ACTA ASTRONOMICA
Vol. **59** (2009) pp. 1–18

The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. III. RR Lyrae Stars in the Large Magellanic Cloud*

I. Soszyński[1], A. Udalski[1], M.K. Szymański[1], M. Kubiak[1], G. Pietrzyński[1,2], Ł. Wyrzykowski[3], O. Szewczyk[2], K. Ulaczyk[1] and R. Poleski[1]

[1] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: (soszynsk,udalski,msz,mk,pietrzyn,kulaczyk,rpoleski)@astrouw.edu.pl
[2] Universidad de Concepción, Departamento de Fisica, Casilla 160–C, Concepción, Chile
e-mail: szewczyk@astro-udec.cl
[3] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
e-mail: wyrzykow@ast.cam.ac.uk

Received March 16, 2009

ABSTRACT

The third part of the OGLE-III Catalog of Variable Stars comprises 24 906 RR Lyr stars in the Large Magellanic Cloud (LMC). This sample consists of 17 693 fundamental-mode (RRab), 4958 first-overtone (RRc), 986 double-mode (RRd) and 1269 suspected second-overtone (RRe) pulsators. 66 objects are foreground Galactic RR Lyr stars. The catalog data include basic photometric and astrometric properties of these RR Lyr stars, multi-epoch *VI* photometry and finding charts.

We detected one new RR Lyr star with additional eclipsing variations. The spatial distribution of RR Lyr stars in the LMC is distinctly non-spherical and it is elongated in the same direction as the LMC bar. The basic statistical features of RR Lyr stars in the LMC are provided. The apparent *V*-band magnitudes for RRab stars have the modal value at 19.36 mag, and for overtone RR Lyr stars it is about 19.32 mag. The mean periods for RRab, RRc and RRe stars are 0.576, 0.337 and 0.270 days, respectively.

Key words: *Stars: variables: RR Lyrae – Stars: oscillations – Stars: Population II – Magellanic Clouds*

1. Introduction

RR Lyr stars are radially pulsating stars with periods in the range between 0.2 and 1.0 day. These are old, relatively low mass stars populating the horizontal

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

branch in the HR diagram. The role of RR Lyr in modern astrophysics cannot be overestimated. They are used for tracing the chemical and dynamical properties of old stellar populations in our and nearby galaxies. RR Lyr variables are one of the cornerstones of the astronomical distance scale. Finally, they are used as test objects for evolutionary and pulsation models of low-mass stars.

Probably, the first known RR Lyr star was a field variable U Leporis discovered by Kapteyn (1890, see the discussion in Smith 1995). However, within the next years hundreds of variable stars of the same type were detected in globular clusters (Pickering and Bailey 1895), therefore the whole class was referred to as "cluster-type variables" at that time. The name "RR Lyr stars" (from the brightest member of the class) was officially accepted by the International Astronomical Union in 1948.

The first RR Lyr variables in the Large Magellanic Cloud (LMC) were identified by Thackeray and Wesselink (1953). This discovery confirmed the Baade's (1952) large revision of the astronomical distance scale and proved the existence of the Population II component in the LMC. Most of the surveys for RR Lyr variables in the LMC undertaken during the subsequent decades covered old clusters and their vicinities (*e.g.*, Alexander 1960, Wesselink 1971, Graham and Ruiz 1974, Graham 1985, Nemec *et al.* 1985, Hazen and Nemec 1992, Walker 1992).

The number of known RR Lyr stars in the LMC was multiplied thanks to the photometric databases collected by the large microlensing surveys: MACHO and OGLE. Alcock *et al.* (1996) announced the discovery of about 7900 RR Lyr stars in the LMC on the basis of the MACHO observations. The OGLE-II project has cataloged 7612 RR Lyr stars (Soszyński *et al.* 2003) detected in the 4.5 square degrees of the central regions of the LMC. Deep photometric and spectroscopic surveys for RR Lyr stars, but covering limited regions in the LMC, were conducted by Clementini *et al.* (2003), Borissova *et al.* (2004, 2006) and Di Fabrizio *et al.* (2005).

