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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. II. Type II Cepheids and Anomalous Cepheids in the Large Magellanic Cloud*

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ABSTRACT

In the second part of the OGLE-III Catalog of Variable Stars (OIII-CVS) we present 197 type II Cepheids and 83 anomalous Cepheids in the Large Magellanic Cloud (LMC). The sample of type II Cepheids consists of 64 BL Her stars, 96 W Vir stars and 37 RV Tau stars. Anomalous Cepheids are divided into 62 fundamental-mode and 21 first-overtone pulsators. These are the largest samples of such types of variable stars detected anywhere outside the Galaxy.

We present the period–luminosity and color–magnitude diagrams of stars in the sample. If the boundary period between BL Her and W Vir stars is adopted at 4 days, both groups differ significantly in $(V-I)$ colors. We identify a group of 16 peculiar W Vir stars with different appearance of the light curves, brighter and bluer than ordinary stars of that type. Four of these peculiar W Vir stars show additional eclipsing modulation superimposed on the pulsation light curves. Four other stars of that type show long-period secondary variations which may be ellipsoidal modulations. It suggests that peculiar W Vir subgroup may be related to binarity. In total, we identified seven type II Cepheids simultaneously exhibiting eclipsing variations which is a very large fraction compared to classical Cepheids in the LMC. We discuss diagrams showing Fourier parameters of the light curve decomposition against periods. Three sharp features interpreted as an effect of resonances between radial modes are detectable in these diagrams for type II Cepheids.

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 of Washington.

1. Introduction

Until the mid of 20th century astronomers were not aware that there exist two different types of Cepheid variables. Only after the famous distance scale revision done by Baade (1952), it became clear that Population I and II Cepheids follow different period–luminosity (PL) relations. On the average type II Cepheids are about 1.5 mag fainter than classical Cepheids of the same periods.

Type II Cepheids (also referred to as Population II Cepheids, although Feast *et al.* 2008 noted that Population II Cepheids are a subset of the type II Cepheids) consist of three subclasses in different evolutionary stages: BL Her, W Vir and RV Tau stars. The shortest-period variables – BL Her stars – are evolving from the horizontal branch toward the asymptotic giant branch (AGB). This group is sometimes called AHB stars ("above horizontal branch", Strom *et al.* 1970, Kraft 1972). The W Vir stars cross the instability strip during their blue-loop excursions from the AGB during helium-shell flashes. The brightest stars in the Population II instability strip are RV Tau stars, which are at the stage of leaving the AGB on the way to the white dwarf domain. A defining characteristic of the RV Tau stars are alternating deep and shallow minima of their light curves.

Anomalous Cepheids (sometimes called BL Boo stars) are metal-poor stars which spread between type I and type II Cepheids in the PL diagram. The pulsation masses of anomalous Cepheids are estimated to be about 1.5 $M_\odot$ (*e.g.*, Wallerstein and Cox 1984, Bono *et al.* 1997). These stars are believed to be formed through the merging of a binary star system and may be related to blue stragglers. The other possibility is that anomalous Cepheids are much younger than other metal-poor stars in their systems. Most of the known anomalous Cepheids were found in nearby dwarf spheroidal galaxies, only a few such stars were identified in globular clusters (Zinn and Dahn 1976, Kaluzny *et al.* 1997).

The first systematic search for type II Cepheids in the Large Magellanic Cloud (LMC) was performed by Hodge and Wright (1963), who surveyed the vicinities of the LMC old clusters. However, as subsequent studies showed, all of the 11 periodic variables detected by Hodge and Wright (1963) turn out to be classical Cepheids. The last object from their list – HV 12904 – was reclassified as a classical Cepheid (OGLE-LMC-CEP-0318) in the previous part of this catalog (Soszyński *et al.* 2008, hereafter Paper I). The first two reliable type II Cepheids in the LMC (HV 2351 and HV 5690) were identified by Hodge and Wright (1969). Then, the significant sample of 17 type II Cepheids in the LMC was included in the catalog of variable stars of Payne-Gaposchkin (1971). The discovery of the first RV Tau star in the LMC (HV 13066) was reported by Wright and Hodge (1971).

The next breakthrough in this field came with the large microlensing surveys: MACHO and OGLE. Alcock *et al.* (1998) presented a list of 33 W Vir and RV Tau stars in the LMC. In the PL diagram the RV Tau stars appeared to be a direct extension of other type II Cepheids to longer periods. The OGLE-II catalog of

Cepheids in the LMC (Udalski *et al.* 1999) contained 35 type II Cepheids which were compared with the bulge variables of that type by Kubiak and Udalski (2003).

Anomalous Cepheids in the LMC have been practically unknown to date. The extragalactic part of the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995) lists no such objects in the LMC. Di Fabrizio *et al.* (2005) reported the discovery of 4 anomalous Cepheids in this galaxy, but we prefer to classify these stars as RR Lyr variables (see Section 3.2).

In this paper we describe the second part of the OGLE-III Catalog of Variable Stars (OIII-CVS) containing 197 type II and 83 anomalous Cepheids in the LMC. These are the largest samples of such objects ever found in any extragalactic system. We discuss the classification criteria, present a preliminary statistical analysis of these Cepheids and show objects worth particular interest.

2. Observations and Data Reduction

OGLE-III observations were carried out with the 1.3 m Warsaw telescope at Las Campanas Observatory, Chile, operated by the Carnegie Institution of Washington. The telescope is equipped with a large field CCD mosaic camera, consisting of eight 2048×4096 pixel SITe ST002A detectors. The pixel size of each of the detectors is 15 μm giving the 0.26 arcsec/pixel scale and field of view 35×35.5 arcmins. The details of the system can be found in Udalski (2003).

The observations span 2400 days from July 2001 to March 2008. A total sky coverage in the LMC was 39.7 square degrees. The photometry of stars in the central parts of the LMC is supplemented by the OGLE-II photometry collected between 1997 and 2000. Photometry is in the standard *VI* bands with about 90% of observations (≈ 400 points per star) in the *I*-band. The exposure time was 180 sec and 225 sec in the *I*- and *V*-bands, respectively.

The photometry was obtained using the Difference Image Analysis (DIA) method – image subtraction algorithm developed by Alard and Lupton (1998) and Alard (2000), and implemented by Woźniak (2000). Udalski *et al.* (2008) gives full details of the data reduction techniques. The uncertainties of the photometry were corrected using methods developed by J. Skowron and described in Paper I.

