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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. IV. Long-Period Variables in the Large Magellanic Cloud[1]

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ABSTRACT

The fourth part of the OGLE-III Catalog of Variable Stars presents 91 995 long-period variables (LPVs) in the Large Magellanic Cloud (LMC). This sample consists of 79 200 OGLE Small Amplitude Red Giants (OSARGs), 11 128 semiregular variables (SRVs) and 1667 Mira stars. The catalog data include basic photometric and astrometric properties of these stars, long-term multi-epoch *VI* photometry and finding charts.

We describe the methods used for the identification and classification of LPVs. The distribution of *I*-band amplitudes for carbon-rich stars shows two maxima, corresponding to Miras and SRVs. Such a distinction between Miras and SRVs is not obvious for oxygen-rich stars. We notice additional period–luminosity sequence located between Wood's sequences C and C′ and populated by SRVs.

Key words: *Stars: AGB and post-AGB – Stars: late-type – Stars: oscillations – Magellanic Clouds*

1. Introduction

Long-period variables (LPVs) are red giant or supergiant pulsating stars with periods ranging from about 10 days to a few years. Traditionally, LPVs are classified into Mira stars, semiregular variables (SRVs) and slow irregular variables.

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

Miras can be distinguished from SRVs by their regular light curves and *V*-band amplitudes larger than 2.5 mag. Irregular variables theoretically exhibit no sign of periodicity in their light curves, but in practice many SRVs with insufficient number of observations to determine periods are categorized as irregulars. The existence of strictly non-periodic stars among red giants is a matter of controversy (*e.g.*, Lebzelter and Obbrugger 2009).

Historically, Mira Ceti was the first known non-supernova variable star. Up to the end of the 19th century Mira-type stars dominated in the catalogs of variable stars because of their large amplitudes in the visual light. First LPVs in the Large Magellanic Cloud (LMC) were identified in the first half of the 20th century, mainly as by-products of searches for Cepheids in this galaxy (Hoffleit 1937, Shapley and Mohr 1940, McKibben Nail 1952). The Harvard catalog of variable stars in the LMC by Payne-Gaposchkin (1971) contained over 100 LPVs, but blue-sensitive surveys allowed to detect only the brightest red giants.

The first survey dedicated to finding LPVs in the LMC was conducted in the *I*- and *V*-passbands by Lloyd Evans (1971). 11 Miras identified during this search were then observed in the near-infrared (NIR) bands which allowed Glass and Lloyd Evans (1981) to discover quite narrow period–luminosity (PL) relation in these wavelengths. Extensive searches for LPVs in the LMC were undertaken in late 80's by Reid *et al.* (1988) and Hughes (1989). These surveys resulted in a discovery of more than 1000 Miras and SRVs in this galaxy.

With the advent of microlensing surveys, like MACHO, OGLE, EROS or MOA projects, the number of known LPVs was dramatically increased. Wood *et al.* (1999) and Wood (2000) used MACHO photometry of about 1500 LPVs in the LMC to show that these stars follow five distinct PL sequences (labeled A–E). This result was confirmed by many other studies (*e.g.*, Noda *et al.* 2002, Lebzelter *et al.* 2002, Cioni *et al.* 2003). The largest catalog of LPVs in the LMC available to date was compiled by Fraser *et al.* (2008) on the basis of the MACHO photometry. This sample comprises 56 453 stars of which 32 899 objects are associated with one of the Woods' PL sequences.

The long-term photometry collected during the OGLE survey allowed to greatly enhance our knowledge about LPVs. The OGLE-II light curves combined with the NIR photometry originated in various sources were studied by Kiss and Bedding (2003, 2004), Ita *et al.* (2004ab), Groenewegen (2004) and Wray *et al.* (2004). We extended the time span of the observations by supplementing the OGLE-II photometry with the OGLE-III data and analyzed various aspects of the red giant variability: OGLE Small Amplitude Red Giants (OSARGs, Soszyński *et al.* 2004a), ellipsoidal and eclipsing binaries that follow sequence E in the PL diagrams (Soszyński *et al.* 2004b), Miras and SRVs (Soszyński *et al.* 2005) and still unexplained Long Secondary Period (LSP) phenomenon that is responsible for sequence D (Soszyński 2007). In the paper by Soszyński *et al.* (2007) we extended to 14 the number of individual sequences in the period *vs.* Wesenheit index plane.

In this paper we describe the catalog of 91 995 pulsating red giant stars identified in the 40 square degrees of the LMC observed regularly between 2001 and 2009 in the course of the third stage of the OGLE project (OGLE-III). This is the fourth part of the OGLE-III Catalog of Variable Stars (OIII-CVS). In the previous parts we presented other types of pulsating stars in the LMC: classical Cepheids (Soszyński *et al.* 2008a), type II and anomalous Cepheids (Soszyński *et al.* 2008b) and RR Lyr stars (Soszyński *et al.* 2009).

The paper is structured as follows. In Section 2 we describe the OGLE photometric data. Section 3 gives the details about the process of LPVs selection and classification. In Section 4 we describe the catalog itself, and in Section 5 we compare our sample with the catalog of LPVs by Fraser *et al.* (2008). In Section 6 we discuss and summarize our results.