In this work we describe the catalog of nearly 25 000 RR Lyr stars in the LMC. Almost 1000 of them are double-mode pulsators. This is the third part of the OGLE-III Catalog of Variable Stars (OIII-CVS) – the catalog which is planned to comprise practically all variable sources in the OGLE-III fields in the Magellanic Clouds and the Galactic bulge. In the previous papers of this series we presented the catalogs of 3361 classical Cepheids (Soszyński *et al.* 2008a, hereafter Paper I), 197 type II Cepheids and 83 anomalous Cepheids in the LMC (Soszyński *et al.* 2008b, hereafter Paper II).

This paper is organized as follows. In Section 2 we describe the reductions and calibrations of the data. In Section 3 details on the RR Lyr stars identification and classification are provided. In Section 4 we describe the catalog itself and compare it with other catalogs of RR Lyr stars in the LMC. In Section 5 we discuss some aspects concerning statistical features of RR Lyr stars in the LMC. In Section 6 we draw our conclusions.

2. Observations and Data Reduction

Photometric observations presented in this catalog were carried out with the 1.3-m Warsaw telescope located at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution of Washington. The "second generation" camera uses eight SITe 2048×4096 CCD detectors with 15 μm pixels resulting in 0.26 arcsec/pixel scale and $35' \times 35\farcm5$ field of view. For the details of the instrumentation setup we refer the reader to Udalski (2003).

OGLE-III fields in the LMC cover nearly 40 square degrees and about 32 million stars. Approximately 400 photometric points per star were accumulated over seven seasons, between July 2001 and March 2008. Most of the observations were done through the Cousin's *I*-band filter with exposure time 180 s. A few dozen observations per star have been obtained with the Johnson's *V*-band and integration time 225 s. The photometry of stars in the central regions of the LMC is supplemented by the OGLE-II data collected between 1997 and 2000 using the same Warsaw telescope. For each individual star their mean magnitudes were derived independently for the OGLE-II and OGLE-III datasets, and the OGLE-II photometry was shifted to agree with the OGLE-III data.

Data reduction pipeline was based on the Difference Image Analysis (DIA – Alard and Lupton 1998, Alard 2000, Woźniak 2000). Photometric errors produced by the DIA package were corrected using a program developed by J. Skowron (the technique is described in detail in Wyrzykowski *et al.* 2009). Full description of the reduction techniques, photometric calibration and astrometric transformations can be found in Udalski *et al.* (2008).

3. Identification and Classification of RR Lyr Stars

3.1. Single-Mode RR Lyr Stars

All light curves in the LMC collected during the OGLE-III project have passed through a period search algorithm using supercomputers at the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM). We used program FNPEAKS (Kołaczkowski, private communication) which is based on the Fourier analysis. The frequency space ranged from 0 to 24 cycles per day, with a search interval of 0.0001 cycles per day. For each star the primary period was derived, then the light curve was pre-whitened with this period and the procedure of period search was repeated on the residual data.

From the sample of 32 million stars in the LMC we filtered out objects with signal-to-noise ratio of the dominant frequency smaller than 5. Then, we subjected for visual inspection all stars with main periods between 0.2 and 1.0 day and brighter than $I = 20$ mag (during further analysis we also examined fainter objects but using higher threshold for the signal-to-noise parameter).

As a result of the visual inspection we removed artefacts, obvious eclipsing binaries and other non-pulsating stars. In case of doubts about the proper classification we used colors, amplitudes and Fourier parameters of the light curve decomposition to compare a given star with the whole sample of RR Lyr variables. However, in a number of cases we were not able to judge the types of variable stars, especially among overtone RR Lyr stars which typically exhibited symmetric light curves, similar to close eclipsing binaries. In the catalog we flagged these objects as uncertain.

During the classification process we detected 11 new classical Cepheids, which were overlooked in Paper I. We also noticed three extremely short-period 1O/2O double-mode Cepheids (or δ Sct stars, depending on the definition) with the first-overtone periods as short as 0.22 days. We included all these objects in the OGLE-III catalog of classical Cepheids in the LMC (Paper I) increasing the whole number of objects in that catalog to 3375. In the short-period domain several dozens of stars were categorized as high amplitude δ Sct (HADS) variables, as they were located on the extension of the Cepheid period–luminosity relation. Some of these objects exhibited secondary periods and followed the sequence of F/1O double-mode HADS in the Petersen diagram. These objects will be presented in one of the next parts of the OIII-CVS.