3. Selection and Classification of Variables

3.1. *Type II Cepheids*

Type II Cepheids in the LMC were selected using the same methods as for classical Cepheids presented in the previous part of the OIII-CVS. The selection process started with a massive period search conducted at the Interdisciplinary Centre for Mathematical and Computational Modelling of Warsaw University (ICM). The calculations were performed for all stars observed by OGLE in the LMC, in total 32 million objects, using program FNPEAKS written by Z. Kołaczkowski. Then,

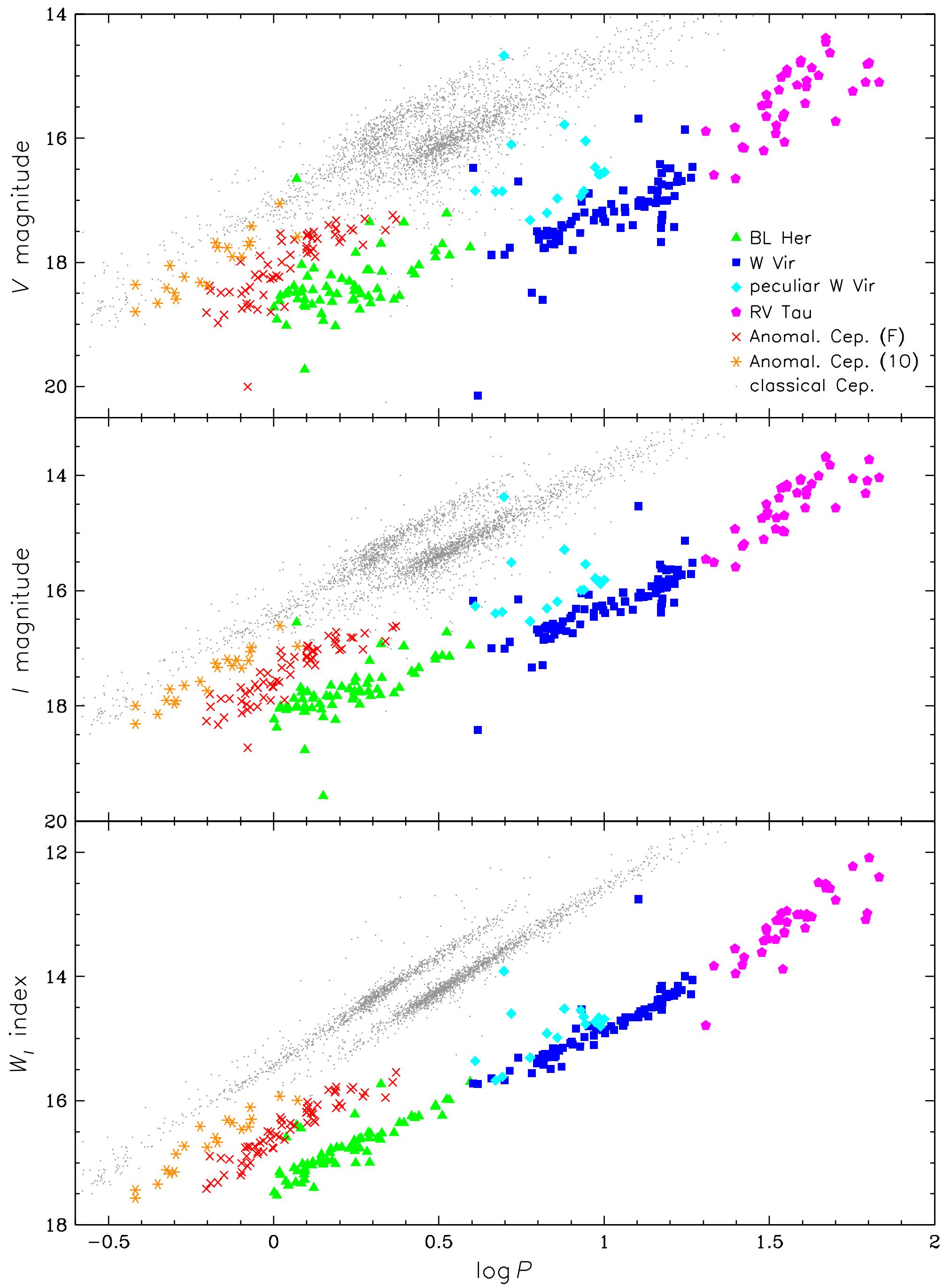

Fig. 1. Period–luminosity diagrams for Cepheids in the LMC. Green, blue, cyan and magenta symbols show type II Cepheids, red and orange – anomalous Cepheids, grey points represent classical Cepheids from Paper I.

we selected a subsample of periodic variables located in the PL diagrams inside a wide strip covering classical and type II Cepheids. We used PL diagrams plotted for the visual luminosities (V, I, Wesenheit index W_I), as well as the near-infrared magnitudes from the 2MASS Point Source Catalog (Cutri *et al.* 2003).

The light curves chosen in such a way were visually inspected and divided into three groups – pulsating-like, eclipsing-like and other variables. In the next phase the pulsating variables were tentatively categorized into classical Cepheids, type II Cepheids, anomalous Cepheids, RR Lyr stars and δ Sct stars. This classification was based on the position of the stars in the PL diagrams. The objects located outside the instability strip in the color–magnitude (CM) diagram were removed from the sample, however it was checked if these objects are not highly reddened by extinction or have erroneous photometry. All the stars lying close to the boundaries between the regions in the PL diagrams, or with unusual positions in the diagrams showing parameters of the Fourier decomposition *vs.* periods, were treated in particular way. The classification was changed for some stars, because it was recognized that these objects are blended.

In the second stage of the type II Cepheids selection we repeated the visual inspection of the periodic light curves collected in our database. This time we chose only those stars which were located in the PL and CM diagrams close to the regions occupied by type II Cepheids identified so far. In this way we changed the previous classification for several variables, for example, we noticed some RV Tau stars with light curves almost indistinguishably similar to eclipsing variables. Only a careful analysis of these light curves revealed a small asymmetry which indicates that these stars are pulsating variables. One should, however, be aware that our final classification may be uncertain in some cases. In several stars of exceptionally "noisy" light curves we were unable to reliably distinguish between eclipsing/ellipsoidal stars and pulsating variables. We flagged these objects as uncertain in our catalog.

The final sample of type II Cepheids contains 197 objects. The PL diagrams of these variables in V, I and extinction insensitive Wesenheit index $W_I = I - 1.55(V-I)$ are plotted in Fig. 1. Significant difference in the scatter of the relations in V and W_I domains suggests that a remarkable number of the stars are affected by reddening. Several outliers visible in the $\log P$–W_I diagram are possibly blended stars (including "eclipsing" Cepheids – see Section 5) but some of them can be atypical Cepheids. In Section 4 we describe a group of peculiar W Vir stars (marked with cyan symbols in Fig. 1), brighter than ordinary stars of this type.

The RV Tau stars are plotted with "single" periods, *i.e.*, defined as the intervals between successive minima. As one can notice, the PL relation are not linear for the whole range of periods covered by type II Cepheids, and actually the PL relations should be fitted separately for BL Her, W Vir and RV Tau stars. This conclusion is especially valid for RV Tau stars which seem to be much brighter than would be expected from the extrapolated relation fitted to shorter-period type II Cepheids (*e.g.*, Demers and Harris 1974, Alcock *et al.* 1998).