2. Observations and Data Reduction

The long time span of observations is crucial in the detection and analysis of LPVs. The OGLE-III photometry was accumulated over the interval of almost 8 years, from July 2001 to May 2009. For stars in the central 4.5 square degrees of the LMC the OGLE-II photometry is available, which increases the time baseline to 13 observing seasons.

All the *VI* standard photometry was obtained with the 1.3 meter Warsaw telescope located at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution of Washington. During the OGLE-III phase the telescope was equipped with the eight-chip CCD mosaic camera of the total resolution 8192×8192 pixels and the field of view of about 35×35.5 arcmin. For details of the instrumental setup we refer to Udalski (2003).

The 116 OGLE-III fields cover almost 40 square degrees in the LMC. The majority of the observations were taken in the *I*-band, typically about 500 points per star. For stars with the OGLE-II observations the number of points reaches 1000. About 40–60 observations per star (≈ 100 with the OGLE-II data) were secured in the *V*-band. The OGLE data reduction pipeline is based on the Difference Image Analysis technique (DIA; Woźniak 2000, Udalski 2003) which produces much better photometry than standard profile-fitting methods. However, the OGLE-III frames were also reduced using program DoPhot (Schechter *et al.* 1993) and independent PSF photometry and astrometry were obtained for all the stars. In this catalog we use the DoPhot photometry for about 500 bright stars that are saturated in the DIA reference frames. These objects are flagged in the remarks of the catalog. Full description of the reduction techniques, photometric calibration and astrometric transformations can be found in Udalski *et al.* (2008a).

To select and classify LPVs in the LMC we used single-epoch near-infrared (NIR) photometry originated in two sources: 2MASS All-Sky Catalog of Point Sources (Cutri *et al.* 2003) and the IRSF Magellanic Clouds Point Source Catalog

(Kato *et al.* 2007). Since LPVs are sometimes heavily reddened by circumstellar matter, we derived for each star the extinction-free Wesenheit indices using the NIR and visual magnitudes:

$$W_{JK} = K_s - 0.686(J - K_s)$$

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

Note that in the above equation I and V are not just the mean magnitudes calculated for our light curves. Because, in general, time coverage of the OGLE observations is different in I and V domains and LPVs sometimes change their mean luminosity in time, we decided to derive individual W_I values for each V point (approximating I-band magnitude for a given epoch using three closest points in the light curve). Then, the series of W_I points were treated as a normal light curves and the intensity mean values of the Wesenheit index were derived by a fitting of a Fourier series.

3. Identification and Classification of LPVs

We began the selection of LPVs in the LMC with the period search for all stars brighter than $I = 18$ mag in the OGLE-III database and $K_s = 14$ mag in the 2MASS catalog. In the further analysis we also checked the periodicities of fainter stars, but with large values of the $(J - K_s)$ index. We searched the frequency space 0–0.5 d^{-1} with a resolution 10^{-6} d^{-1} using the FNPEAKS code (Z. Kołaczkowski, private communication). For each star the procedure was as follows. After finding the primary period the third order Fourier series was fitted to the light curve and this function was subtracted from the data. Then, this step was repeated on the residual data, until we found 15 periods per star.

The stars were plotted in the PL diagrams (Fig. 1) and the well-known series of sequences (Soszyński *et al.* 2007) appeared. The location in the $\log P$–W_{JK} diagram was the primary criterion used to select and classify LPVs. The I-band light curves of stars with the primary periods in sequences C and C′ were inspected by eye. In some cases the primary periods were judged to be spurious and new periods were found. Stars which followed other PL sequences or had primary period outside any of the ridge were visually inspected only if their amplitude of variability was larger than about 0.1 mag. Again, in some cases we decided to correct the primary periods.

Classification of LPVs is a complex issue, because of the complicated nature of their light curves which often show multiperiodicity, irregular variations, changes of the mean magnitudes or modulations of periods, phases and amplitudes. Moreover, there is a contribution of young stellar objects (YSO), quasars in the background, and Galactic red dwarfs in the foreground of the LMC among red variable objects.

To filter out these undesirable objects we used the recently published catalog of YSO in the LMC (Gruendl and Chu 2009) and the list of candidates for quasars behind the LMC (Kozłowski and Kochanek 2009). We cross-identified objects from