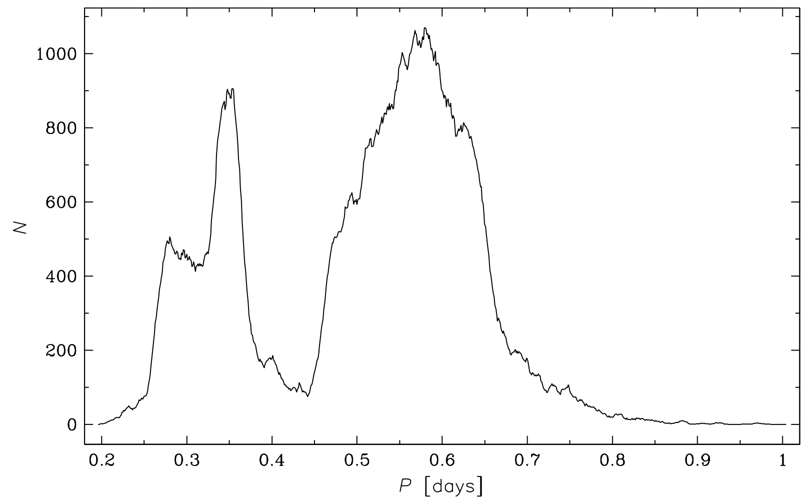

Fig. 1. Period distribution of RR Lyr stars in the LMC. The function is composed of ten histograms (with the bin width equal of 0.01 days) shifted by 1/10 of the bin width with respect to each other.

Our final sample of RR Lyr stars consists of 24 906 objects. This is the largest set of RR Lyr stars detected so far in any environment. The period distribution for the entire sample is shown in Fig. 1. This plot is composed of ten histograms (with the bin width of 0.01 days) shifted by 1/10 of the bin width with respect to each other. In such a way we could visualize more subtle effects of the period distribution.