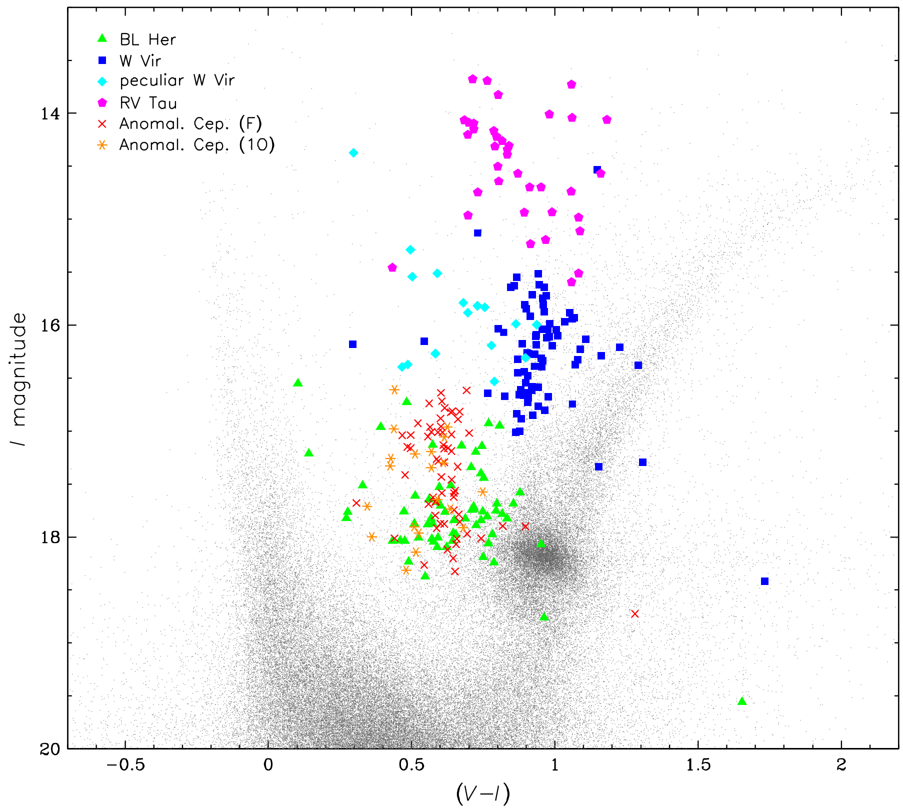

Fig. 2. Color–magnitude diagram for type II and anomalous Cepheids in the LMC. The color symbols are the same as in Fig. 1. In the background all stars from the subfield LMC100.1 are shown.

The number density in the period distribution of type II Cepheids peaks around three values, corresponding to BL Her, W Vir and RV Tau stars. We separated these groups using the following criteria. As the limiting period defining the boundary between RR Lyr and BL Her stars we adopted 1 day. This is the most often used value (*e.g.*, Arp 1955, Payne-Gaposchkin 1956, Harris 1985, Clement *et al.* 2001), though other limiting periods were also sometimes used, like $P = 0.75$ days in Wallerstein and Cox (1984) or $P = 0.8$ days in Gautschy and Saio (1996). However, our choice of the boundary period was not motivated only by tradition. We found that the distribution of Population II pulsating stars has the minimum for $P = 1$ day. Moreover, we noticed a small discontinuity (drop from 5.5 to 4.5) for this period in the $\log P - \phi_{21}$ diagram (see Section 7).

The transition between BL Her and W Vir stars is also not clearly defined. The boundary periods provided in the literature range from 3 to 10 days. We decided to define the threshold between both subtypes of type II Cepheids at $P = 4$ days, because around this value we noticed the frequency minimum of the sample. Moreover, for $P = 4$ days we found a clear discontinuity in the CM diagram (Fig. 2) – a shift in the mean $(V - I)$ colors from about 0.6 to 0.9 mag.

The distinction between W Vir and RV Tau stars is somewhat ambiguous. It has been known for years that there is an overlap in the properties of W Vir and RV Tau stars. Sometimes stars classified as W Vir variables do show alternating depth of minima (Arp 1955). Besides, infrared excess usually observed in RV Tau variables is also detectable in some W Vir stars (Welch 1987, Laney 1991).

In our sample of type II Cepheids all stars with periods longer than 20 days are considered to be RV Tau stars. Again, we noticed a local minimum in the period-frequency distribution around this period. The vast majority of variables above this limit exhibit alternating deep and shallow minima, or at least larger scatter of points in the minima, what may be caused by switching deep and shallow

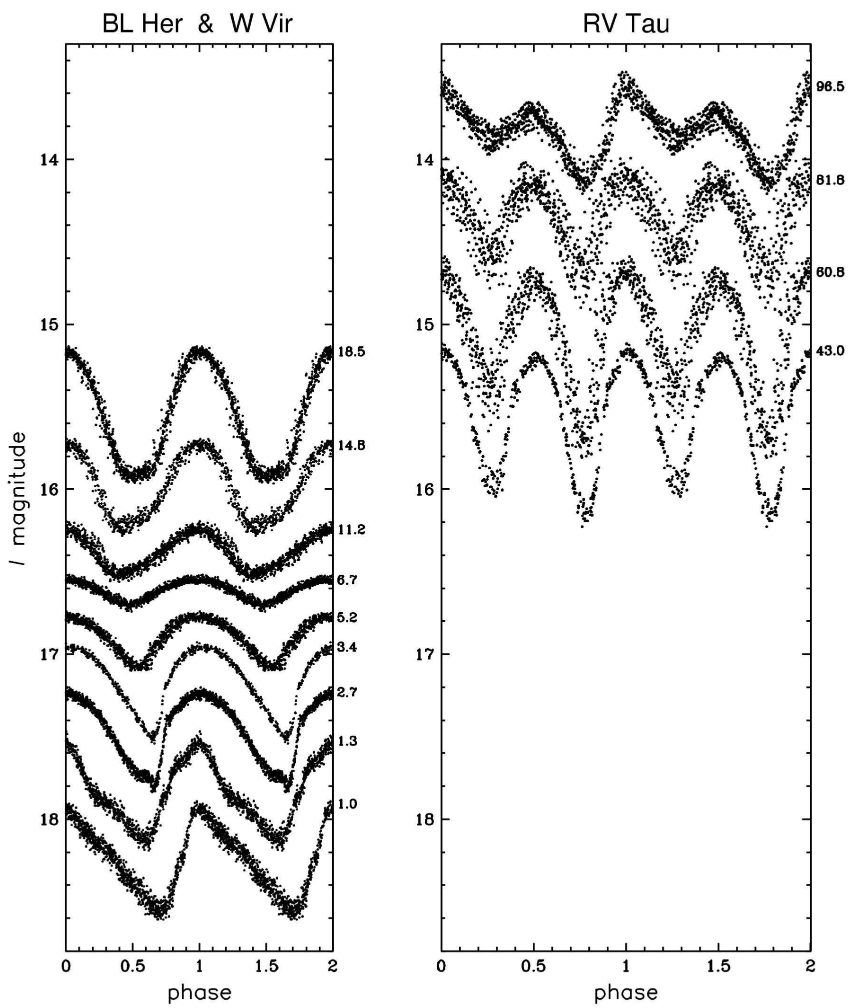

Fig. 3. Exemplary light curves of type II Cepheids in the LMC. *Left panel* shows BL Her and W Vir stars, while *right panel* presents RV Tau stars phased with "double" (formal) periods. Small numbers at the right side of each panel show the rounded periods in days of the light curves presented in panels.

minima observed in many RV Tau stars. It is important to mention that our criterion categorized as a W Vir star at least one star with distinct alternation of cycles (OGLE-LMC-T2CEP-002 with semi-period equal to 18.3 days) and several stars with equal minima fell within the RV Tau range of periods.