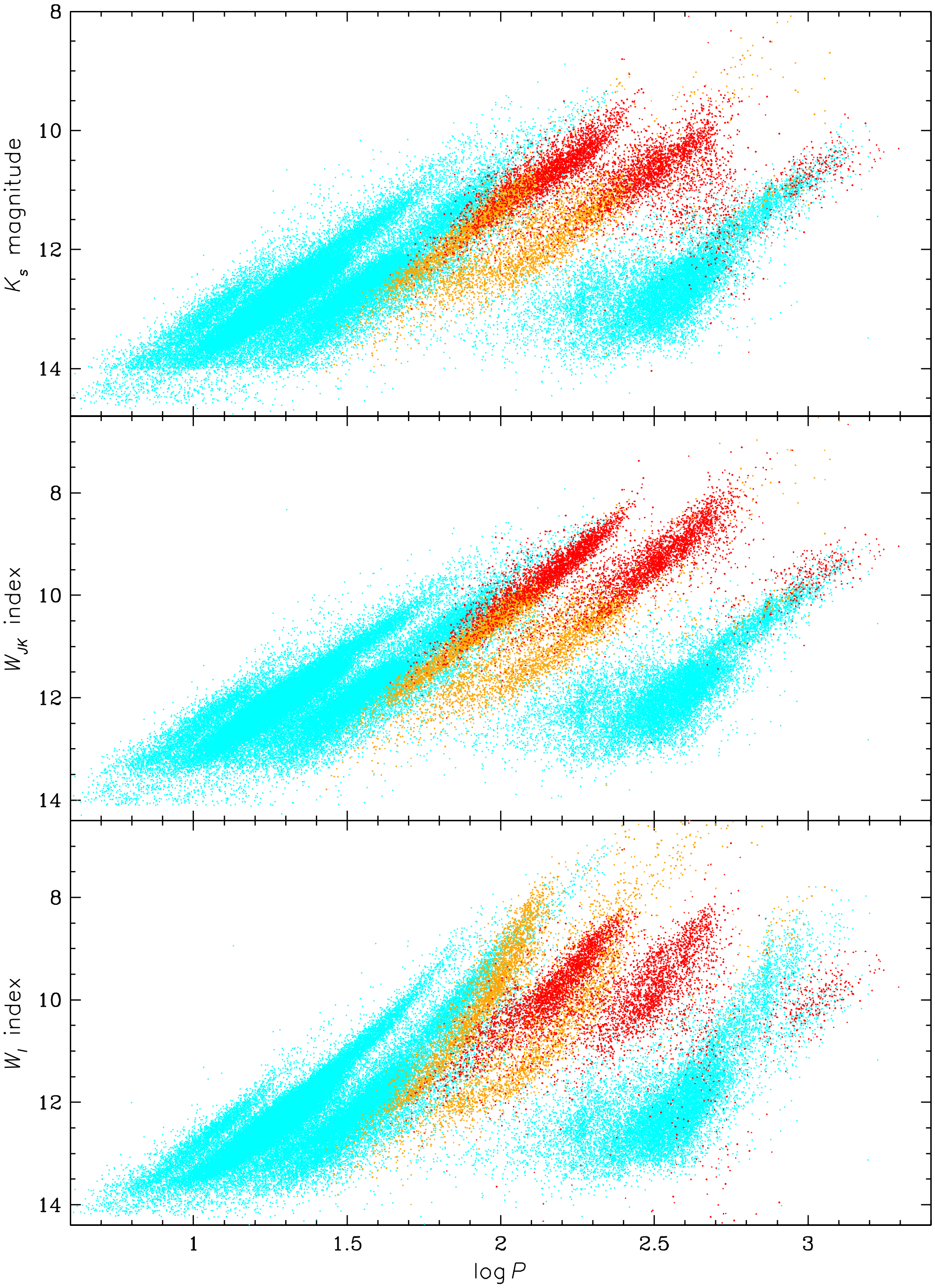

Fig. 1. Period–luminosity diagrams for LPVs in the LMC. *Upper, middle* and *bottom panels* show $\log P-K_s$, $\log P-W_{JK}$ and $\log P-W_I$ diagrams, respectively. Cyan points mark OSARG variables, orange points indicate O-rich Miras and SRVs, and red points show positions of C-rich Miras and SRVs. Each star is represented by one (the primary) period.

these catalogs with our preliminary list of red variable stars in the LMC and inspected their light curves. With the exception of a few cases which were judged to be evident LPVs, we removed these objects from our catalog. To exclude Galactic red stars from the sample we checked the proper motions of all stars in our preliminary list. We used the DoPHOT astrometric measurements obtained independently for each observation. Stars with measurable proper motions (down to about 2.5 mas/year) were recognized as nearby red dwarfs and removed from the sample.

The stars in the catalog are divided into three main classes: OSARGs, SRVs and Miras. With the exception of several R CrB stars (which will be published in another part of the OIII-CVS), we did not notice red giants with no sign of periodicity, *i.e.*, irregular variables. Also, red giants showing eclipsing or ellipsoidal variations (sequence E stars) are not included in this part of the OIII-CVS, unless they exhibit pulsational variability superimposed on the primary periods.

OSARGs constitute the most numerous class of LPVs, and this is probably the most numerous class of variable stars in the LMC at all (at least in the range of luminosities and amplitudes available for the Warsaw telescope). Note that in the traditional classification scheme (Kholopov *et al.* 1985) there is no such type of LPVs as OSARGs. Most of the OSARGs from our catalog (if they were detected at all despite their small amplitudes) would be categorized as SRVs. However, Soszyński *et al.* (2004a) noticed that OSARG variables characterize with the unique features, different than for "classical" SRVs. For example, OSARGs obey different PL relations than SRVs and Miras. Also the Petersen diagrams show completely different patterns for OSARGs and SRVs.

Although OSARGs and SRVs seem to belong to two different types of variable stars, their distinction is not an easy task, because both groups partly overlap in all diagrams that can be plotted using the OGLE data. To separate OSARGs and SRVs we utilized the algorithm described by Soszyński *et al.* (2007). In brief, this algorithm uses characteristic period ratios observed for OSARG variables, and their positions in the period *vs.* Wesenheit index diagrams. The larger number of periods in a given object which fall within the OSARG PL sequences, the higher probability that the star belong to this class of variable stars.

