulsators are anomalous Cepheids. However, their long pulsation periods – 4.15 d and 4.22 d, respectively – suggest that both objects belong to a different class of pulsating stars: the so called peculiar W Vir stars discovered by Soszyński *et al.* (2008) in the LMC. Indeed, OGLE light curves show that a large fraction (at least 30%) of peculiar W Vir stars are members of binary systems.

7. Conclusions

We presented a collection of 250 ACs in the Magellanic Clouds, which probably exceeds the total number of ACs known in all other galaxies. Such a big sample of these rare pulsating stars is sufficient to perform various statistical tests concerning their evolution, PL relations, spatial distributions, features of the light curves, metallicities, etc. In the LMC, ACs and classical Cepheids clearly constitute two separate classes of variable stars, while in the SMC both groups of Cepheids partly overlap in the PL diagram and exhibit much more similar light curves, which is associated with a lower metallicity of classical Cepheids in the SMC than in the LMC. This similarity could confirm the suggestion of Caputo *et al.* (2004) that ACs are natural extension of classical Cepheids to lower metal contents and smaller masses, so ACs do not constitute in fact a separate class of variable stars. However, we demonstrated that ACs and classical Cepheids in the SMC follow completely different spatial distributions which, in turn, indicates different evolutionary histories of both groups of pulsators.

The discovery of four fundamental-mode ACs in the foreground of the Magellanic Clouds proves that ACs are quite numerous in the Galactic halo, but until now there was no good method to distinguish them from other types of Cepheids. We showed that Fourier parameters ϕ_{21} and ϕ_{31} are useful discriminants of ACs and classical Cepheids.

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REFERENCES

Alard, C., and Lupton, R.H. 1998, *ApJ*, **503**, 325.
Artyukhina, N.M., *et al.* 1995, General Catalogue of Variable Stars, 4rd ed., vol.V. Extragalactic Variable Stars, "Kosmosinform", Moscow.
Baade, W., and Swope, H.H. 1961, *AJ*, **66**, 300.
Bauer, F., Afonso, C., Albert, J.N., *et al.* 1999, *A&A*, **348**, 175.
Bono, G., Caputo, F., Santolamazza, P., Cassisi, S., and Piersimoni, A. 1997, *AJ*, **113**, 2209.
Caputo, F., Castellani, V., Degl'Innocenti, S., Fiorentino, G., and Marconi, M. 2004, *A&A*, **424**, 927.
Cioni, M.-R.L., Clementini, G., Girardi, L., *et al.* 2011, *A&A*, **527**, A116.
Cusano, F., Clementini, G., Garofalo, A., *et al.* 2013, *ApJ*, **779**, 7.
Demarque, P., and Hirshfeld, A.W. 1975, *ApJ*, **202**, 346.
Duncan, S.P.R., Tobin, W., Watson, R.D., and Gilmore, A.C. 1993, *MNRAS*, **265**, 189.
Fiorentino, G., and Monelli, M. 2012, *A&A*, **540**, A102.
Graham, J.A. 1975, *PASP*, **87**, 641.
Landi Dessy, J. 1959, *Bol. Inst. Mat., Astr., Fis. Univ. Nac. de Cordoba 1, No. 2*.
Marconi, M., Fiorentino, G., and Caputo, F. 2004, *A&A*, **417**, 1101.
Norris, J., and Zinn, R. 1975, *ApJ*, **202**, 335.
Osborn, W., Kopacki, G., and Haberstroh, J. 2012, *Acta Astron.*, **62**, 377.
Pietrzyński, G., Graczyk, D., Gieren, W., *et al.* 2013, *Nature*, **495**, 76.
Pritzl, B.J., Armandroff, T.E., Jacoby, G.H., and Da Costa, G.S. 2002, *AJ*, **124**, 1464.
Renzini, A., Mengel, J.G., and Sweigart, A.V. 1977, *A&A*, **56**, 369.
Ripepi, V., *et al.* 2014, *MNRAS*, **437**, 2307.
Schwarzenberg-Czerny, A. 1996, *ApJ*, **460**, L107.
Sipahi, E., İbanoğlu, C., Çakırlı, Ö., Dal, H.A., and Evren, S. 2013a, *Revista Mexicana de Astronomía y Astrofísica*, **49**, 239.
Sipahi, E., İbanoğlu, C., Çakırlı, Ö., and Evren, S. 2013b, *MNRAS*, **429**, 757.
Soszyński, I., *et al.* 2008, *Acta Astron.*, **58**, 293.
Soszyński, I., *et al.* 2010, *Acta Astron.*, **60**, 17.
Swope, H.H. 1968, *AJS*, **73**, 204.
Szabados, L., Kiss, L.L., and Derekas, A. 2007, *A&A*, **461**, 613.
Thackeray, A.D. 1950, *The Observatory*, **70**, 144.
Tifft, W.G. 1963, *MNRAS*, **125**, 199.
Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszyński, I., Woźniak, P., and Żebruń, K. 1999, *Acta Astron.*, **49**, 201.
Udalski, A., Szymański, M.K., and Szymański, G. 2015, *Acta Astron.*, **65**, 1.
van Agt, S.L.T.J. 1967, *Bull. Astron. Inst. Neth.*, **19**, 275.
Wesselink, A.J., and Shuttleworth, M. 1965, *MNRAS*, **130**, 443.
Woźniak, P.R. 2000, *Acta Astron.*, **50**, 421.
Zinn, R., and Searle, L. 1976, *ApJ*, **209**, 734.