The longest (single) period of the RV Tau star in our sample is equal to 68 days. Above this limit we found some semiregular variables with a behavior similar to the RV Tau stars, *i.e.,* alternating deep and shallow minima. However, these stars were removed from our list, because their colors were much redder than for typical Cepheids. These stars follow the PL relations for semiregular variables (Soszyński *et al.* 2007) and will be included in the sample of variable red giants which will be published in a future paper.

Finally, we divided the sample into 64 BL Her, 96 W Vir and 37 RV Tau stars. Fig. 3 shows typical *I*-band light curves of type II Cepheids. Light curves of BL Her and W Vir stars are presented in the left panel. The right panel shows four RV Tau stars phased with the "double" (formal) period. Type II Cepheids show a wide variety of light curve shapes, although generally there is a clear progression of light curve shapes with period. However, some diversity of the observed light curves is expected, because of the great sensitivity of the light curve shapes on stellar parameters (Moskalik and Buchler 1993). Fig. 3 does not contain peculiar W Vir stars detected in our data, exhibiting somewhat different colors, magnitudes and light curve appearance than regular variables of that type (see Section 4).

Note that, with exception of the two faintest stars, the considerable scatter visible in the phased light curves is not caused by photometric errors. For many stars from our sample this scatter is even more significant which is a well-known feature of type II Cepheids. Most of the unstable light curves can be explained by a variable period.

3.2. Anomalous Cepheids

After the manual selection of pulsating stars in our database and plotting them in the PL diagram (Fig. 1), the sequence of fundamental-mode anomalous Cepheids was clearly visible. This PL relation is located between classical and type II Cepheid strips, up to the periods of about 2.4 days. Thus, the identification of anomalous Cepheids with periods exceeding 1 day was a relatively easy task, also because these stars occurred to constitute quite homogeneous class of variables. Light curves of several anomalous Cepheids are shown in Fig. 4. As one can notice the fundamental-mode pulsators have asymmetric light curves with rapid rise to maximum and slow decline. The vast majority of these stars exhibit a small bump just before the rise to maximum light.

The situation with fundamental-mode anomalous Cepheids with periods below 1 day was more complicated. Their light curves practically have the same morphology as fundamental-mode RR Lyr (RRab) stars, so, in general, it is impossible to photometrically distinguish between the LMC short-period anomalous Cepheids

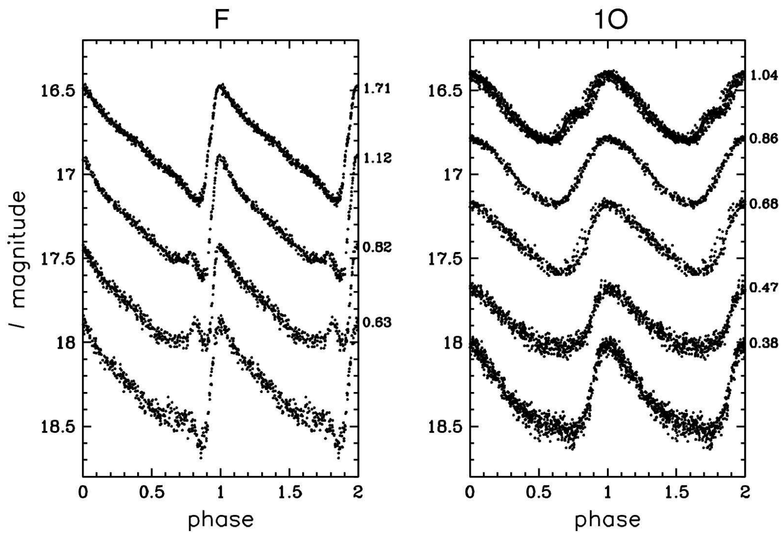

Fig. 4. Exemplary light curves of anomalous Cepheids in the LMC. *Left panel* shows fundamental-mode pulsators, while *right panel* presents first-overtone stars. Small numbers at the right side of each panel show the rounded periods in days of the light curves presented in panels.

and RR Lyr stars located somewhat closer to us. Moreover, we detected a considerable number of blended RR Lyr stars with brightness increased by unresolved stars. These objects should have smaller amplitudes in the magnitude scale, but it is not always unambiguously detectable, because RR Lyr variables cover wide range of typical amplitudes.

Our selection criteria of short-period anomalous Cepheids were based on the features of these stars with $P > 1$ day. We searched for objects brighter than typical RR Lyr stars and with light curves similar to those presented in the left panel of Fig. 4. Since we have not observed Blazhko effect for long-period anomalous Cepheids, we also excluded light curves with considerable scatter which usually is caused by this phenomenon. We emphasize that our procedure might not be perfect and some of the short-period anomalous Cepheids could actually be RR Lyr stars. 62 fundamental-mode anomalous Cepheids with periods between 0.62 and 2.35 days passed our selection criteria.

The candidates for anomalous Cepheids pulsating in the first overtone were selected on the basis of their position in the PL diagram and the appearance of their light curves. Several such light curves are presented in the right panel of Fig. 4. Generally, the light curves are smoother than for the fundamental-mode pulsators, with rounded maxima and minima, although some stars exhibit somewhat sharper maximum. The light curves resemble two known Galactic anomalous Cepheids: BL Boo (Zinn and Dahn 1976) and XZ Cet (Teays and Simon 1985), which are proved to be overtone pulsators (*e.g.,* Zinn and King 1982, Szabados *et al.* 2007). The PL relation of the overtone anomalous Cepheids falls on the extension to shorter periods of the fundamental-mode classical Cepheids, but the light curves of both groups are distinctly different. We found only two first-overtone anomalous Cepheid with period longer than 1 day (OGLE-LMC-ACEP-015, OGLE-LMC-ACEP-050), *i.e.,* in the range occupied by classical Cepheids. These objects have been distinguished on the basis of their light curve morphology. In total, we selected 21 candidates for overtone anomalous Cepheids with periods ranging in 0.38–1.18 days.

It is remarkable that none of the 4 candidates for anomalous Cepheids in the LMC detected by Di Fabrizio *et al.* (2005) passed our selection criteria. Two of these stars have decreased amplitudes and are probably blended RR Lyr stars, one is a Blazhko RRab star with the mean *I*-band magnitude equal to 18.4 mag (*i.e.,* in the LMC RR Lyr range), and one is probably an RRc star, although it is fainter than other stars of that type ($I = 19.5$).

4. Peculiar W Vir stars

During the inspection of the light curves we noticed a group of W Vir stars with periods between about 6 and 10 days with somewhat different light curve shapes than other stars of that type. The typical type II Cepheid with the period in this range shows a light curve with slow rise and more rapid decline, or, at least, a symmetric light curve with broad flat maximum. We noticed several Cepheids with the rising branch steeper than declining one. In this paper we call these objects "peculiar W Vir stars". Fig. 5 compares light curves for the peculiar and ordinary W Vir stars at similar periods.