The majority of OSARGs in our catalog were selected with this method. Sometimes, our algorithm failed, for example for blended stars (which do not lie exactly on the PL relations), or for stars with no measurements in one of the passband which are used to construct Wesenheit indices, or just for stars with insufficient number of detectable periods that place a star in various PL sequences. These objects were treated individually. We categorized them as OSARGs if their parameters located them in the region occupied by OSARGs in the period–luminosity, period–amplitude and color–magnitude diagrams.

In total, 79 200 stars were classified as OSARGs. Note, that we inspected by eye only a small fraction of their light curves, so the contribution of spurious detections is possible. The primary periods provided in our catalog are not always the pulsation periods which locate the stars on one of the OSARG sequences a_1–a_4 or b_1–b_3 (Soszyński *et al.* 2007). In many cases the primary periods belong to sequence D (LSP) or E (eclipsing or ellipsoidal variables).

OSARG variables were divided into two groups: first-ascent red giant branch stars (RGB) and asymptotic giant branch stars (AGB). Of course, all the stars brighter than the tip of the RGB ($K_s = 12.05$ mag) are AGB variables. Below the tip we used the criterion discovered by Soszyński *et al.* (2004a). If any of the period falls on the shortest-period sequence a_4, the star was categorized as an AGB variable. The remaining OSARGs are classified as RGB stars, however one should remember that there might be a subset of AGB stars that have no periods in sequence a_4 among these objects.

The remaining LPVs were classified as Mira stars and SRVs. Most of them lie on sequence C or C′, and very often on both sequences. However, there is no doubt that another, dimmer PL ridge is located between sequences C and C′ (see Section 6). There is also a number of SRVs with the primary periods on sequence D.

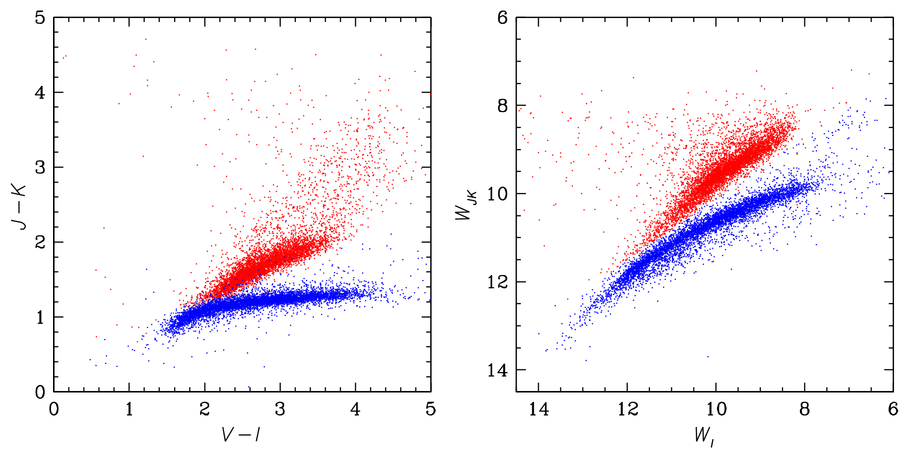

Fig. 2. Color–color (*left panel*) and W_I–W_{JK} (*right panel*) diagrams for Miras and SRVs in the LMC. Blue points show O-rich, while red points represent C-rich stars.

We divided Miras and SRVs into oxygen-rich (O-rich) and carbon-rich (C-rich) stars. Soszyński *et al.* (2005) showed that both classes can be distinguished on the period *vs.* W_I diagram. However, the additional ridge between sequences C and C′ complicates this pattern, so we used another method to discriminate between O-rich and C-rich stars. Both classes are well separated in the $(V-I)$ *vs.* $(J-K)$ color–color diagram (Fig. 2, left panel) and even better distinguished in the W_I–W_{JK} diagram (Fig. 2, right panel). The later plane was used to separate O-rich and C-rich stars. Note that our classification is based on the photometric measurements only and should be confirmed spectroscopically. Moreover, there is a region in the diagrams where both populations overlap, so our classification may be wrong for stars in these surroundings. It is possible that this region is occupied by stars in an intermediate stage between O-rich and C-rich giants, *i.e.*, S-type stars.

Formally, Miras and SRVs can be distinguished by their amplitudes. In the General Catalogue of Variable Stars (GCVS; Kholopov *et al.* 1985) the limiting amplitude is defined at 2.5 mag in the *V*-band, however even within the GCVS this rule is not strictly obeyed. One should also remember that Miras and some of the SRVs follow the same PL relation, *i.e.*, sequence C, so both type of stars must be closely related to each other.

Since the *V*-band measurements are sparse in the OGLE database, we decided to use *I*-band amplitudes to discriminate between Miras and SRVs. Before we derived the amplitudes the light curves had been detrended by fitting and subtracting cubic splines. It was necessary especially for C-rich stars, because many of them exhibit strong irregular variations of their mean brightness. The third-order Fourier series were fitted to the light curves. The amplitudes A_I were defined as the differences between maximum and minimum values of these functions.

