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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. VII. Classical Cepheids in the Small Magellanic Cloud*

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ABSTRACT

The seventh part of the OGLE-III Catalog of Variable Stars (OIII-CVS) consists of 4630 classical Cepheids in the Small Magellanic Cloud (SMC). The sample includes 2626 fundamental-mode (F), 1644 first-overtone (1O), 83 second-overtone (2O), 59 double-mode F/1O, 215 double-mode 1O/2O, and three triple-mode classical Cepheids. For each object basic parameters, multi-epoch *VI* photometry collected within 8 or 13 years of observations, and finding charts are provided in the OGLE Internet archive.

We present objects of particular interest: exceptionally numerous sample of single-mode second-overtone pulsators, five double Cepheids, two Cepheids with eclipsing variations superimposed on the pulsation light curves. At least 139 first-overtone Cepheids exhibit low-amplitude secondary variations with periods in the range 0.60–0.65 of the primary ones. These stars populate three distinct sequences in the Petersen diagram. The origin of this secondary modulation is still unknown. Contrary to the Large Magellanic Cloud (LMC) we found only a few candidates for anomalous Cepheids in the SMC. This fact may be a clue for the explanation of the origin of the anomalous Cepheids. The period and luminosity distributions of Cepheids in both Magellanic Clouds suggest that there are two or three populations of classical Cepheids in each of the galaxies. The main difference between the LMC and SMC lays in different numbers of Cepheids in each group. We fit the period–luminosity (PL) relations of SMC Cepheids and compare them with the LMC PL laws.

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

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

1. Introduction

Classical Cepheids (also called δ Cep stars, type I Cepheids or Population I Cepheids) provide us with precise tests of stellar interiors and evolution. These are also the milestones of the extragalactic distance scale through their famous period–luminosity (PL) relation. Huge samples of Cepheids and other variable stars detected in recent years by microlensing surveys have increased our knowledge about statistical features of these objects, but also reveal very rare or previously unknown subtypes of variable stars.

Classical Cepheids in the Small Magellanic Cloud (SMC) played an important historical role. Leavitt (1908) derived periods for 16 SMC Cepheids and noticed that "the brighter variables have the longer periods", which was the first hint of the PL relation. Within the next few decades the number of known Cepheids in the SMC grew significantly, mainly as a result of the extensive survey of the Magellanic Clouds carried out by the Harvard Observatory. In 1955 periods were derived for 670 Cepheids in the SMC (Shapley and McKibben Nail 1955, and references therein). The Harvard catalog of variable stars in the SMC by Payne-Gaposchkin and Gaposchkin (1966) comprised as many as 1155 Cepheids.

A larger sample of Cepheid variables in the SMC was only released when the Optical Gravitational Lensing Experiment entered its second phase (OGLE-II) and collected the photometric database of stars in the Magellanic Clouds. Udalski *et al.* (1999abd) published the catalog of Cepheids in the SMC, consisting of 2062 single-mode pulsators (including several type II Cepheids) and 93 double-mode variables. From the recent catalogs, it is worth mentioning the EROS-2 catalog of double-mode Cepheids in the Magellanic Clouds (Marquette *et al.* 2009), which includes 170 beat Cepheids in the SMC.

The OGLE-III Catalog of Variable Stars (OIII-CVS) is intended to include all variable sources detected among about 400 million stars monitored during the third phase of the OGLE survey. In the previous papers of this series we presented the catalogs of over 120 000 pulsating stars in the Large Magellanic Cloud (LMC): classical Cepheids (Soszyński *et al.* 2008b, hereafter Paper I), type II and anomalous Cepheids (Soszyński *et al.* 2008c), RR Lyr stars (Soszyński *et al.* 2009a), long-period variables (Soszyński *et al.* 2009b), and δ Sct stars (Poleski *et al.* 2010). In the present paper we describe the first part of the OIII-CVS that contains variable stars in the SMC.

Our sample doubles the number of known classical Cepheids in the SMC. The catalog comprises 4630 variables – the largest set of Cepheids identified to date in this and any other galaxy. As in previous parts of the OIII-CVS, we release the photometric and astrometric information about each star. These data are described in Section 2. In Section 3 we present methods used to select Cepheids in the SMC. The catalog itself is described in Section 4. In Section 5 we compare the distributions of periods and luminosities of the LMC and SMC Cepheids. In Section 6 we present the PL relations and in Section 7 we draw our conclusions.

2. Observational Data

The observational data provided with this catalog were collected during the OGLE-III project between 2001 and 2009 with the 1.3-meter Warsaw telescope at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution of Washington. The telescope was equipped with the "second generation" camera consisting of eight SITe 2048×4096 CCD detectors with 15 μm pixels which corresponded to 0.26 arcsec/pixel scale. The gain of the chips was adjusted to be about 1.3 e^-/ADU with the readout noise from 6 to 9 e^- depending on the chip. Details of the instrumentation setup can be found in Udalski (2003).

Observations covered over 14 square degrees (41 fields) distributed over the densest regions of the SMC. Typically about 700 points in the Cousins *I*-band and 50–70 points in the Johnson *V*-band were collected, although for some stars we obtained two or even three times more points, since they were located in the overlapping parts of two or three adjacent fields. It is worth noting that imperfections in the telescope pointing compensated for small gaps between the CCD chips of the mosaic, so the completeness of the catalog is virtually not affected by these gaps, though stars located at the very edge of the fields sometimes have a smaller number of observations.

For about 2300 stars in the central 2.4 square degrees of the SMC the OGLE-III photometry was supplemented with the OGLE-II observations (Szymański 2005) collected from 1997 through 2000. These are additional 300–400 points in the *I*-band and 30–40 measurements in the *V*-band. We tied both datasets by shifting the OGLE-II photometry to agree with the OGLE-III light curves.

The photometry was obtained with the standard OGLE data reduction pipeline (Udalski *et al.* 2008) based on the Difference Image Analysis (DIA, Alard and Lupton 1998, Alard 2000, Woźniak 2000). For 17 brightest Cepheids there is no DIA *I*-band photometry, because these stars saturate in the reference frames. Instead, we provide the DOPHOT (Schechter *et al.* 1993) photometry for these objects, derived independently on individual images. These objects are flagged in the remarks of the catalog. Since at least part of the observations of these bright objects were saturated, the DOPHOT light curves are much more noisy than the DIA ones, but their quality is good enough to study periods and light curve shapes. Nevertheless, we do not recommend using this photometry for absolute calibration of the Cepheid brightness.

3. Selection of Cepheids

3.1. Single-Mode Cepheids

The process of the variable stars selection began with a period search for all stars monitored during the OGLE-III project in the SMC. About 6 million stars were subjected to a Fourier-based frequency analysis with the FNPEAKS code

(Z. Kołaczkowski, private communication) at the Interdisciplinary Centre for Mathematical and Computational Modelling of the University of Warsaw (ICM). For each star the ten highest peaks in the periodograms were selected and archived with the corresponding amplitudes and signal-to-noise (S/N) ratios. Then, the light curve was prewhitened with the primary period and the procedure of the period search was repeated on the residual data.

For every object with $\mathrm{S/N} > 5$ we derived the mean *I*- and *V*-band magnitudes and constructed the period–W_I diagram, where W_I is the extinction-insensitive Wesenheit index, defined as:

$$W_I = I - 1.55(V - I).$$

In this plane classical Cepheids follow distinct PL relations and were easy to spot. For further analysis we selected stars located in the wide region above and below these sequences in order to also include blended Cepheids and type II Cepheids. All these light curves were visually inspected and divided into three groups: pulsation-like, eclipsing-like and other variable objects. The pulsation-like light curves were tentatively categorized into classical Cepheids, type II Cepheids, RR Lyr stars and δ Sct stars. To distinguish between first-overtone Cepheids and δ Sct stars we adopted the same limiting period as in the LMC *i.e.*, 0.24 days. We emphasize that this is an arbitrary value, because δ Sct stars are located at the extension of the PL relation of Cepheids, so our shortest-period Cepheids may be called δ Sct stars in other investigations.

During the selection process we identified several dozen type II Cepheids in the SMC. Their list will be published in the subsequent part of the OIII-CVS. Somewhat surprisingly, we did not notice any PL relation spreading between classical and type II Cepheids and populated by anomalous Cepheids, like in the LMC where 62 fundamental-mode anomalous Cepheids were found (Soszyński *et al.* 2008c). In the SMC we selected only 3 candidates for fundamental-mode and 3 candidates for first-overtone anomalous Cepheids. These stars are located slightly below the PL relations for classical Cepheids and their light curves are similar to the light curves of anomalous Cepheids in the LMC. Two of the candidate fundamental-mode anomalous Cepheids have periods shorter than any other fundamental-mode classical Cepheid. However, it cannot be excluded that these objects are classical Cepheids located farther than other classical Cepheids or are RR Lyr stars in the foreground of the SMC. Table 1 gives basic information about our six candidates for anomalous Cepheids in the SMC. These stars are also flagged in the remarks of the Catalog.