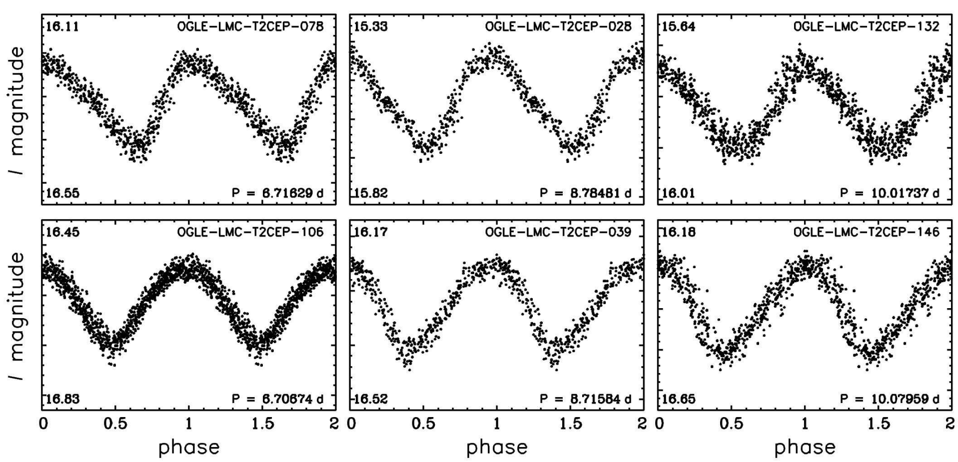

Fig. 5. Three pairs of light curves of peculiar (*upper panels*) and ordinary (*lower panels*) W Vir stars. Each column presents variables of similar periods.

We separated the peculiar W Vir stars from the typical ones and noticed other differences. The different appearance of the light curves shows up in the diagrams presenting the Fourier parameters *vs.* periods, especially in the phase differences

ϕ_{21} and ϕ_{31}. We found that using these parameters it is possible to distinguish two groups of W Vir stars also for shorter-period stars, down to 4 days. In total we selected 16 peculiar W Vir stars with periods in the range 4–10 days. Four of these stars exhibit additional eclipsing variations superimposed on the pulsation light curve (see Section 5). Four other peculiar W Vir stars show secondary periods in the range of 40–77 days that may be ellipsoidal modulation (in such a case the orbital periods should be twice as long as the secondary periods). Taking into account that there must be unfavorable orbital inclinations for detecting binarity, it is safe to assume that all peculiar W Vir stars are members of binary systems. In such a case their current pulsations could be a consequence of the previous evolution in binary systems.

In Figs. 1 and 2 the peculiar W Vir stars are represented by cyan symbols. As one can notice, these stars are systematically brighter by about 0.5 mag in the I-band and 0.7 mag in the V-band than typical W Vir stars of the same periods. Both groups also differ significantly in $(V-I)$ colors. The peculiar variables tend to be bluer, although their color distribution seems to be more scattered than for regular W Vir stars. The median $(V-I)$ value for the peculiar W Vir stars is equal to 0.72 mag, *i.e.,* similar to BL Her stars. There is only little difference between both groups of W Vir stars in the $\log P - W_I$ diagram, because the differences in magnitudes and colors cancel out in the W_I index.

5. "Eclipsing" Type II Cepheids

In our samples of type II and anomalous Cepheids we failed to identify any distinct double-mode pulsator with two radial modes simultaneously excited. Nevertheless, we detected a number of objects with low-amplitude secondary periodicities. For example, there is an interesting group of several type II Cepheids with secondary periods 5–10 longer than pulsation period. Four of these stars are the peculiar W Vir stars described in the previous section. We provide the information about the most prominent additional periods in the remarks of the catalog.

During the search for double-periodic stars we detected seven type II Cepheids with eclipsing modulation overimposed on the pulsation variations. Three of these objects (OGLE-LMC-T2CEP-052, OGLE-LMC-T2CEP-093, OGLE-LMC-T2CEP-098) were previously reported by Welch *et al.* (1999). The light curves of all eclipsing type II Cepheids are shown in Fig. 6. Here we present the original I-band photometry folded with the pulsation periods and the data after subtraction of the Cepheid light curves and folded with the orbital periods. The scatter visible in some light curves is usually caused by variable pulsation periods, and the full solution requires fitting these changes before subtracting the light curves. We did it only for the star with the most unstable light curve – OGLE-LMC-T2CEP-093 – for which we measured periods and fitted the light curves separately for each observing season.

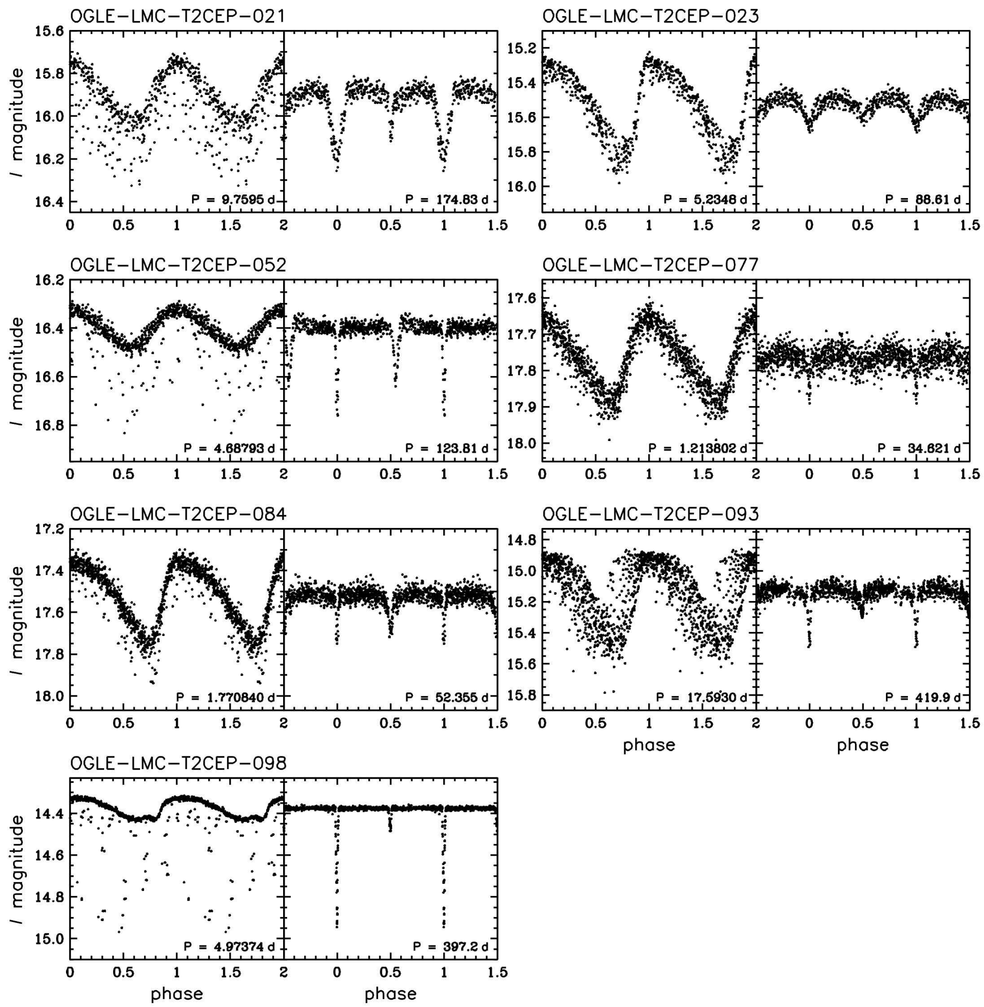

Fig. 6. Light curves of type II Cepheids with additional eclipsing variability. In each pair of diagrams *left panels* show the original photometric data folded with the Cepheid periods, while *right panels* show eclipsing light curves after subtracting the Cepheid component.