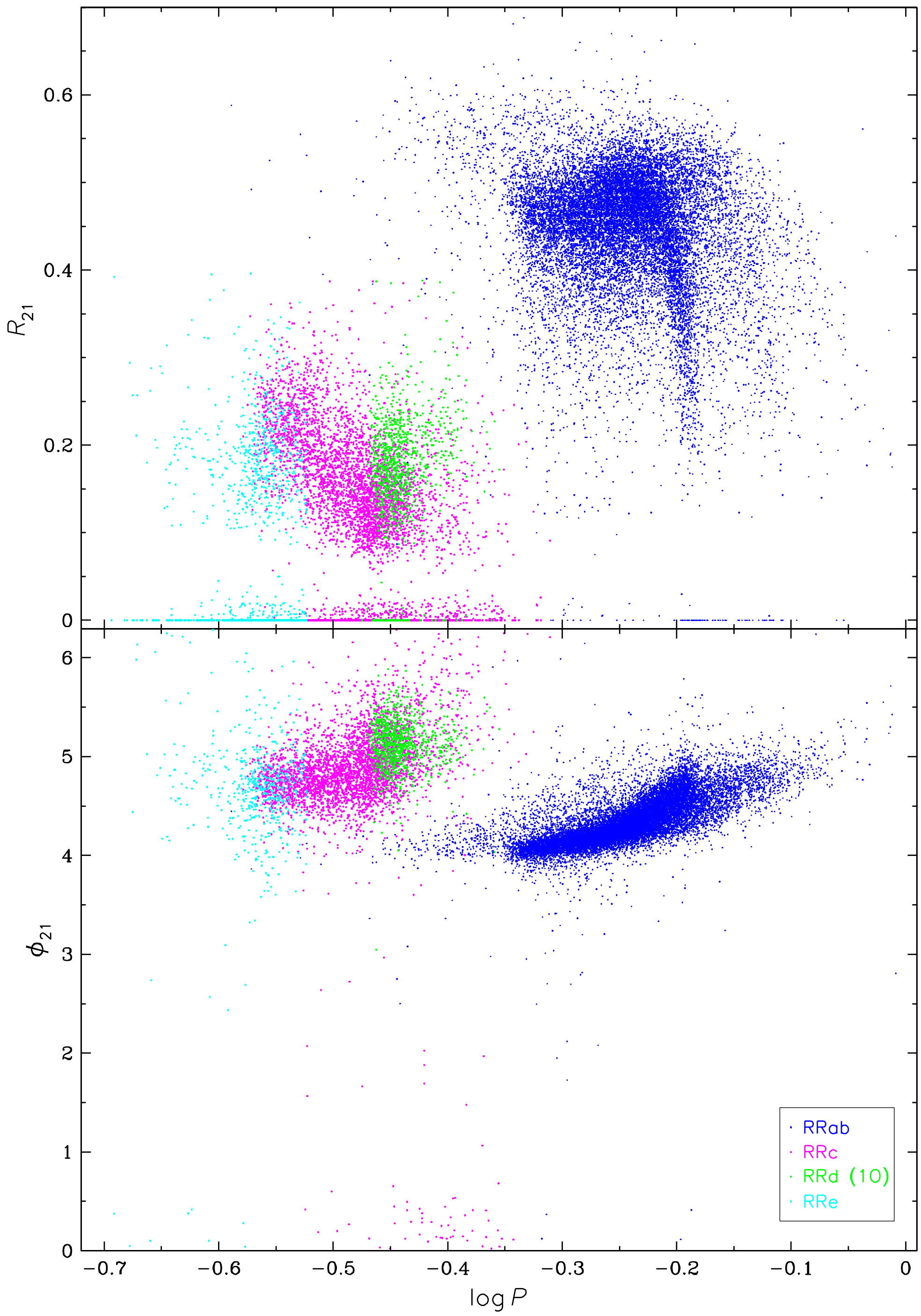

Fig. 2. Fourier parameters R_{21} and ϕ_{21} *vs.* $\log P$ for RR Lyr in the LMC. Blue, magenta, green and cyan points show RRab, RRc, RRd (first overtone) and RRe stars, respectively.

In Fig. 1 we identify three well-known maxima at periods of about 0.58, 0.35 and 0.28 days. The first two peaks correspond to fundamental-mode (RRab or RR0) and first-overtone (RRc or RR1) RR Lyr stars. We distinguished between both classes using shapes of their light curves that can be quantitatively described with the parameters of the Fourier decomposition: amplitude ratios $R_{k1} = A_k/A_1$ and phase differences $\phi_{k1} = \phi_k - k\phi_1$ (Simon and Lee 1981). Fig. 2 presents Fourier parameters R_{21}, ϕ_{21} plotted against $\log P$. The number of harmonics of the Fourier decomposition in each star was adjusted to minimize the χ^2 per degree of freedom. In some stars, mainly first-overtone pulsators, such solution gave only a pure sinusoid fit, and obviously for these objects R_{21} is equal to zero, while ϕ_{21} is not defined.

As can be noticed in Fig. 2, RRab and RRc stars are well separated in the diagrams showing the Fourier coefficients *vs.* periods. Thus, we used these planes to divide RR Lyr stars into fundamental-mode and overtone pulsators. A number of objects lying close to the boundary between both classes were visually examined and, in some cases, the automated classification was changed.

The origin of the shortest-period maximum in the period distribution is ambiguous. Alcock *et al.* (1996) suggested that such an additional peak may be a signature of the second overtone oscillations (RRe or RR2 stars). The other possibility is that these short period variables belong to a more metal-rich population of the first overtone RR Lyr stars (Bono *et al.* 1997). Regardless of the cause of this excess in the short-period domain, we designate these objects as RRe stars.