A modest number of anomalous Cepheids in our data was rather unexpected, because the General Catalog of Variable Stars (GCVS, Artyukhina *et al.* 1995) listed as many as 42 BL Boo stars (*i.e.*, anomalous Cepheids) in the SMC. We verified this classification for 38 variables that are located in the OGLE-III fields. Most of them (31 objects) are regular classical Cepheids populating the same PL relations as other pulsators of that type. For 17 stars from this group the periods

Table 1

Candidates for anomalous Cepheids in the SMC

Star name	RA [J2000.0]	DEC [J2000.0]	Pulsation Mode	P [days]	$\langle I\rangle$ [mag]	$\langle V\rangle$ [mag]
OGLE-SMC-CEP-0366	$00^h40^m36\overset{s}{.}07$	$-72°38'04\overset{''}{.}2$	1O	0.6209232	18.254	18.611
OGLE-SMC-CEP-0677	$00^h44^m42\overset{s}{.}95$	$-73°11'26\overset{''}{.}8$	F	0.8278529	18.460	19.167
OGLE-SMC-CEP-2343	$00^h55^m07\overset{s}{.}45$	$-72°44'34\overset{''}{.}1$	1O	0.5703437	18.342	18.779
OGLE-SMC-CEP-2740	$00^h57^m46\overset{s}{.}17$	$-72°14'33\overset{''}{.}6$	F	0.8297559	18.249	18.835
OGLE-SMC-CEP-3540	$01^h03^m45\overset{s}{.}77$	$-73°53'09\overset{''}{.}8$	1O	0.5208060	18.387	18.794
OGLE-SMC-CEP-4608	$01^h22^m07\overset{s}{.}39$	$-71°31'47\overset{''}{.}9$	F	1.2563281	17.819	18.256

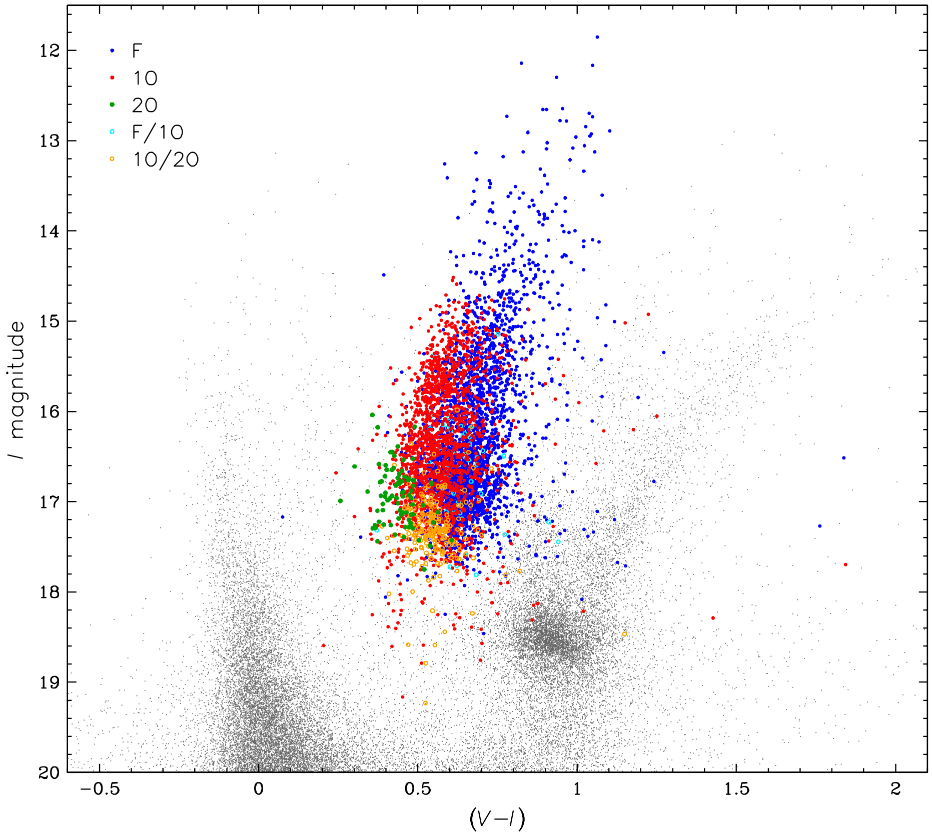

Fig. 1. Color–magnitude diagram for classical Cepheids in the SMC. Blue symbols show single-mode F Cepheids, red – 1O, green – 2O, cyan – double-mode F/1O and orange – 1O/2O pulsators. The background gray points show stars from the subfield SMC100.1.

provided in the GCVS are daily aliases of the real periods. The remaining stars categorized as anomalous Cepheids in the GCVS have periods below 1 day and are brighter than classical Cepheids with similar periods. These are likely Galactic

RR Lyr stars in the foreground of the SMC. It is worth noting that recently Bernard *et al.* (2010) reported the absence of anomalous Cepheids in another metal-poor galaxy – IC 1613. This fact may indicate that anomalous Cepheids avoid galaxies such as SMC or IC 1613, or that in these galaxies anomalous Cepheids are indistinguishable from short-period classical Cepheids.

The final list of classical Cepheids was prepared after careful visual inspection of the light curves, mean brightness and colors of the stars, including near-infrared magnitudes from the IRSF/SIRIUS survey (Kato *et al.* 2007). We also utilized the information about proper motions of stars archived in the OGLE databases to remove a few evident Galaxy members from the list of candidates for SMC Cepheids. We believe the sample of Cepheids published in this catalog is very clean, although it includes several doubtful objects, *e.g.*, stars which obey the PL relations in each bandpass, but show unusual light curves. Several objects show Cepheid-like light curves, but they are located outside the instability strip in the color–magnitude diagram (CMD, Fig. 1). The photometry of these stars may be affected by a strong reddening or by crowding. We mark these objects as "uncertain" in the catalog remarks.

The division into fundamental-mode (F) and first-overtone (1O) pulsators was performed based on both, the position in the PL diagrams and the light curve morphology represented by the Fourier coefficients. Figs. 2 and 3 show Fourier parameters R_{21}, ϕ_{21}, R_{31} and ϕ_{31} (Simon and Lee 1981) plotted as a function of $\log P$. When the amplitude of the first (second) harmonic is statistically insignificant, then $R_{21} = 0$ ($R_{31} = 0$) and ϕ_{21} (ϕ_{31}) is undefined. Our catalog includes several variables with atypical light curves that do not match the patterns visible in Figs. 2 and 3. Their position in the PL diagram does not always unambiguously indicate the mode of pulsation, because of the overlap between PL sequences. Thus, our classification may be uncertain for several single-mode Cepheids in the SMC.

We paid special attention to single-mode second-overtone (2O) Cepheids. Udalski *et al.* (1999b) identified 13 such stars in the SMC, while in the LMC we found 14 Cepheids pulsating solely in the second overtone (Paper I). As a result of our selection process in the SMC, we found a considerable number of periodic stars with nearly sinusoidal light curves, relatively small amplitudes ($A_I < 0.14$ mag), located just above the PL relation of 1O Cepheids and at the blue edge of the instability strip in the CMD (Fig. 1). These stars have been recognized as 2O Cepheids. Our catalog includes 83 firm candidates for 2O pulsators with periods in the range of 0.40–0.92 days. This is, obviously, the largest sample of single-periodic second overtone Cepheids detected so far.

The SMC hosts proportionally much larger number of 2O Cepheids (1.8%) than the LMC (0.4%). Bernard *et al.* (2010) identified two second-overtone pulsators (4%) among 49 classical Cepheids in the IC 1613. This confirms the suggestion of Antonello and Kanbur (1997) that 2O Cepheids are more common in metal-poor environments.