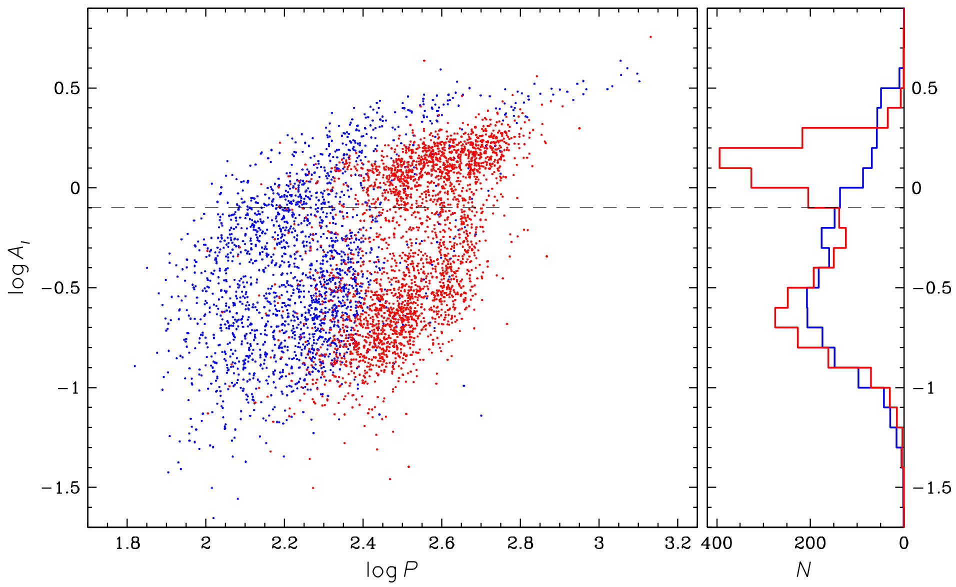

Fig. 3. Period–amplitude diagram (*left panel*) for the sequence C stars (Miras and SRVs). Blue points show O-rich, while red points represent C-rich stars. The *right panel* presents the distribution of amplitudes for O-rich (blue line) and C-rich (red line) stars. Black dashed line marks the limiting amplitude ($A_I = 0.8$ mag) used to separate Miras and SRVs in this paper.

Fig. 3 shows the period–amplitude diagram for stars classified as SRVs and Miras and located in sequence C. In the right panel we show histograms of $\log A_I$ separately for O-rich and C-rich stars. C-rich stars evidently have bimodal distribution of amplitudes with local maxima at $A_I = 0.25$ mag and $A_I = 1.3$ mag. This feature clearly defines the transition between Miras and SRV. For O-rich stars such a bimodality of the amplitude distribution is invisible or barely visible. After all, we decided to use the same limiting amplitude $A_I = 0.8$ mag for both spectral types to distinguish between Miras and SRVs. The dashed line shows this boundary value in Fig. 3.

4. The Catalog

The OGLE-III Catalog of LPVs in the LMC comprises 91 995 stars, of which 79 200 are classified as OSARG variables, 11 128 as SRVs and 1667 as Mira stars. OSARG variables are divided into 45 528 RGB and 33 672 AGB stars. Miras and SRVs consist of 6445 O-rich and 6350 C-rich giants. In Fig. 4 we present spatial distribution of our samples, separately for OSARG variables, O-rich and C-rich Miras and SRVs. It is clearly seen that C-rich stars are more concentrated toward the LMC bar than O-rich variables.

The catalog data are available on-line from the OGLE Internet Archive through the WWW interface or *via* anonymous FTP site:

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

In the FTP site the full list of LPVs is given in the file ident.dat. Stars are listed in order of increasing right ascension and designated with symbols OGLE-LMC-LPV-NNNNN, where NNNNN is a five digit consecutive number. The file ident.dat contains the following information about each star: the object designation, a cross-identification with the OGLE-III photometric maps of the LMC (Udalski *et al.* 2008b; lack of the identification means that the star is saturated in the DIA database and we publish the DoPhot photometry or the OGLE-II photometry only), classification (Mira, SRV, OSARG), evolutionary status (RGB, AGB), spectral type (O-rich, C-rich), equinox J2000.0 right ascension and declination, cross-identifications with the OGLE-II database (Szymański 2005), with the MACHO catalog of LPVs in the LMC (Fraser *et al.* 2008), with the extragalactic part of the GCVS (Artyukhina *et al.* 1995).

Physical parameters of the stars – mean I and V magnitudes, periods, and amplitudes – are provided in the files OSARGs.dat, SRVs.dat, and Miras.dat. The multi-epoch I- and V-band photometry is written in separate files in the subdirectory phot/. The subdirectory fcharts/ contains finding charts for 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. The file remarks.txt contains additional information about some objects. Here we flag the stars with the LSP (periods in sequence D) or ellipsoidal/eclipsing variations (sequence E), but this is not a full list of such objects. Our selection includes only about 7000 of the largest-amplitude sequence D variable stars and about 2000 eclipsing/ellipsoidal red giants.