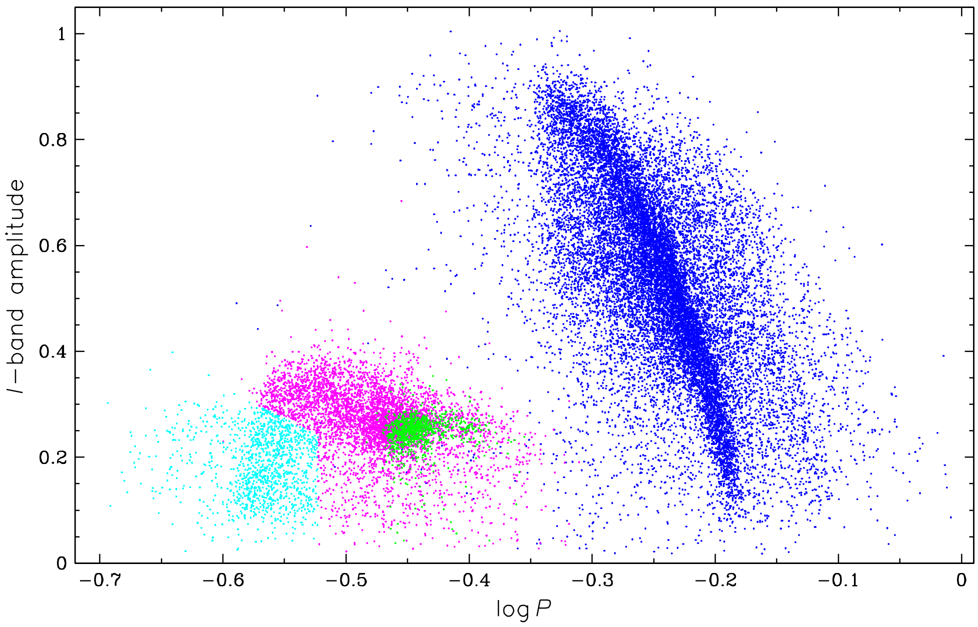

Fig. 3. Period–amplitude diagram for RR Lyr stars in the LMC. The color symbols are the same as in Fig. 2.

We note that RRc and RRe variables overlap in all diagrams that can be plotted using the OGLE-III data, so distinguishing between both groups is correct only in a statistical sense. In individual cases it can be wrong. To separate RRc and RRe stars we used period–amplitude diagram (sometimes called the Bailey diagram) presented in Fig. 3. RR Lyr stars with periods shorter than 0.3 days were divided into two groups according to their *I*-band amplitudes. Objects with lower amplitudes were classified as RRe stars.

3.2. Multi-Periodic RR Lyr Stars

Double-mode RR Lyr stars, known as RRd or RR01 stars, exhibit simultaneous oscillations in the fundamental and first overtone radial modes. Alcock *et al.* (1997a, 2000) reported the discovery of 181 RRd stars in the LMC. In the OGLE-II catalog of RR Lyr stars in the LMC (Soszyński *et al.* 2003) 230 objects were classified as double-mode pulsators.

The search for multi-periodic RR Lyr stars was carried out in two ways. First, we used the database of periods derived for all stars in the LMC. We selected the light curves that had statistically significant primary and secondary periods and their position in the Petersen diagram (*i.e.*, the plot of the period ratio *vs.* the longer period) was in agreement with the region occupied by RRd stars, *i.e.*, the longer period ranged between 0.44 and 0.60 days and the period ratio was between 0.74 and 0.75. These light curves were visually inspected and the initial list of double-mode RR Lyr stars was prepared.

The second part of the double-mode search was performed for all RR Lyr stars selected before. Each light curve was fitted with the Fourier series and the residuals of the fit were searched for secondary frequencies. Again, we visually examined the light curves with periods and period ratios similar to these of RRd stars.

Our final list of RRd variables contains 986 objects. Fig. 4 shows the Petersen diagram for these stars. The well known curved sequence in this diagram is clearly visible, although several outlying points also exist. These stars may be RRd variables with unusual physical properties (see Popielski *et al.* 2000), but it is also possible that the secondary periods in these objects are caused by something else than the radial pulsations (*e.g.*, nonradial oscillations, blending with another periodic variable, etc.). Lower panel of Fig. 4 shows ratio of *I*-band amplitudes in both modes (first overtone to fundamental mode) against $\log P$. The first overtone dominates in most of the RRd stars, but in some cases the fundamental mode variations have larger amplitudes, in particular for stars with the shortest periods. It is evident that the typical minimum and maximum values of the A_{1O}/A_F amplitude ratios are correlated with periods.

Apart from RRd stars, we found a number of double-periodic RR Lyr variables with ratios of periods inconsistent with simultaneous oscillations in the fundamental mode and the first overtone. For about 20% of RRab stars, 19% of RRc and 25% of RRe stars we detected secondary frequencies very close to the primary ones,