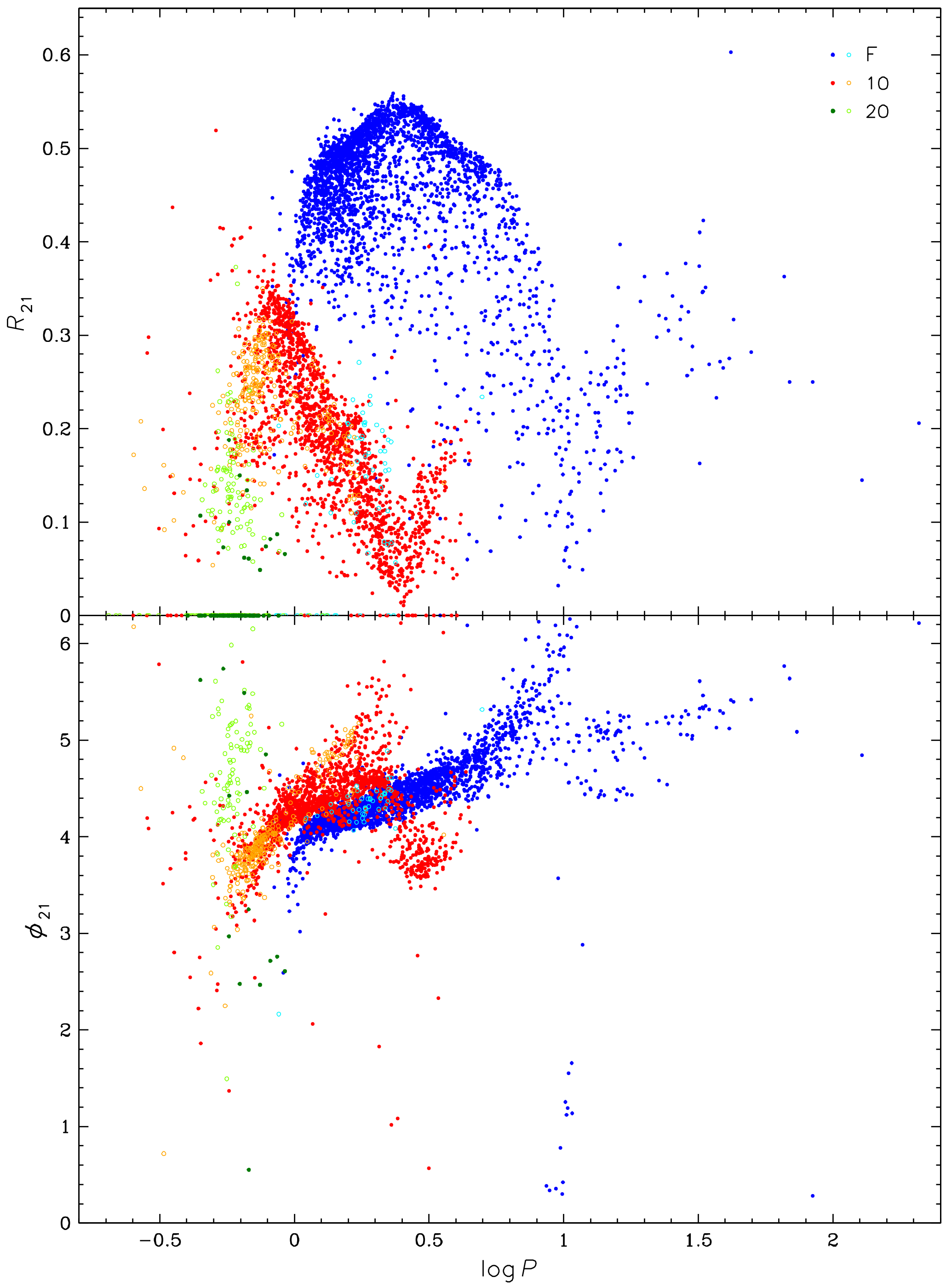

Fig. 2. Fourier parameters R_{21} and ϕ_{21} *vs.* $\log P$ for classical Cepheids in the SMC. Blue, red, and dark-green solid circles mark F, 1O and 2O single-mode Cepheids, respectively. Cyan, orange and light-green empty circles represent F, 1O and 2O modes from double-mode Cepheids (two points per star).

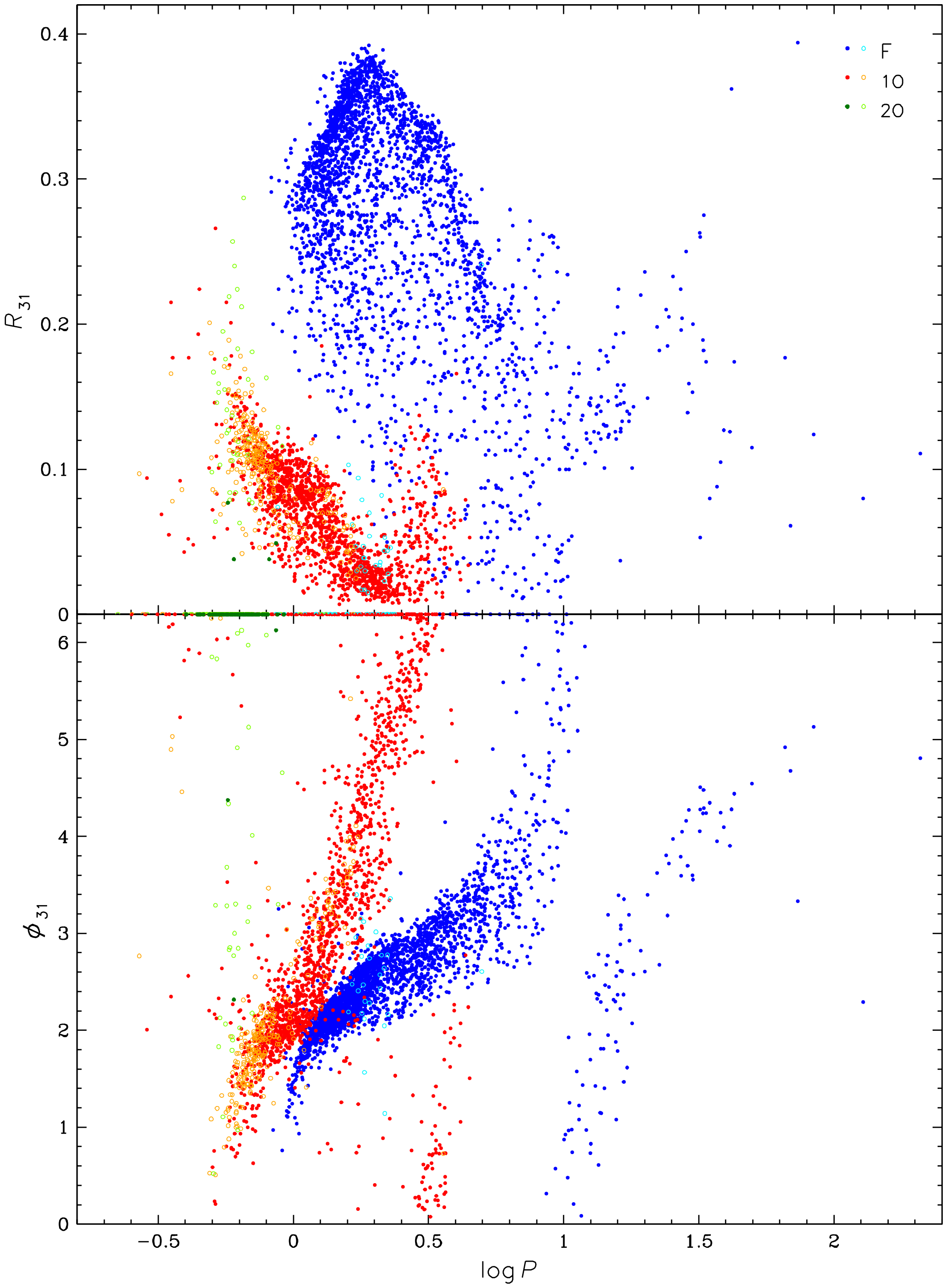

Fig. 3. Fourier parameters R_{31} and ϕ_{31} *vs.* $\log P$ for classical Cepheids in the SMC. Color symbols represent the same modes of pulsation as in Fig. 2.

3.2. Multimode Cepheids

Multimode pulsating stars are very valuable objects, because each mode gives independent constraints on stellar parameters (*e.g.*, Buchler and Szabó 2007, Dziembowski and Smolec 2009a). First double-mode Cepheids (called also beat Cepheids) in the SMC were discovered by Beaulieu *et al.* (1997), who reported the sample of 4 stars beating in the fundamental mode and first overtone (F/1O) and 7 first/second overtone (1O/2O) pulsators. Then, the list of double-mode Cepheids in the SMC was extended by Alcock *et al.* (1997, 7 F/1O and 20 1O/2O Cepheids), Udalski *et al.* (1999a, 23 F/1O and 70 1O/2O Cepheids) and Marquette *et al.* (2009, 41 F/1O and 129 1O/2O Cepheids).

Double-mode Cepheids presented in this catalog were identified with two methods. First, we used the periods derived for all stars observed in the SMC to select objects with two primary periods typical for beat Cepheids. The light curves of the tentatively selected objects were inspected by eye and some of them were judged to be F/1O or 1O/2O Cepheids. Second, we tested the secondary periods of all previously identified Cepheids. Each light curve was fitted with a Fourier series with a number of harmonics minimizing the χ^2 per degree of freedom, the function was subtracted from the observational data and the period search was performed on the residual data. We visually examined the light curves with characteristic period ratios and those with the largest S/N of the secondary periods. This iterative procedure was repeated several times on each light curve, to ensure that we found all double-mode Cepheids and to identify possible triple-mode pulsators.