It is striking that among 3361 classical Cepheids in the LMC (Paper I) we found only three stars with eclipses and one eclipsing system of two classical Cepheids, while the sample of 197 type II Cepheids contains as many as seven eclipsing variables. Of course, confirmation that these objects are binary systems with a Cepheid as one of the components requires further studies.

It is even more surprising that four of our "eclipsing" type II Cepheids have been classified by their Fourier parameters as the peculiar W Vir stars described in the previous section. Only three eclipsing/pulsating stars are regular type II Cepheids. It is also worth noting that three Cepheids with eclipsing modulation pulsate with periods between 4 and 6 days, *i.e.*, in the frequency minimum between BL Her and W Vir stars.

6. The Catalog

The catalog data are available through the WWW interface or by anonymous FTP sites:

http://ogle.astrouw.edu.pl/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/lmc/t2cep/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/lmc/acep/

In the FTP type II Cepheids and anomalous Cepheids are placed in two separate directories. The variables are arranged according to increasing right ascension and designated with symbols OGLE-LMC-T2CEP-NNN and OGLE-LMC-ACEP-NNN (where NNN is a consecutive number) for type II Cepheids and anomalous Cepheids, respectively. The files ident.dat in each directory contain coordinates and cross-identifications of the stars with other catalogs. The following columns give the object designation, OGLE-III field and the database number of a star, classification (BL Her, W Vir or RV Tau for type II Cepheids, F or 1O for anomalous Cepheids), RA and DEC coordinates for the epoch 2000.0, cross-identification with the OGLE-II Catalog of Cepheids (Udalski *et al.* 1999), the MACHO sample of type II Cepheids (Alcock *et al.* 1998) and the GCVS vol. V (Artyukhina *et al.* 1995). In the last column there are other designations taken from the GCVS.

The parameters of the Cepheids are given in the files t2cep.dat, acepF.dat and acep1O.dat. The consecutive columns contain: Cepheid designations, I and V-band intensity mean magnitudes, periods in days and their uncertainties, epochs of maximum light, amplitudes in the I-band, and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} derived for the I-band light curves. Periods and their uncertainties were derived using program TATRY by Schwarzenberg-Czerny (1996). Information about individual objects of particular interest are provided in the files remarks.txt. The subdirectories phot/ contain multi-epoch OGLE-II (if available) and OGLE-III photometry of the stars in our catalog. The subdirectories fcharts/ contain finding charts of all objects – the $60'' \times 60''$ subframes of the I-band DIA reference images, oriented with N up, and E to the left.

Fig. 7 shows the position of type II and anomalous Cepheids in the LMC overplotted on the picture taken by the ASAS survey (Pojmański 1997). A cross-check of our variables with previously published list of type II Cepheids in the LMC revealed 72 objects in common – 125 Cepheids are identified for the first time. Our catalog includes all objects detected by Alcock *et al.* (1998) in the LMC. The GCVS lists 23 objects in the LMC of types CWA, CWB, RV or RVA. Our catalog contains 16 of them. Six stars are outside the OGLE-III fields and one (HV 12904) was reclassified as a classical Cepheid. On the other hand, object HV 12509, classified in the GCVS as DCEP (classical Cepheid), occurred to be an "eclipsing" (and thus blended) type II Cepheid.

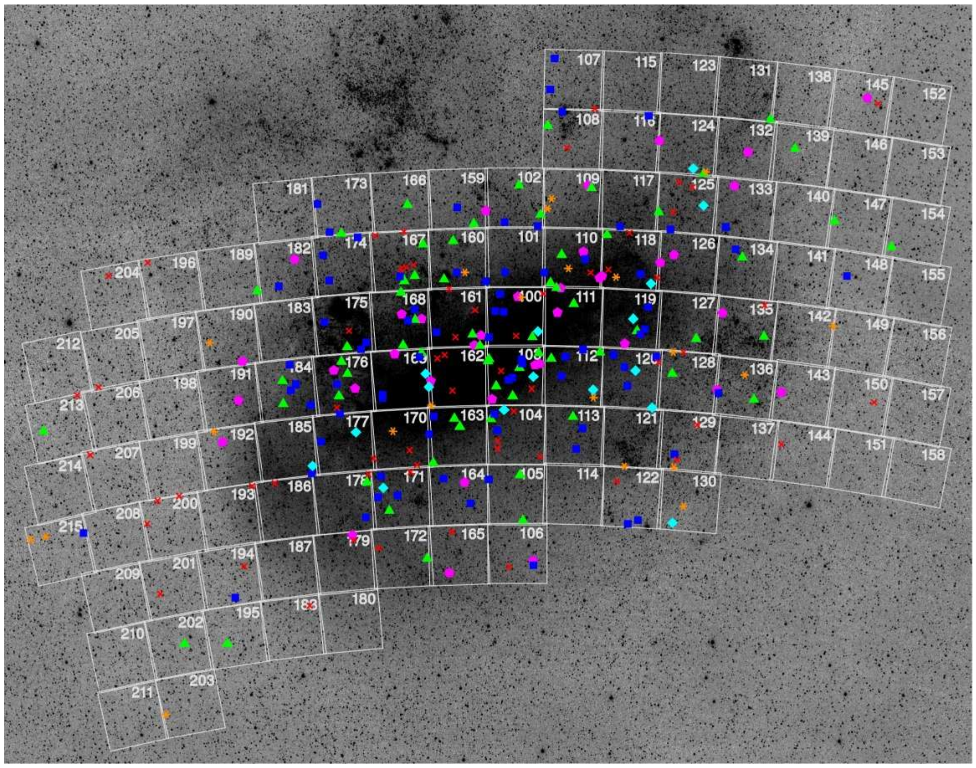

Fig. 7. Spatial distribution of type II and anomalous Cepheids in the LMC. Color symbols represent the same types of stars as in Fig. 1. The background image of the LMC is originated from the ASAS wide field sky survey.

It seems that anomalous Cepheids in the LMC were not known to date. As we mentioned before, the four candidates for stars of that type detected by Di Fabrizio *et al.* (2005) are, in our opinion, RR Lyr stars. In the GCVS we identified only one anomalous Cepheid from our sample, OGLE-LMC-ACEP-009 = LMC V0464 = NGC 1786 V1, but it is classified as RRab star, though with a remark "BLBOO type? A star of the Galaxy?" (BLBOO is a designation of anomalous Cepheids in the GCVS). Nemec *et al.* (1994), besides NGC 1786 V1, proposed the variable star NGC 1786 V8 ($P = 0.36391$ days) as a candidate for anomalous Cepheid in the LMC. We identified this object in our database, and found that 0.36391 days is an evident one-day alias of the real period: $P = 0.57183$ days. NGC 1786 V8 is undoubtedly an RRab star. The OGLE-II catalog of Cepheids in the LMC (Udalski *et al.* 1999) contains several objects from our sample of anomalous Cepheids, but they are categorized together with type II Cepheids as "fainter" than classical Cepheids. Thus, in this paper we present the first reliable identifications of anomalous Cepheids in the LMC. It is worth mentioning that the size of our sample is comparable with the number of all known anomalous Cepheids in all the remaining environments.