For each star we provide three periods. Only for Miras and SRVs and only the primary periods were visually checked and corrected, if necessary. Thus, these primary periods may not correspond to the highest peak in the power spectrum. For

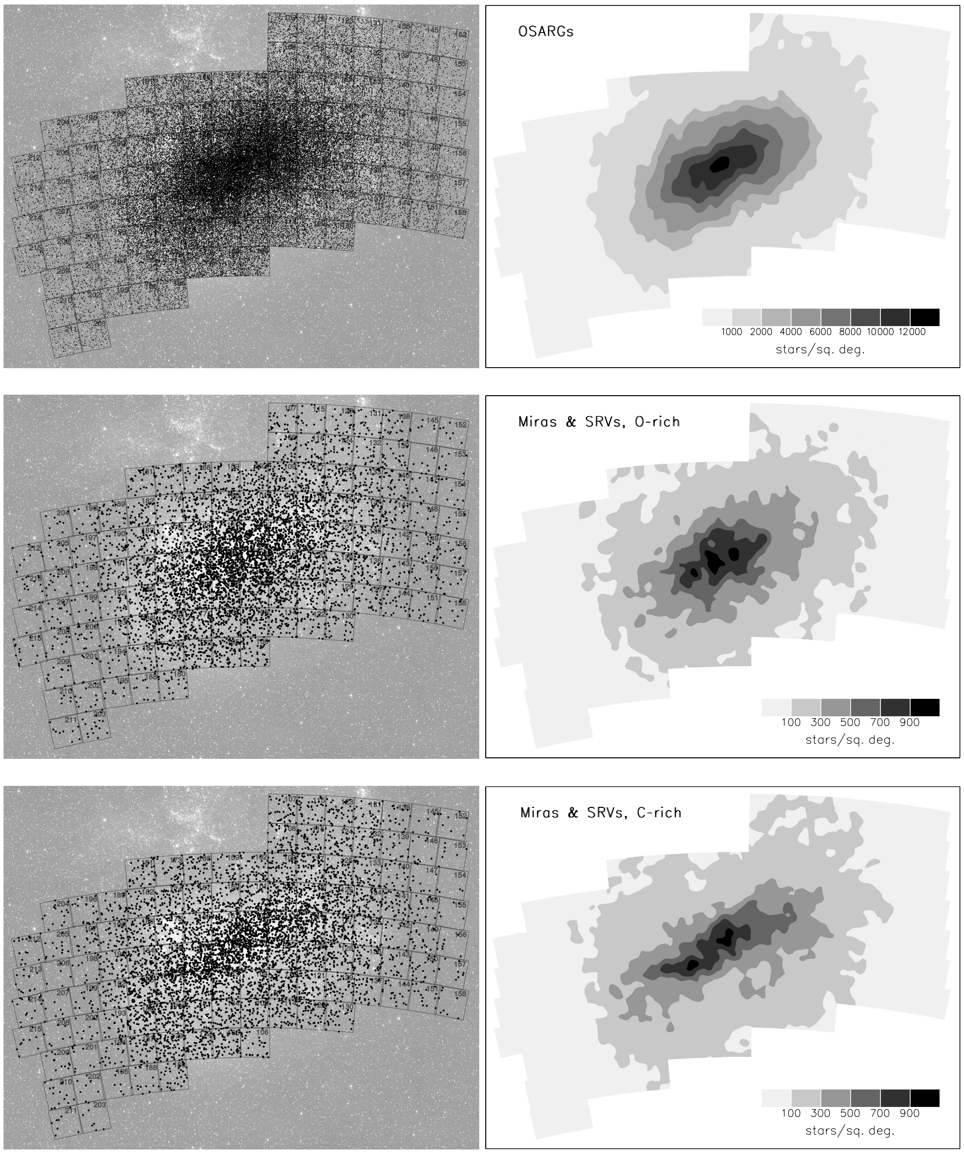

Fig. 4. Spatial distribution of LPVs in the LMC. *Left panels* show positions of stars overplotted on the LMC image originated from the ASAS sky survey (Pojmański 1997). Right panels present surface density maps obtained by smoothing of the distributions with the Gaussian filter. *Upper panels* show OSARG variables, *middle panels* – O-rich SRVs and Miras and *bottom panels* – O-rich SRVs and Miras.

example, Fourier analysis of a light curve with strong irregular component sometimes gives dominant period than cannot be associated with any real period. In such case we replaced the primary period with one selected from the secondaries. The second and the third periods provided in the catalog tables were derived fully automatically after prewhitening the light curves with the first periods. These secondary periods may not by associated with any real periodicity. For the complex frequency analyzes of our sample of LPVs we recommend to perform independent period search using the photometry attached to this catalog.

5. Completeness of the Catalog

The completeness of our sample strongly depends on the amplitudes of variations. The catalog is nearly complete for Miras (with the exception of objects that are too bright and saturate in our data, or too faint – below the detection limit). On the other side are the faintest OSARG variables which simultaneously have the smallest amplitudes, on the detection limit of the OGLE photometry. It cannot be ruled out that despite of our cleaning procedure there is still a small contribution of different types of red variable objects: foreground stars, YSO, quasars, etc. in our sample of LPVs.