Sometimes the Cepheids in our database presented very high rates of period changes. In such cases the secondary periods were usually very close to the primary ones. To search for beat Cepheids among these objects we performed an additional procedure. For each Cepheid the photometry was divided into individual observing seasons and the periods were adjusted separately for each of these chunks. Then, these periods were used to prewhiten the light curves independently in each season, and the frequency analysis was carried out on the residual data. In this way we identified several additional double-mode Cepheids.

In total, we detected 59 F/1O, 215 1O/2O and three triple-mode Cepheids in the SMC. The Petersen diagram (shorter-to-longer period ratio *vs.* the logarithm of the longer period) is shown in Fig. 4. The number of multimode Cepheids in the SMC is almost the same as in the LMC (61 F/1O, 206 1O/2O, two 1O/3O and five triple-mode Cepheids), but, naturally, their incident rate (6%) is smaller than in the LMC (8%), because the total number of classical Cepheids in the SMC is larger than in the LMC. We draw the reader's attention to the exceptionally long-period F/1O Cepheid OGLE-SMC-CEP-1497, with the fundamental-mode period of about 5 days, but connected with an extremely small (and thus uncertain) amplitude of about 0.008 mag. A similar outlying F/1O Cepheid (of even longer periods) was found in the LMC (Paper I). Another interesting object among double-mode Cepheids is OGLE-SMC-CEP-0998 – the only 1O/2O Cepheid in both Magellanic

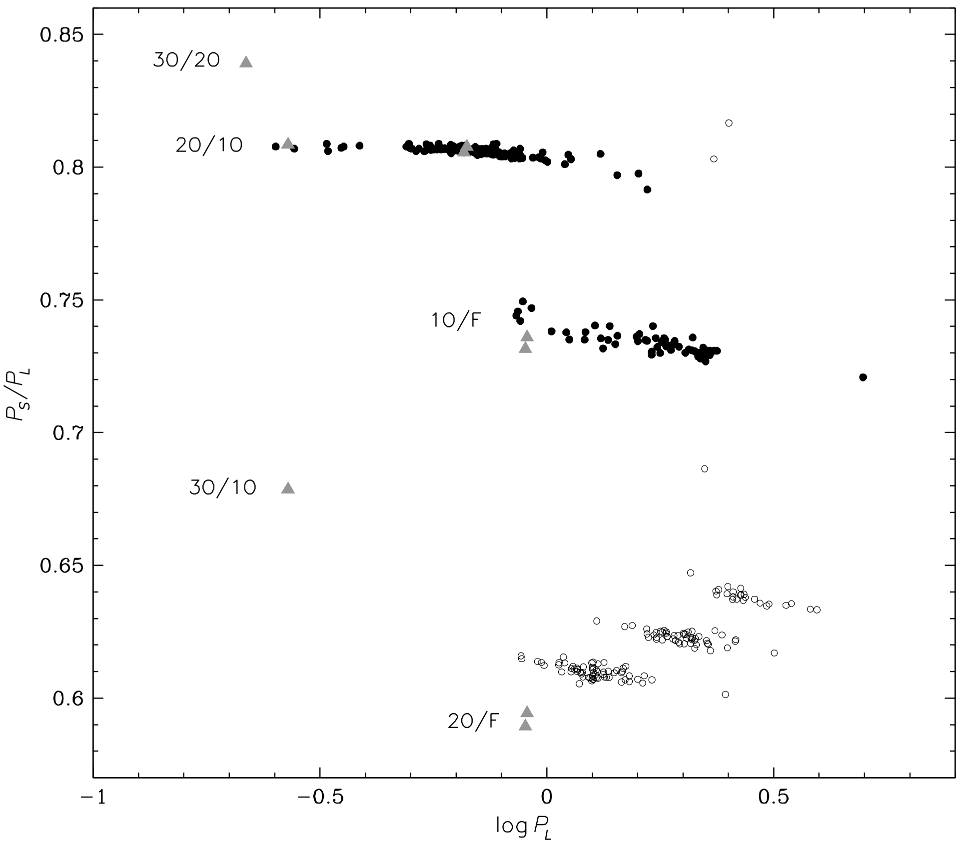

Fig. 4. Petersen diagram for multiperiodic Cepheids in the SMC. Solid dots represent double-mode (F/1O and 1O/2O) Cepheids, gray triangles show triple-mode Cepheids (three points per star) and empty circles show selected other stars with significant secondary periods.

Clouds with the second-overtone dominating over the first overtone.

The main observational properties of the three candidates for triple-mode Cepheids in the SMC are summarized in Table 2. Fig. 5 shows their light curves folded with three primary periods, each one after prewhitening with the other two modes. As one can see, the dominant periods of these stars are always related to the first-overtone mode, just like in the five known triple-mode Cepheids in the LMC (Soszyński *et al.* 2008a). The mode identification in our triple-mode Cepheids relies on their position in the Petersen diagram (gray triangles in Fig. 4). Two stars have fundamental mode, first and second overtones (F/1O/2O) excited, while one object is a 1O/2O/3O pulsator. The fundamental-mode variations in the former Cepheids are of very low amplitudes, just above the detection limits of the OGLE photometry, and should be treated as uncertain detections. The latter star is undoubtedly a triple-mode pulsator, but the periods are very short, thus it can also be classified as a δ Sct star. As we pointed out already, the nomenclature is a matter of convention.

Table 2

Candidates for triple-mode Cepheids in the SMC

F/1O/2O Cepheids

Star name	$\langle I\rangle$ [days]	$\langle V\rangle$ [mag]	P_F [days]	A_I^F [mag]	P_{1O} [days]	A_I^{1O} [mag]	P_{2O} [mag]	A_I^{2O} [mag]
OGLE-SMC-CEP-1077	17.599	18.137	0.89734	0.018	0.6565184	0.301	0.528880	0.046
OGLE-SMC-CEP-1350	17.471	18.087	0.90494	0.010	0.6659937	0.239	0.537878	0.057

1O/2O/3O Cepheid

Star name	$\langle I\rangle$ [days]	$\langle V\rangle$ [mag]	P_{1O} [days]	A_I^{1O} [mag]	P_{2O} [days]	A_I^{2O} [mag]	P_{3O} [mag]	A_I^{3O} [mag]
OGLE-SMC-CEP-3867	18.585	19.055	0.2688471	0.269	0.2173800	0.052	0.1824204	0.058

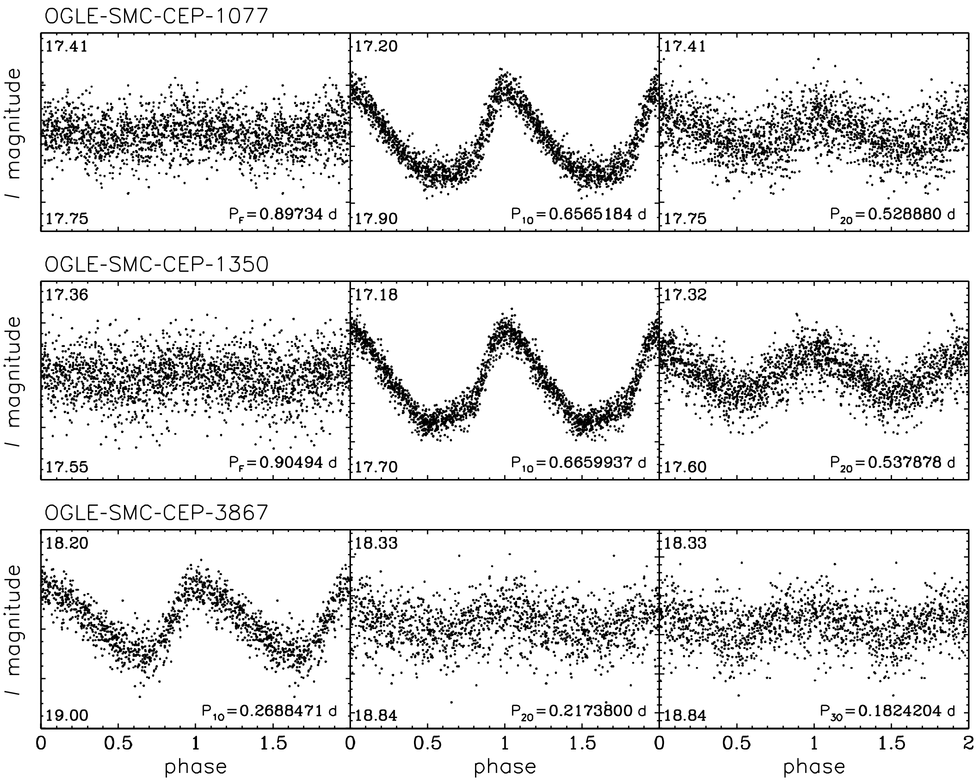

Fig. 5. *I*-band light curves of triple-mode Cepheids in the SMC. Each mode is shown after prewhitening with the other two modes. Note that the range of magnitudes varies from panel to panel. Numbers in the left corners show the lower and the upper limits of magnitudes.