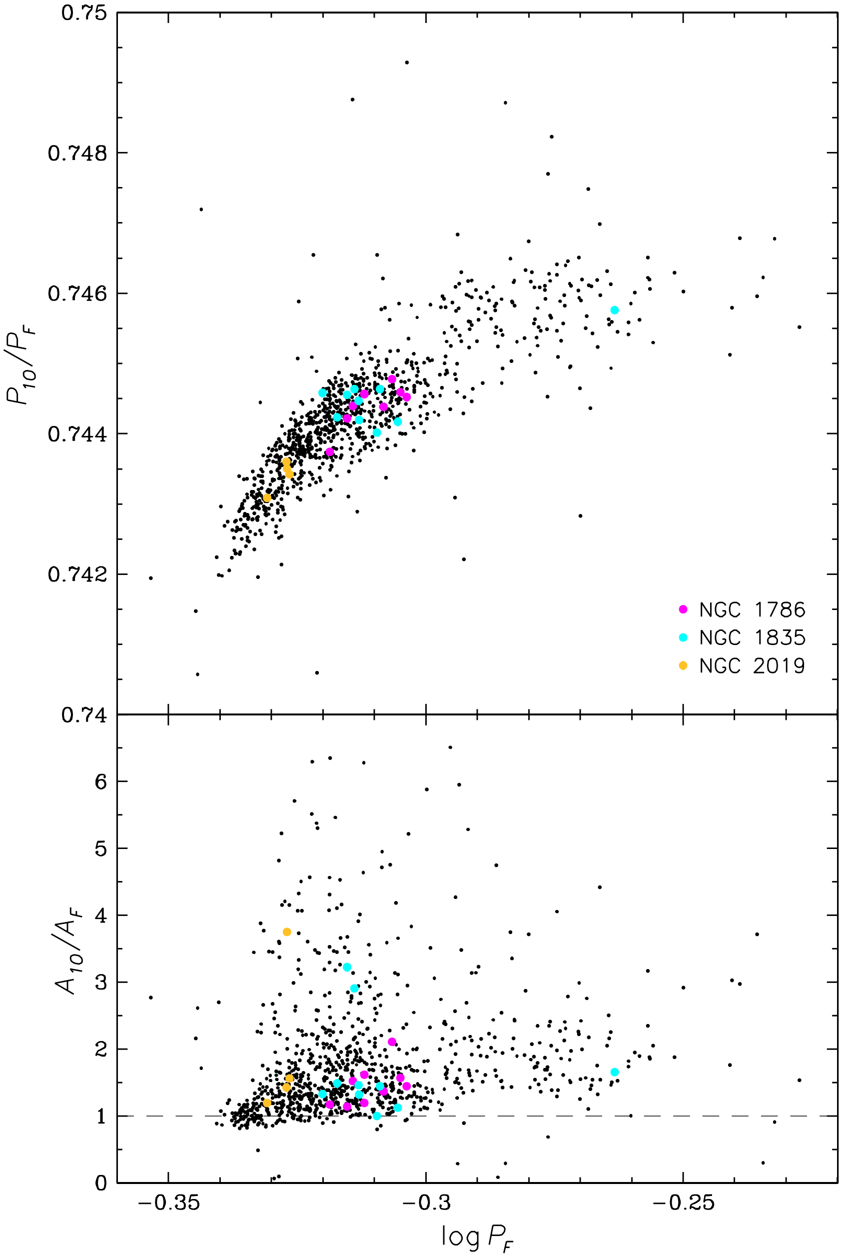

Fig. 4. Petersen diagram for RRd stars in the LMC (*upper panel*) and the amplitude ratio between first overtone and fundamental mode *vs.* $\log P$ (*lower panel*). Color symbols mark RRd stars in the three LMC globular clusters: NGC 1786 (magenta), NGC 1835 (cyan) and NGC 2019 (yellow).

with period ratios larger than 0.9. Such stars, commonly referred to as Blazhko RR Lyr stars, are suspected to exhibit nonradial modes of pulsation (Olech *et al.* 1999, Dziembowski and Mizerski 2004). Alcock *et al.* (2000) distinguished several variants of this behavior, with two, three or more close frequency components in the power spectra. Our simple frequency analysis does not settle the question of which variant is exhibited in a given object. Moreover, the secondary periods in the residual data may also be produced by RR Lyr stars changing their periods. Temporal coverage of the OGLE photometric database is long enough to study the period changes of RR Lyr stars. For many objects, mainly RRc stars, we noticed that their light curves cannot be folded with the constant periods, because the rates of the period changes are so large. Similar considerable period changes that cannot be explained by the evolutionary effects were recently found in the LMC classical Cepheids by Poleski (2008). The relatively large (compared to other investigations) incident rate of RRc stars with close frequencies is likely caused by these period-changing pulsators.