To test the completeness of the catalog we compared it with the MACHO catalog of LPV in the LMC recently published by Fraser *et al.* (2008). 48 141 of stars in this catalog could be found in the OGLE-III fields, but only 28 257 of these variable stars are assigned by Fraser *et al.* (2008) to one of the sequences in the PL space. The remaining objects are classified as "one-year artifacts", are outside the boundaries of any PL sequence, or have no classification at all. These stars are not firm LPVs, so we removed them from the sample which were matched with our catalog.

We cross-identified the OGLE and MACHO lists and found no counterparts for 1208 MACHO variables. We carefully checked all these stars which are not present in our sample. 716 of these objects are sequence E stars (ellipsoidal and eclipsing binaries) which will be published in the future. 98 of missing objects occurred to be Cepheids, RR Lyr stars, young stellar objects, quasars, nearby red dwarfs or other types of variable objects. From the remaining 394 stars (1.4% of the MACHO sample) 134 objects had extremely low amplitudes (we included some of them in our catalog, for others we did not detect any significant variability), 81 were affected by a small number of observations due to their location close to the edge of the OGLE field and 179 were saturated in our frames.

6. Discussion

The catalog of LPVs in the LMC is the largest part of the OIII-CVS published to date. It contains the most heterogeneous sample of variable stars. The catalog includes stars as bright as $I = 12$ mag and as faint as $I = 20$ mag. The amplitudes of variations cover a range from millimagnitudes to several magnitudes. Periods range from a few days to years.

OSARGs which constitute the vast majority of our catalog are one of the less studied variable stars. In the paper by Soszyński *et al.* (2007) we suggested that the mechanism responsible for the OSARG variability may be a stochastic (solar-like) excitation. It is still an open question if there exist stars which exhibit features of both classes – OSARGs and "classical" SRVs (or Miras). Our classification procedure is not perfect and cannot definitely answer this question. Most of the OSARG variables are O-rich stars. Fig. 4 shows that the spatial distribution of OSARGs is similar to the distribution of O-rich SRVs and Miras. However, about 3300 OSARGs are located in the region of C-rich stars in the $W_I - W_{JK}$ diagram (Fig. 2). Some of these stars may have spuriously measured magnitudes, but there is no doubt that true C-rich OSARGs also exist. We found even a few candidates for R Crb stars among C-rich OSARGs.

In total, we detected several dozen candidates for R CrB stars. Some of them show characteristic light curves with rapid, deep and irregular declines in brightness, other candidates are not so evident and demand a spectroscopic confirma-

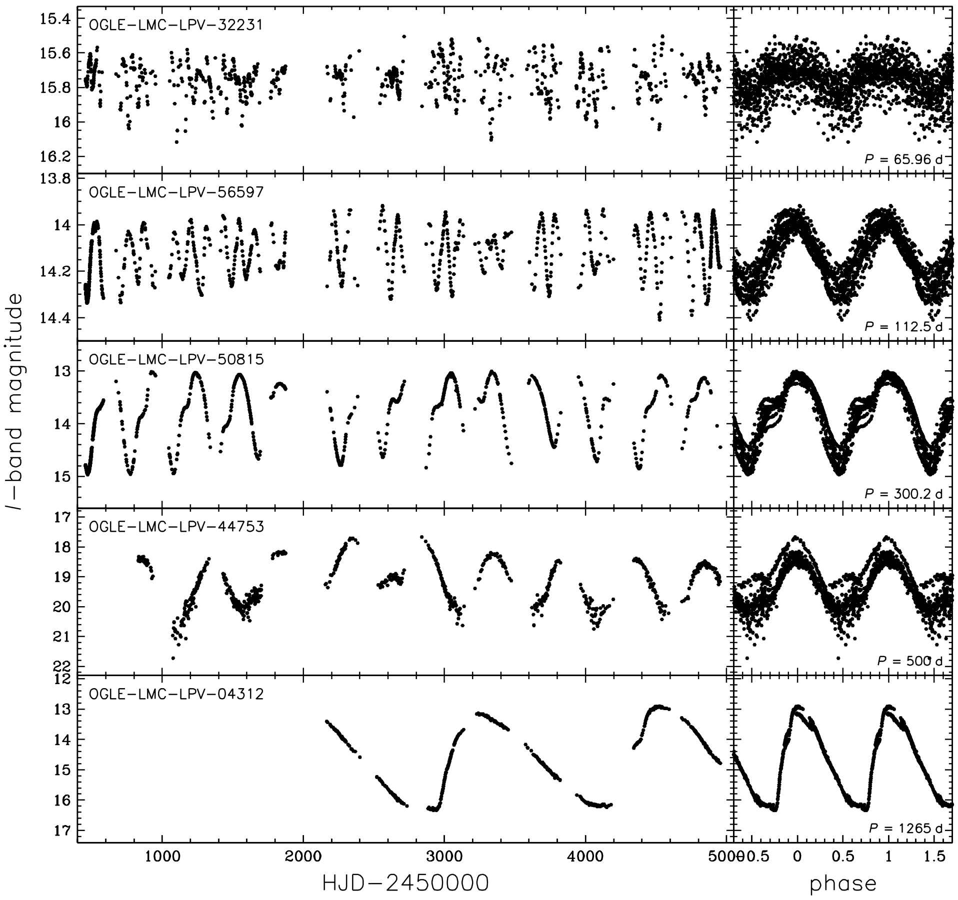

Fig. 5. Exemplary light curves of stars from PL sequence C. *Left panels* show unfolded OGLE-II (if available) and OGLE-III *I*-band light curves. *Right panels* show the same light curves folded with the primary periods.

tion. However, deeper or shallower declines at irregular intervals are very common feature in C-rich giants, and this feature can be helpful in distinguishing between C-rich and O-rich stars. In this catalog we included only these R CrB stars which exhibited any signs of pulsations and it was possible to derive their periods. We mark these stars in the remarks of the catalog. The full list of candidates for R CrB stars will be published in one of the forthcoming parts of the OIII-CVS.