Table 3

Double Cepheids in the SMC

Star name	Mode of Cepheid 1	P_1 [days]	Mode of Cepheid 2	P_2 [days]
OGLE-SMC-CEP-1526	F	1.2902286	F	1.8043107
OGLE-SMC-CEP-2699	F	2.1174814	1O	2.5623049
OGLE-SMC-CEP-2893	F	1.3215528	F	1.1358572
OGLE-SMC-CEP-3115	F	1.2519421	F	1.1597911
OGLE-SMC-CEP-3674	F	2.8960473	1O	1.8277592

Table 4

Cepheids with additional eclipsing variability

Star name	Pulsation Mode	$P_{\rm cep}$ [days]	$P_{\rm ecl}$ [days]	$A_I^{\rm ecl}$ [mag]	$T_{\rm min}^{\rm ecl}$ [HJD]
OGLE-SMC-CEP-0411	1O	1.1009833	43.4979	0.102	2450626.7133
OGLE-SMC-CEP-1996	1O	2.3179487	95.5944	0.018	2450424.4961

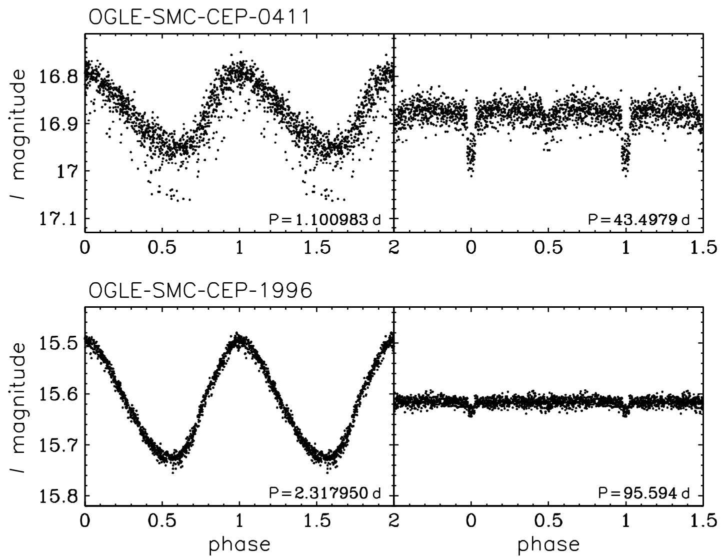

Fig. 6. Light curves of Cepheids with additional eclipsing variability. *Left panels* show the original photometric data folded with the Cepheid periods. *Right panels* show the eclipsing light curves after subtracting the Cepheid component. The ranges of magnitudes are the same in each pair of the panels.

During our search for multiperiodicity we found a considerable number (139 objects) of first-overtone Cepheids with additional small-amplitude ($A_I < 0.015$ mag) modulation with periods of about 0.60–0.65 of the dominant ones. These stars follow three distinct sequences in the Petersen diagram (Fig. 4). The first stars of this kind were discovered in the LMC by Moskalik and Kołaczkowski (2008). In Paper I we identified over 30 such Cepheids in the LMC and noticed that these stars follow two sequences in the Petersen diagram. In the SMC we identified three sequences and a much bigger number of stars of that type, but the origin of these secondary periods remains a mystery (Dziembowski and Smolec 2009b).

As a by-product of our analysis we found five double Cepheids – unresolved pairs of Cepheids which may be physically related. Only one object of that type (OGLE-SMC-CEP-1526 = SMC_SC5_208044) was known before in the SMC (Udalski *et al.* 1999a). Table 3 lists all double Cepheids in our catalog. Information about these objects is also given in the remarks.

Two of our Cepheids show additional eclipsing variations superimposed on the pulsational light curves. These objects may be optical blends of a Cepheid and eclipsing variable, or the pulsating star may be a member of the eclipsing binary system. Table 4 presents periods, amplitudes and epochs of the minimum light of the eclipsing variability in these potentially interesting objects. Fig. 6 presents the original photometry folded with the Cepheid periods and the residual data (after subtracting the pulsations) phased with the eclipsing periods. Note, the eclipses in OGLE-SMC-CEP-1996 are very shallow, at the level of about 0.018 mag.

Finally, a significant number of Cepheids exhibit secondary periods very close to the primary ones. After the first iteration of the multiperiod analysis (*i.e.*, after prewhitening with the primary period), such a behavior was observed for about 2% of F, 33% of 1O and 24% of 2O Cepheids. The period ratios of about 1 may indicate non-radial pulsations, but it may also be an indicator of Cepheids with high rates of period changes. Poleski (2008) showed that the latter behavior is very common among LMC Cepheids, in the SMC it may be even more frequent.

4. The Catalog of Classical Cepheids in the SMC

The OGLE-III catalog of classical Cepheids in the SMC contains 4630 stars: 2626 fundamental-mode, 1644 first-overtone, 83 second-overtone, 59 double-mode F/1O, 215 double-mode 1O/2O, two triple-mode F/1O/2O and one triple-mode 1O/2O/3O Cepheids. The catalog data are available through the user-friendly WWW interface or by the anonymous FTP site:

http://ogle.astrouw.edu.pl/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/smc/cep/

The FTP site is organized as follows. The file named ident.dat contains the full list of Cepheids. The variables have been numbered in order of increasing right ascension and designated as OGLE-SMC-CEP-NNNN, where NNNN is a four-digit number. The consecutive columns of the ident.dat file contain: the object designation, OGLE-III field and internal database number of a star (consistent with the photometric maps of the SMC by Udalski *et al.* 2008b), mode(s) of pulsation (F, 1O, 2O, F/1O, 1O/2O, F/1O/2O, or 1O/2O/3O), equinox J2000.0 right ascension and declination, cross-identifications with the OGLE-II catalog of Cepheids in the SMC (Udalski *et al.* 1999abd), cross-identifications with the extragalactic part of the GCVS (Artyukhina *et al.* 1995), and other designations taken from the GCVS. Stars without the internal OGLE-III number provided have no counterparts in the SMC photometric maps. These are usually bright saturated objects, only with the DoPhot photometry available.

Files cepF.dat, cep1O.dat, cep2O.dat, cepF1O.dat, cep1O2O.dat, cepF1O2O.dat, and cep1O2O3O.dat contain observational properties of the single-, double- and triple-mode Cepheids with the corresponding modes excited. We provide there: the intensity mean magnitudes in the *I*- and *V*-bands, periods in days and their uncertainties (derived with the Tatry code of Schwarzenberg-Czerny 1996), epochs of maximum light, peak-to-peak amplitudes in the *I*-band, and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} derived for *I*-band light curves.

The remarks.txt file contains additional information on some Cepheids: comments about uncertain classifications, high rates of period change, blends, additional periods, etc. The subdirectory phot/ contains multi-epoch *I*- and *V*-band OGLE photometry of the stars. If available, the OGLE-II data have been merged with the OGLE-III photometry. The subdirectory fcharts/ contains finding charts of all objects. These are the $60'' \times 60''$ subframes of the *I*-band DIA reference images, oriented with N up, and E to the left.

Fig. 7 illustrates typical *I*-band light curves of single-mode Cepheids in our sample. Two of the brightest light curves were obtained with the DoPhot package on partly saturated stars, therefore this photometry is more scattered than the regular OGLE data. The Hertzsprung progression (Hertzsprung 1926) of the light curve shapes is clearly visible for F Cepheids.

The spatial distribution of classical Cepheids in the SMC is presented in Fig. 8. Bottom panels show surface density maps for fundamental-mode Cepheids with periods shorter (left panel) and longer (right panel) than 8 days. The distribution of fundamental-mode Cepheids is highly correlated with their periods. The longer-period Cepheids are concentrated toward the bar of the SMC, while the shorter-period pulsators are distributed more homogeneously over the galaxy.