7. Fourier Analysis

The progression of light curve shapes with periods, clearly visible in Fig. 3 for type II Cepheids, is analogous to the Hertzsprung progression observed for classical Cepheids. Stobie (1973) was the first who noticed the changes of bump phases with period in the type II Cepheids. Kubiak and Udalski (2003) noticed that the progression of light curve shapes of classical Cepheids, observed in the range of periods between 6 and 24 days, is reproduced in type II Cepheids but in the period range 0.9–3 days. The theoretical models show that such a behavior is caused by the progressive shift through the 2:1 resonance between the fundamental and second overtone modes (*e.g.,* King *et al.* 1981, Carson *et al.* 1981, Carson and Stothers 1982, Hodson *et al.* 1982).

The quantitative description of the Hertzsprung progression is possible thanks to the parameters of the Fourier light curve decompositions (Simon and Lee 1981). Fourier analysis of type II Cepheids was performed by Petersen and Diethelm (1986) and Simon (1986). The standard parameters used in the light curve analysis are amplitude ratios $R_{k1} = A_k/A_1$ and phase differences $\phi_{k1} = \phi_k - k\phi_1$, where A_k and ϕ_k are parameters of the truncated Fourier series fitted to the photometric data.

We have fitted Fourier series to the light curves using program J-23 by T. Mizerski. To avoid overfitting the maximum harmonic was adjusted to minimize the value of χ^2 per degree of freedom. For light curves with insignificant higher harmonics the amplitude ratios are equal to zero, while the appropriate phase differences are not defined.

In Figs. 8 and 9 we plot the Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} against $\log P$. For comparison we include the same coefficients of fundamental-mode and first-overtone classical Cepheids from Paper I. As one can notice, various types of Cepheids follow generally different sequences in these planes which reflects the progression of light curves shapes with periods.

For BL Her stars the ϕ_{21} parameter increases slowly with periods in agreement with the theoretical predictions (Moskalik and Buchler 1993), while the ϕ_{31} grows very fast and reaches value 2π for $P \approx 1.5$ days. This is the progression center (Petersen and Diethelm 1986) where the 2:1 resonance between fundamental and second overtone modes is expected. For longer periods ϕ_{31} starts growing from zero, because the phase differences are defined modulo 2π.

The next similar feature occurs for W Vir stars with periods of about 6 days. Amplitude ratios, as well as amplitudes of the light curves, reach minimum values for this period, while ϕ_{21} and ϕ_{31} cross zero. Similar behavior seem to appear again for W Vir stars with periods 16–20 days. This time it is better visible in the $\log P$–R_{21} and $\log P$–ϕ_{21} planes. This latter feature can be interpreted as a signature of the 2:1 resonance between the fundamental mode and the first overtone, which is expected to occur at $P \approx 17$ (Carson *et al.* 1981). For RV Tau stars Fourier parameters are spread over larger area, but it should be remembered that

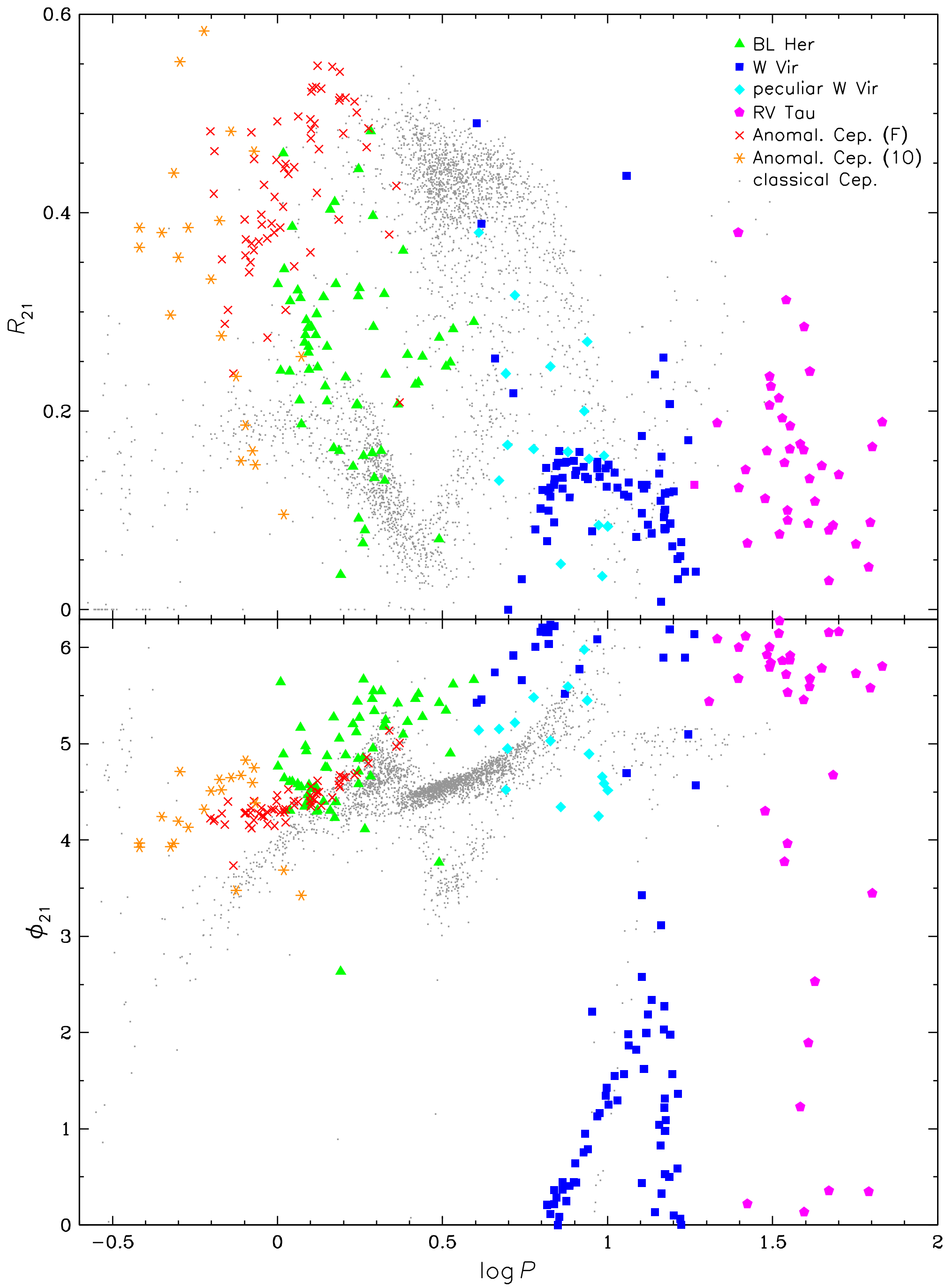

Fig. 8. Fourier parameters R_{21} and ϕ_{21} *vs.* $\log P$ for Cepheids in the LMC. Symbols are the same as in Fig. 1.