During the variability selection we detected about 250 very red ($(J-K)>2$ mag) and very faint in the *I*-band ($I>18$ mag) Mira stars. One such light curve (OGLE-LMC-LPV-44753) is shown in Fig. 5. For the majority of these Mira variables we have no *V*-band observations, because the stars are too faint in this passband. These stars are also fainter in the K_s-band than other Miras with similar periods (Fig. 1), but most of them lie on sequence C in the diagram constructed with the extinction independent W_{JK} index. These objects are heavily obscured by circumstellar dust shells, like those stars detected by Ita *et al.* (2009). Most of these Miras are categorized to C-rich stars, in agreement with Zijlstra *et al.* (2006), who noticed that the vast majority of dust-enshrouded AGB stars belong to this spectral class. Some of these objects are just above the OGLE detection limit, and there is no doubt that there must exist stars which are too faint to be detected by our project.

In the period–amplitude diagram (Fig. 3) there is a distinct group of 10 Miras with periods longer than 1000 days and with very large amplitudes ($A_I \approx 4$ mag). With the exception of one object their light curves are much more stable than for typical C-rich Miras, so we suppose that these are O-rich stars. The light curve of one of the longest-period Mira in our catalog is shown in the bottom panel in Fig. 5.

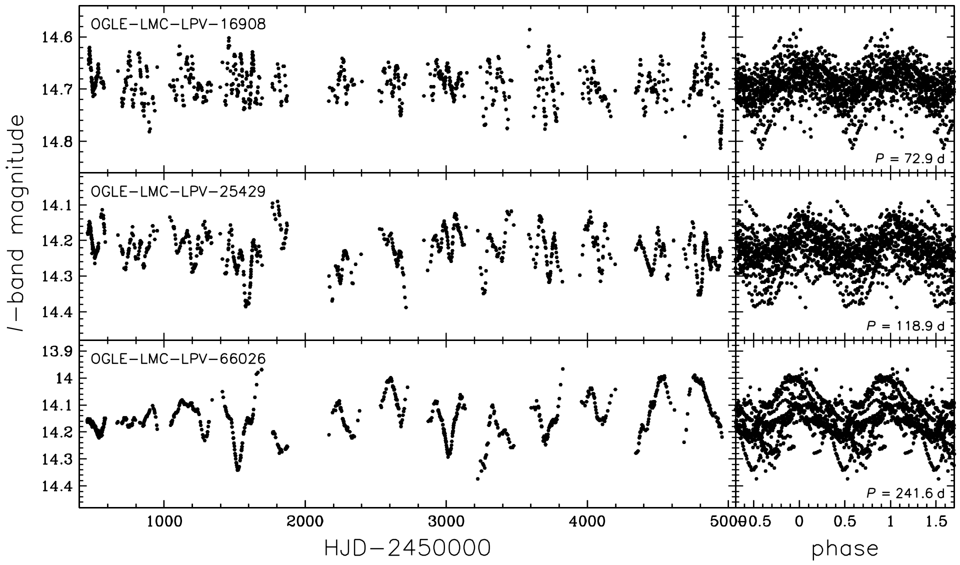

Fig. 6. Exemplary light curves of stars from the additional PL sequence located between sequences C and C′.

Some of these objects were discovered by Wood *et al.* (1992). They suggested that these long-period Miras are AGB stars with initial masses (on the AGB) $\gtrsim 4$ $M_{\odot}$.

As it was mentioned in Section 3, it seems that there is an additional PL sequence between sequences C′ and C. It is visible most clearly in the middle panel ($\log P$–W_{JK}) of Fig. 1. This dim sequence was first noticed by Soszyński *et al.* (2005). Stars that populate this ridge are SRVs with generally smaller amplitudes than stars in sequence C. We show three illustrative light curves in Fig. 6. The secondary periods of these stars usually fall on sequence C′. Further studies are needed to answer the question, if this additional sequence corresponds to different pulsation mode than sequence C, or rather the mode is the same, but stars are somewhat different. The former possibility would change the current identification of pulsating modes in LPVs (stars in sequence C are thought to be fundamental-mode pulsators, while sequence C′ represents the first overtone). The latter hypothesis means that we have two populations of LPVs in the LMC.

We significantly increased the number of known LPVs in the LMC. The long-term OGLE photometry is ideal for performing various tests on the pulsating red giants. We believe that our sample may be used to address the problem of mode identification in red pulsators, help to resolve the mystery of long secondary periods in red giants or give clues to the understanding of the star formation history in the LMC.

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