As a test of completeness we cross-identified the preliminary version of our catalog with the largest sample of Cepheids in the SMC published to date – the OGLE-II catalog of Cepheids (Udalski *et al.* 1999abd). We did not find counterparts for 19 objects from the OGLE-II list. Seven of the missing Cepheids were saturated in the OGLE-III DIA database, and in the final version of the OIII-CVS we included the DoPhot photometry for these stars. Further ten objects have been

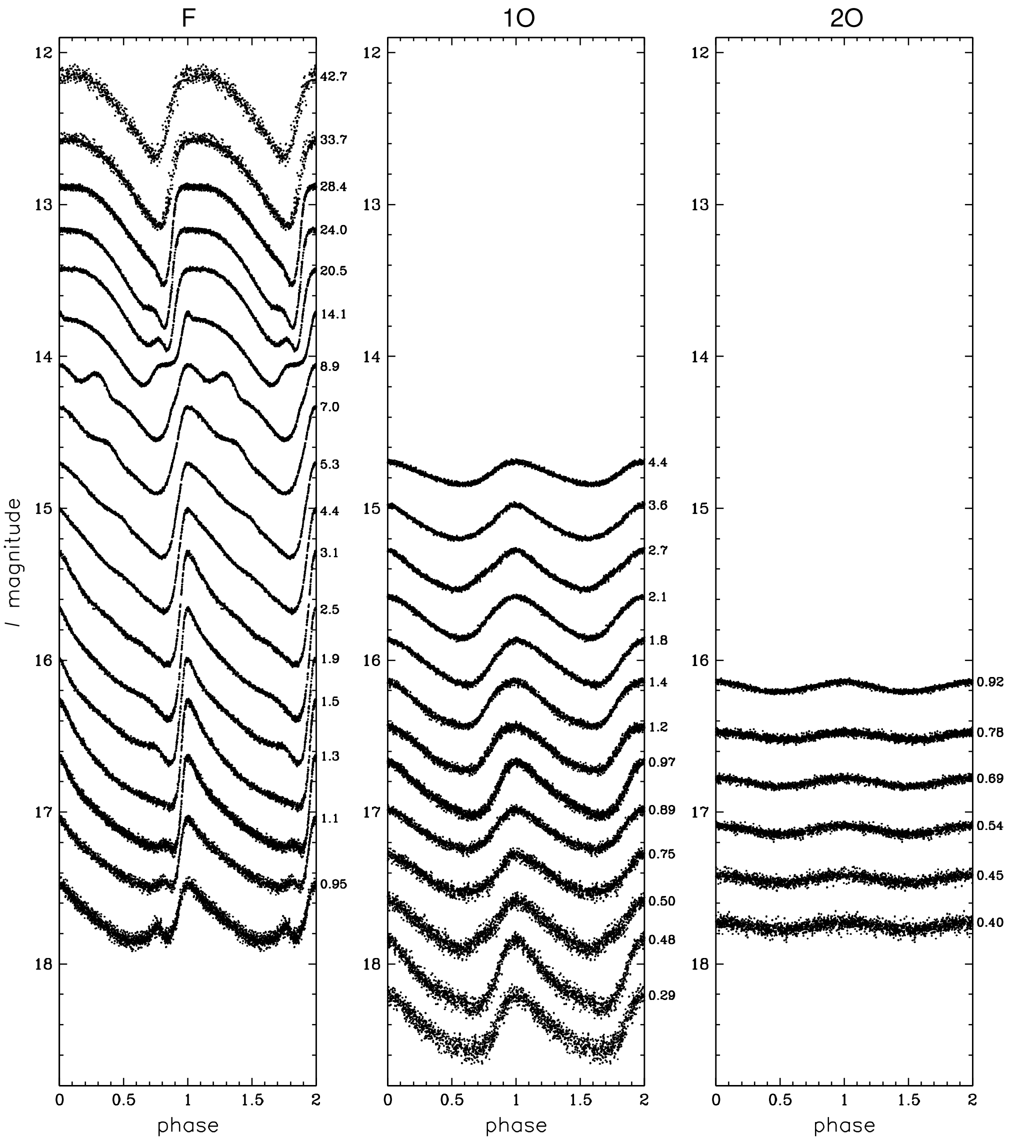

Fig. 7. Examples of light curves of single-mode Cepheids in the SMC. *Left panel* presents fundamental-mode stars, *middle panel* – first-overtone, and *right panel* – second-overtone pulsators. Small numbers at the right side of each panel show the rounded periods in days of the light curves presented in panels.

reclassified as non-Cepheid variables (usually as ellipsoidal variables). Only two missing stars occurred to be unsaturated classical Cepheids, both were affected by a poor quality of the photometry due to the neighborhood of a very bright star. The missing Cepheids were added to the final version of our catalog.

We also compared our list of double-mode Cepheids with the EROS-2 catalog of 41 F/1O and 129 1O/2O Cepheids by Marquette *et al.* (2009). Four EROS-2 double-mode Cepheids lie outside the OGLE-III fields. Our catalog contains all

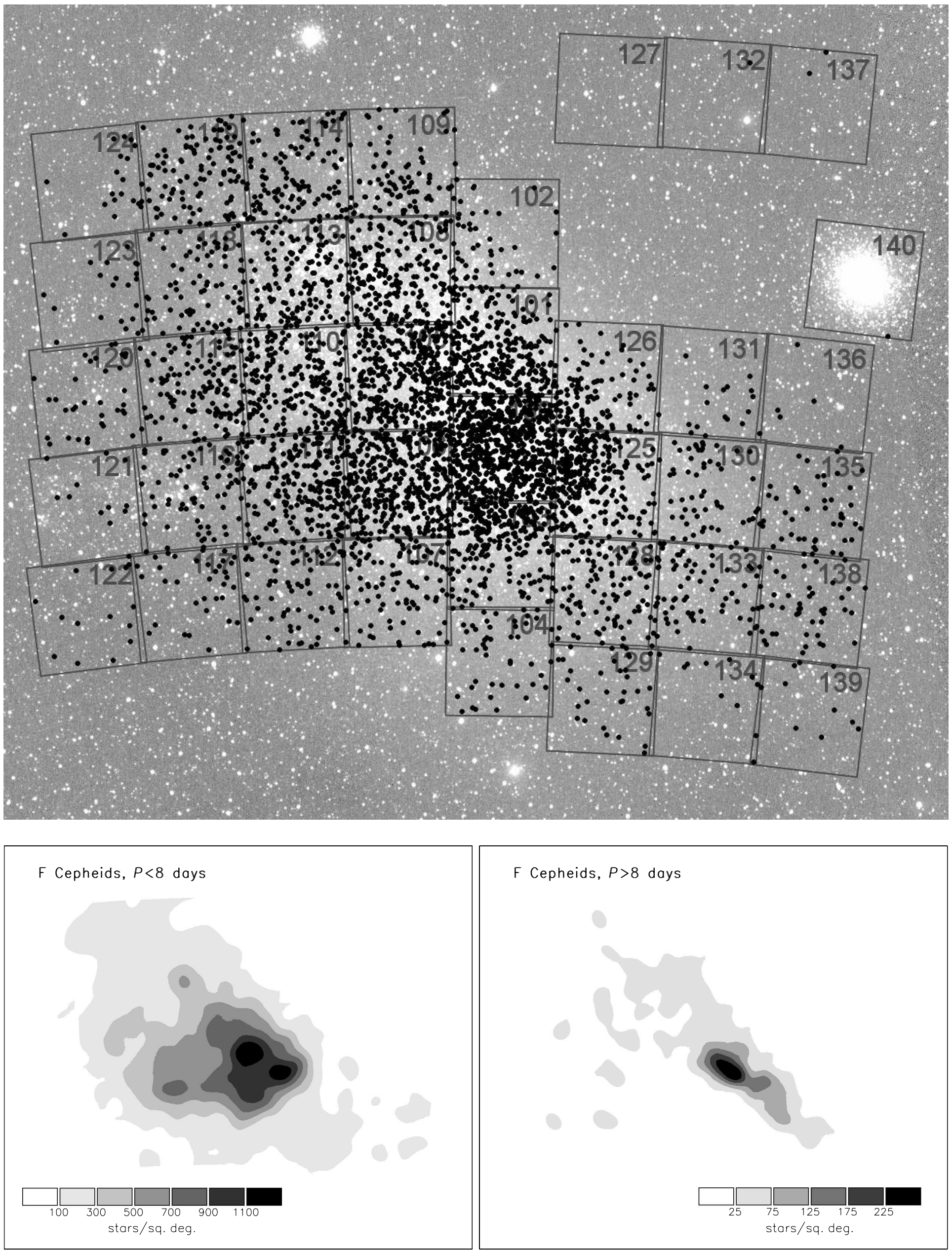

Fig. 8. Spatial distribution of classical Cepheids in the SMC. The background image in the *upper panel* is originated from the ASAS wide field sky survey (Pojmański 1997). The contours show OGLE-III fields. *Bottom panels* show the distribution of fundamental-mode Cepheids with $P<8$ days (*left panel*) and $P>8$ days (*right panel*).

the remaining stars, but three of them were not classified as double-mode Cepheids. One objects was recognized in our catalog as a superposition of two Cepheids (double Cepheid), in two other cases we could not identify the secondary mode in the OGLE data. The tests show that our catalog of classical Cepheids in the SMC is practically complete in the regions covered by the OGLE-III fields.