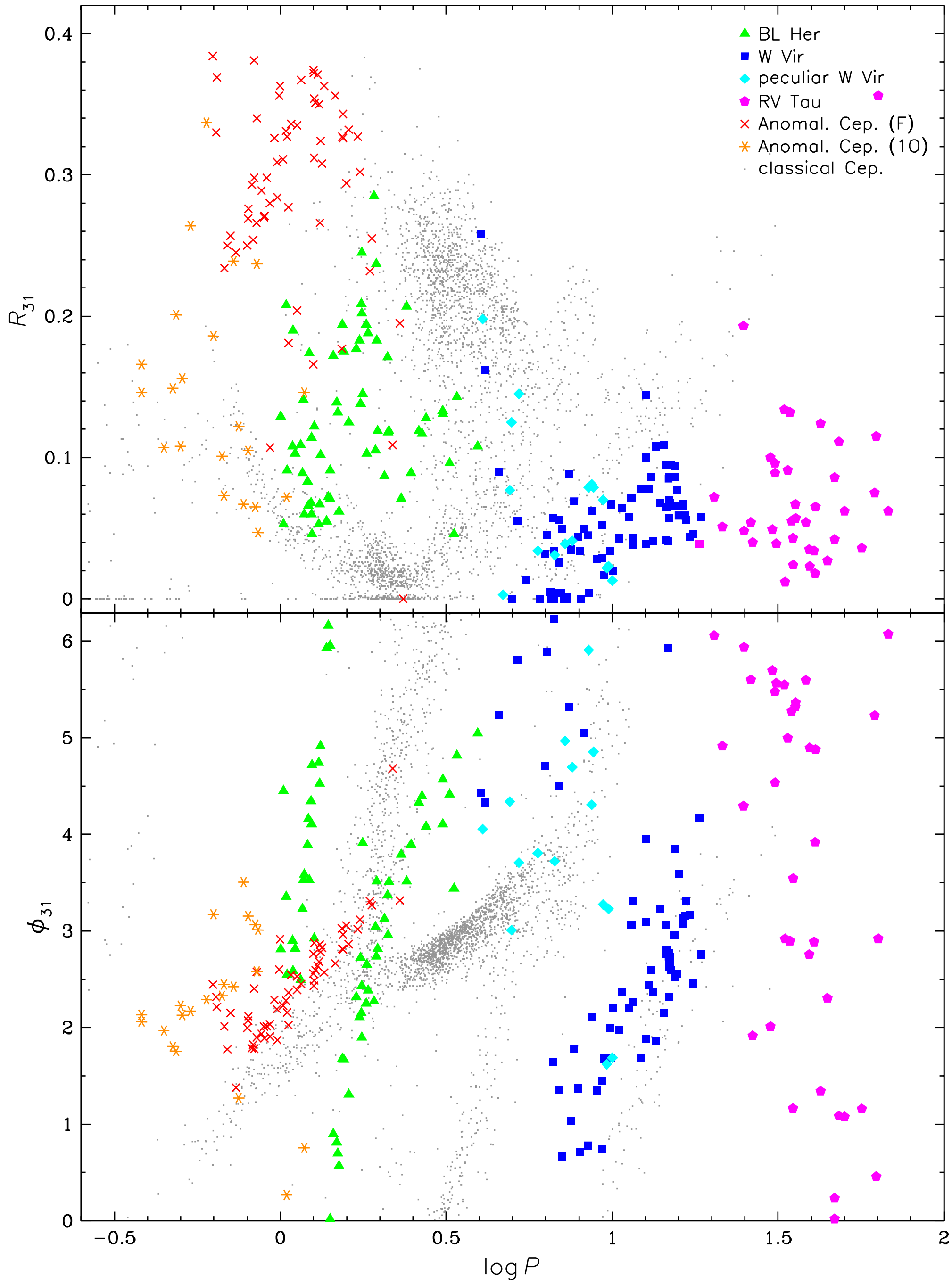

Fig. 9. Fourier parameters R_{31} and ϕ_{31} *vs.* $\log P$ for Cepheids in the LMC. Symbols are the same as in Fig. 1.

the uncertainties of these quantities may be significant due to large scatter of the light curves and alternation of cycles (the Fourier series was fitted to light curves phased with "single" periods).

8. Discrimination between Type I and Type II Cepheids

The problem of distinguishing between classical and type II Cepheids is particularly important for field variables in the Galaxy, because in general it is impossible to place a given Cepheid in the absolute PL diagram. A number of criteria were used to identify both types of Cepheids in the Milky Way – distance from the Galactic plane, spectral features and appearance (morphology and stability) of the light curves – but none of these method offered unambiguous and complete classification. The large OGLE-III samples of Cepheids offer the possibility to improve the distinction criteria, especially these depending on the light curves shapes. The tool used for quantitative description of light curve shapes are Fourier decomposition parameters (Figs. 8 and 9).

The problem of discrimination between type I and type II Cepheids using their light curves were discussed, among others, by Kwee (1967), Diethelm (1983), Fernie and Ehlers (1999) and Schmidt *et al.* (2004). Fernie and Ehlers (1999) showed that the phase differences ϕ_{i1} are good, although not perfect, discriminants between both types of variables, while the R_{i1} parameters are useless for this purpose. Schmidt *et al.* (2004) discussed various criteria – morphology of the light curves, Fourier parameters and light-curve stability – in terms of differentiation between type I and type II Cepheids. They concluded that the shapes of the light curves are quite useful tool for the classification.

In Figs. 8 and 9 each of the groups: fundamental-mode classical Cepheids, first-overtone classical Cepheids, type II Cepheids and anomalous Cepheids, traces different patterns in the Fourier parameters *vs.* period diagrams, however the strips cross each other at various ranges of periods. Thus, it is not possible to draw lines separating all these classes simultaneously for all periods, but it is possible to delineate regions in the parameter space occupied by given types of variables.

For example, type II Cepheids with periods between 2 and 9 days can be reliably distinguished by their ϕ_{21} parameters, while for shorter-period type II Cepheid we recommend using the ϕ_{31} coefficient. Probably the best way to separate long-period W Vir stars would be using R_{31} parameter. Anomalous Cepheids seem to be well separated from fundamental-mode classical Cepheids in the $\log P$–ϕ_{31} diagram, while it is better to use R_{31} parameter to distinguish them from first-overtone type I Cepheids.

9. Summary

In this paper we extend the OIII-CVS with other pulsating stars in the LMC populating the upper part of the instability strip – type II and anomalous Cepheids.

We significantly increase the number of known type II Cepheids in the LMC and discovered the first anomalous Cepheids in this galaxy. Such large samples will make important contributions to our understanding of these stars – their evolution, internal structure and pulsation mechanisms. The PL relations which can be precisely determined from our data should open new possibilities for using type II and anomalous Cepheids as distance indicators.

Our preliminary investigation has shown several new features of the type II Cepheids. BL Her and W Vir stars differ significantly in $(V-I)$ colors, although there is a subset of W Vir stars which have, on average, similar colors as BL Her stars. This class of peculiar W Vir stars is also distinguishable by their light curve shape and luminosity. Seven of the type II Cepheids in the LMC exhibit additional eclipsing modulation what is a very large fraction compared to the sample of classical Cepheids. The distribution of the Fourier parameters of type II Cepheids shows systematic pattern with three sharp features for periods around 1.5, 6 and 17 days. Such a behavior is interpreted as an effect of resonances between two radial modes of pulsation.

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