5. Comparison of the SMC and LMC Cepheids

The large and complete samples of variable stars presented in the OIII-CVS give an opportunity to compare various stellar populations in the LMC, SMC and, in the future, in the Galaxy. Fig. 9 shows period distributions of single-mode Ce-

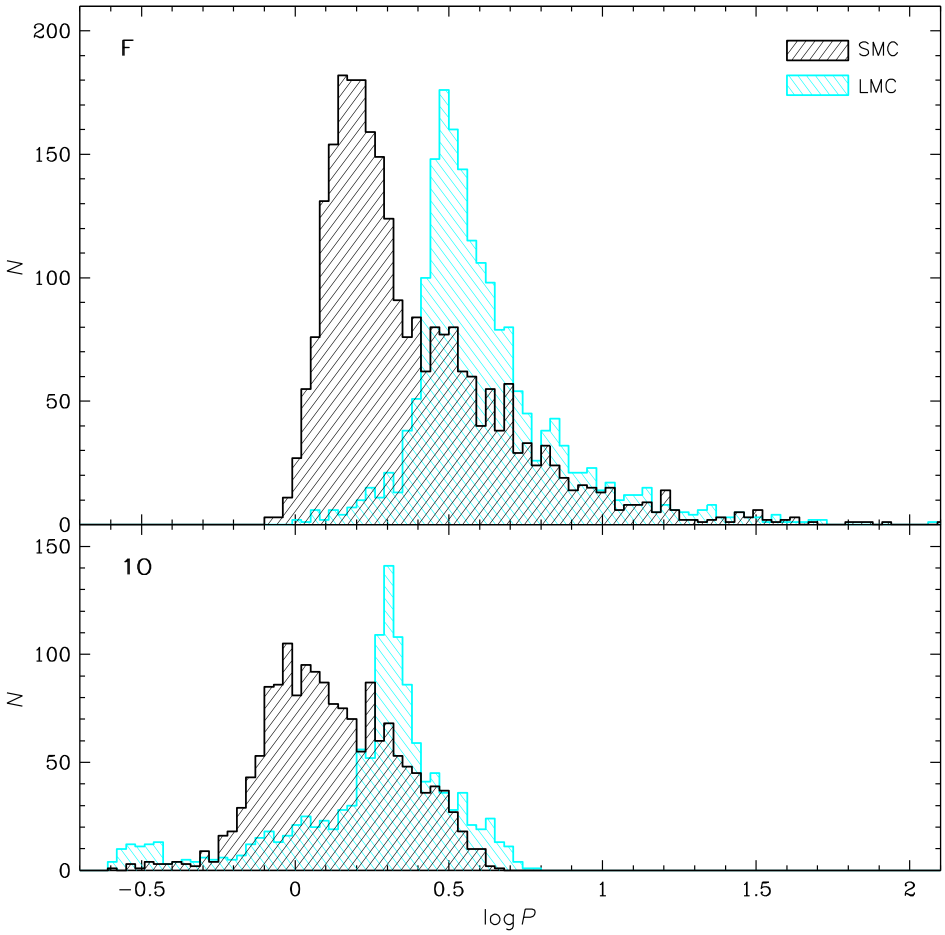

Fig. 9. Period distribution of single-mode Cepheids in the SMC (black) and LMC (cyan). *Upper panel* shows fundamental-mode, and *bottom panel* – first-overtone Cepheids.

pheids in both Magellanic Clouds, separately for the fundamental mode and first overtone. In Fig. 10 we compare the *I*-band apparent mean magnitude distributions of the same samples. There is no doubt that LMC and SMC host two different populations of classical Cepheids. In the SMC there are many more short-period and fainter Cepheids in each pulsation mode. This difference in the period distribution may be explained by different metal abundances in both galaxies (Hofmeister 1967, Becker *et al.* 1977). The low-massive metal-poor stars experience more extended blue loop excursion during their evolution in the HR diagram. Thus, in the metal-poor environments (like in the SMC) the low-mass cut-off for the Cepheids crossing the instability strip for the second and the third time is lower than in the more metal-rich galaxies (like in the LMC).

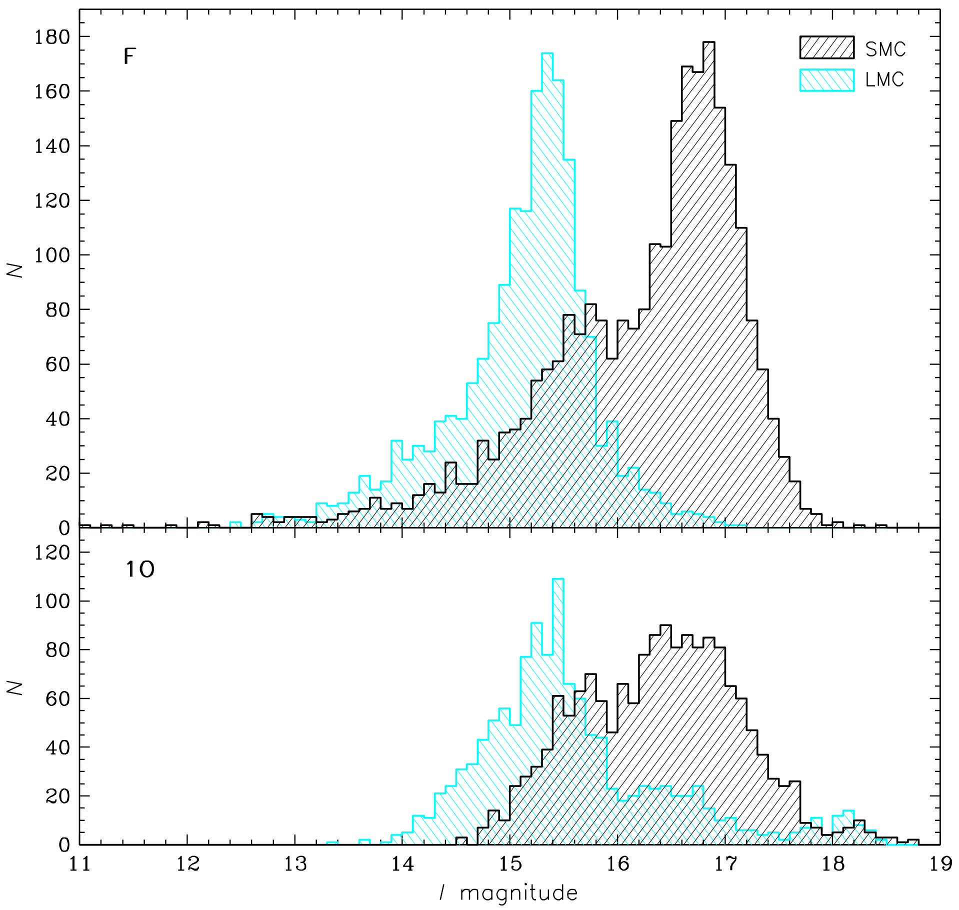

Fig. 10. Distribution of mean I-band magnitudes of single-mode Cepheids in the SMC (black) and LMC (cyan). *Upper panel* shows fundamental-mode, and *bottom panel* – first-overtone Cepheids.

However, the period and luminosity distributions of fundamental-mode Cepheids in the SMC seem to have two maxima: the main peak is at $\log P \approx 0.2$ ($I \approx 16.8$ mag) and the secondary maximum is at $\log P \approx 0.5$ ($I \approx 15.8$ mag). The latter maximum is the same as the main frequency peak of the LMC Cepheids (for magnitudes one has to apply appropriate shift of about 0.4 mag to compensate different distances and reddenings toward both Clouds). The first-overtone pulsators seem to have three maxima in the period and luminosity distributions in both galaxies: at $\log P \approx -0.5$, $\log P \approx 0.0$, and $\log P \approx 0.3$. The difference between LMC and SMC lays in different numbers of Cepheids in every group.

We conclude that each of the Magellanic Clouds hosts two or three different populations of classical Cepheids, which differ in periods, luminosities and also probably in metal abundances and ages. The spatial distribution of Cepheids in the SMC, which is different for short- and long-period Cepheids, confirms this conclusion. In both galaxies we can find representatives of each population of Cepheids, but the LMC prefers the long-period pulsators, while in the SMC the short-period Cepheids dominate.

6. Period–Luminosity Relation

The PL relations for classical Cepheids are one of the most powerful tools to measure distances within and outside the Galaxy. The Magellanic Clouds play an unique role in the calibrations of PL relations, because both galaxies are at small distances to us, have different metal abundance, and host very rich populations of Cepheids.

The PL diagrams in the *V*- and *I*-band magnitudes and in the W_I Wesenheit index are shown in Fig. 11. The scatter of the relations is generally larger than in the LMC (Paper I), because the SMC is thought to have larger depth along the line of sight. However, in the LMC we observed more individual Cepheids located significantly below the $\log P{-}I$ and $\log P{-}V$ relations, *i.e.*, objects suffering from heavy reddening. It shows that the spatial distribution of interstellar matter in the SMC is more homogeneous than in the LMC. The points located above the appropriate PL relations are usually affected by blending.

The fundamental-mode Cepheids show a break in the slope of the PL relation for a period of about 2 days. This non-linearity was first reported by Bauer *et al.* (1999) and confirmed by Udalski *et al.* (1999c), Sharpee *et al.* (2002) and Sandage *et al.* (2009). This feature may be another clue that the SMC hosts at least two populations of classical Cepheids – stars with shorter periods have a different chemical composition and thus obey a different PL law.

The non-linear relation between $\log P$ and luminosities of Cepheids in the SMC complicates the efforts to compare PL laws in various environments. Following Udalski *et al.* (1999c) and Sandage *et al.* (2009) we removed from our solution all F Cepheids with $\log P < 0.4$. We also excluded from the sample several of the longest-period Cepheids that saturate on the OGLE frames. We take no account for possible break of the linearity of the PL relation at $P = 10$ days for F Cepheids (Sandage *et al.* 2009). The PL relations provided below are not compensated for interstellar extinction, so for the $\log P{-}I$ and $\log P{-}V$ relations we can compare the slopes of the relations only.

The least squares solution with 3σ clipping gives the following PL relations

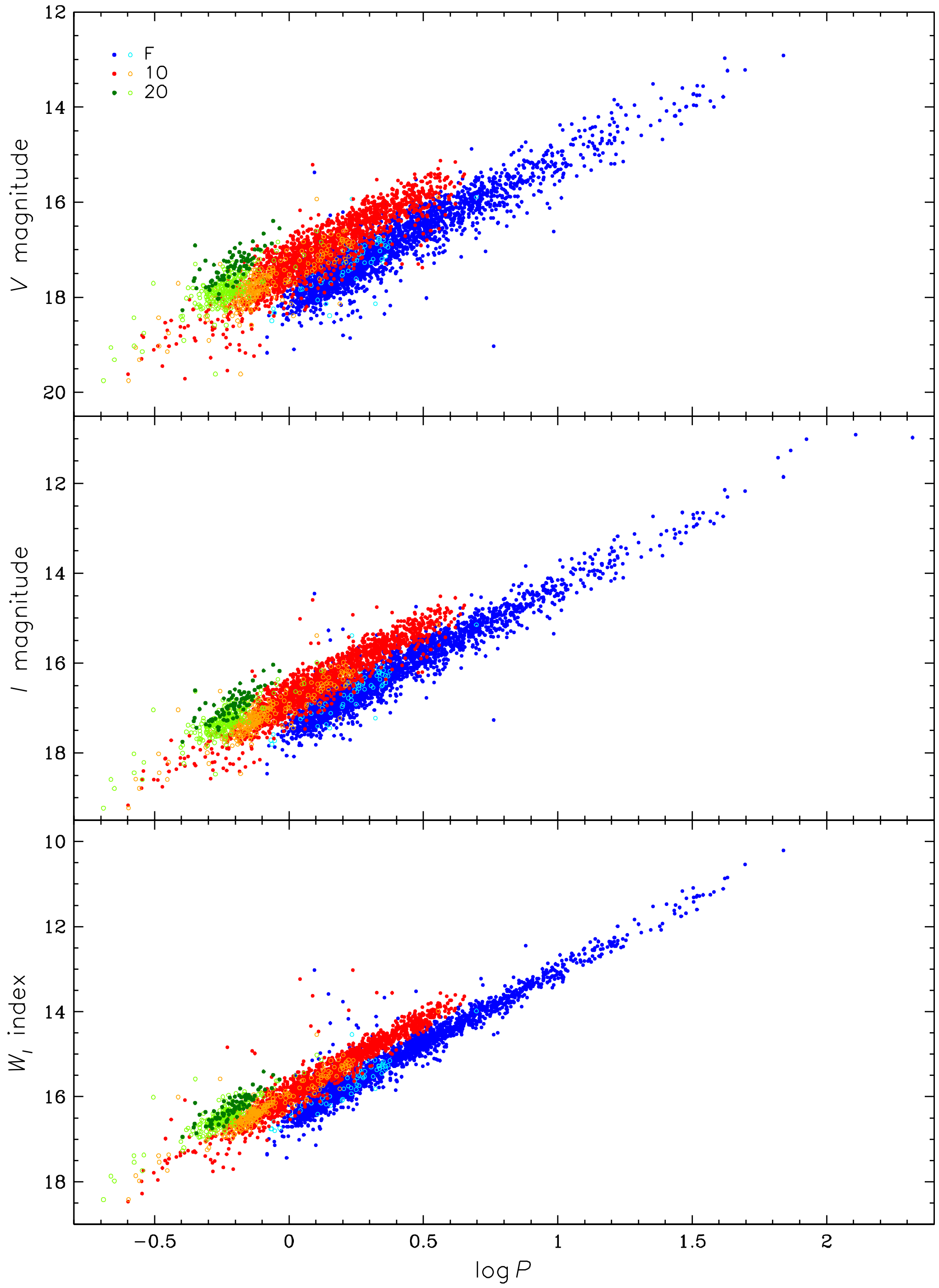

Fig. 11. Period–luminosity relations for classical Cepheids in the SMC. The color symbols are the same as in Fig. 2.

for single-mode fundamental-mode classical Cepheids in the SMC:

$$\begin{aligned} V &= -2.646(\pm 0.036)\log P + 17.792(\pm 0.026) \qquad \sigma = 0.28 \text{ mag} \\ I &= -2.908(\pm 0.029)\log P + 17.240(\pm 0.021) \qquad \sigma = 0.22 \text{ mag} \\ W_I &= -3.326(\pm 0.019)\log P + 16.383(\pm 0.014) \qquad \sigma = 0.15 \text{ mag} \end{aligned}$$

and for first-overtone Cepheids:

$$\begin{aligned} V &= -3.171(\pm 0.034)\log P + 17.372(\pm 0.008) \qquad \sigma = 0.28 \text{ mag} \\ I &= -3.349(\pm 0.027)\log P + 16.827(\pm 0.007) \qquad \sigma = 0.23 \text{ mag} \\ W_I &= -3.623(\pm 0.020)\log P + 15.971(\pm 0.005) \qquad \sigma = 0.16 \text{ mag.} \end{aligned}$$

The slopes of the PL relations agree within up to 2σ with the fits of Udalski *et al.* (1999c)[†] to the OGLE-II sample of Cepheids in the SMC (with exception of the $\log P - W_I$ relation for 1O Cepheids, where the difference is at the level of 2.4σ). It would be interesting to compare the PL relations in both Magellanic Clouds to answer the question how different metal abundances influence the PL laws of Cepheids. Recently, Sandage *et al.* (2009) stated that there is a statistically significant difference between slopes of the PL relations for LMC and SMC Cepheids. Indeed, comparing the above fits with the PL laws obeyed by the LMC fundamental-mode Cepheids (Paper I, Ngeow *et al.* 2009) we find a difference in the slopes of the $\log P - V$ relations at the level $> 3\sigma$. In the *I*-band the difference has a significance of only 1.8σ, while the $\log P - W_I$ relations for F Cepheids are statistically indistinguishable in both Clouds. For the first-overtone Cepheids the *V*-band PL relations in the LMC and SMC are almost the same, the *I*-band relations differ at the level of about 2σ, while the $\log P - W_I$ relations differ very significantly, at the level of $> 8\sigma$.

7. Conclusions

In this paper we described the catalog of 4630 classical Cepheids in the SMC. This is the largest set of Cepheids detected so far in any environment. We make available to the astronomical community a precise, standard *VI* photometry of these stars collected within 8 (OGLE-III) or 13 (OGLE-II + OGLE-III) years of observations. These data may be utilized for studying many fundamental problems, such as the universality of the PL and PLC relations, the accuracy of stellar modeling, the structure and history of the SMC. With the OGLE-III catalog of 3375 classical Cepheids in the LMC (Paper I) our samples provide a unique opportunity to perform detailed comparative studies between both populations.

[†]the revised coefficients of the fit are available from:
ftp://ftp.astrouw.edu.pl/ogle/ogle2/var_stars/smc/cep/catalog/README.PL

Among large number of variable stars one can discover very rare objects and phenomena. Our preliminary analysis described in this paper revealed extraordinarily large set of single-mode second-overtone Cepheids, three triple-mode pulsators, two classical Cepheids with eclipses, and five double Cepheids. We discovered a large number 1O Cepheids with additional periods of about 0.60–0.65 of the primary ones.

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