A number of RR Lyr stars show secondary periodicities which are distinctly different than primary ones, but these objects cannot be unambiguously categorized to any group. For example, in two stars (OGLE-LMC-RRLYR-11983, OGLE-LMC-RRLYR-14178) we detected secondary periods that give period ratios of about 0.60–0.61. Similar objects were recently discovered by Olech and Moskalik (2009) in ω Cen. Information about the secondary periodicities for individual stars is provided in the remarks in the catalog.

Olech and Moskalik (2009) also announced the discovery of a candidate double-mode RR Lyr star with the first and the second overtones excited. In our sample we did not find any reliable candidate for such an object. Admittedly, one of the RRd stars (OGLE-LMC-RRLYR-02746) shows an additional period of 0.291121 days giving the period ratio of 0.806 with the first-overtone mode, but we detected another RR Lyr variable (OGLE-LMC-RRLYR-02743) with the same period (0.291121 days) and located at a distance of only $0\overset{\prime\prime}{.}7$ from the former star. Since this distance is smaller than the typical size of the seeing disk in the OGLE-III frames ($1\overset{\prime\prime}{.}2$), we suspect the tertiary period in OGLE-LMC-RRLYR-02746 is an artefact produced by blending with the other RR Lyr star. The image taken by the Hubble Space Telescope and retrieved from the Hubble archive indeed confirms that two close stars are present in this location.

A special attention was paid to search for RR Lyr stars with additional, eclipsing variations overimposed on the pulsation light curves. At present, no RR Lyr star being a member of an eclipsing binary system is known. The OGLE-II project yielded three RR Lyr stars with simultaneous eclipsing modulation (Soszyński *et al.* 2003), but all of these objects turned out to be optical blends (Prša *et al.* 2008). In the present sample of RR Lyr stars we re-detected these three cases and found one additional RR Lyr variable with eclipses. OGLE-LMC-RRLYR-03541 has orbital period equal to 16.229 days and it is a good candidate for RR Lyr star in an eclipsing binary system. The light curve of this object is plotted in Fig. 5. The original I-band photometry folded with the pulsation period is shown in the left panel, while the right panel shows the eclipsing light curve after subtracting the RR Lyr component.

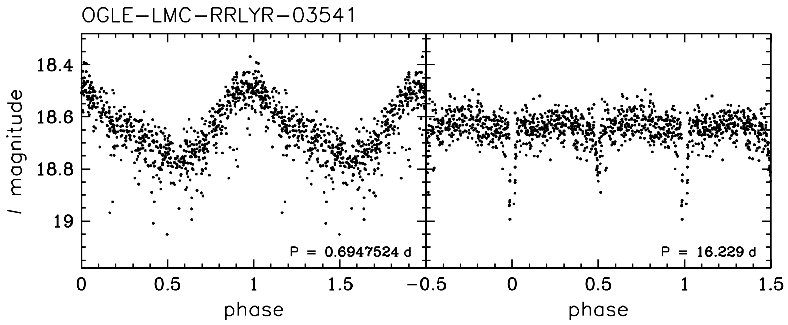

Fig. 5. Light curve of the RR Lyr star with additional eclipsing variability. *Left panel*: the original photometric data folded with pulsation period. *Right panel*: eclipsing light curve after subtracting the RR Lyr component.

It is interesting that among 24 906 RR Lyr stars we found only one candidate for eclipsing binary system with a pulsating star as one of the components, while the catalog of 3361 classical Cepheids in the LMC (Paper I) contains four such objects (including an eclipsing system of two Cepheids) and the catalog of 197 type II Cepheids in the LMC (Paper II) lists as many as seven pulsating stars with eclipses. These extremely different incident rates of binary systems among pulsating stars can be explained by different evolution of these stars in the past. The radius of a star at the tip of the red giant branch is by a factor of 15 larger than the radius of a star located on the horizontal branch. Thus, only long-period binary systems (with periods longer than several hundred days; Dziembowski, private communication) can avoid mass exchange in the phase of the first ascent red giant branch. Now, in the RR Lyr phase, the stars have much smaller sizes and the probability of producing eclipses in such long-period binary systems is very low.

Assuming that OGLE-LMC-RRLYR-03541 is a member of the binary system, its orbital period is too short for the system to remain detached during the previous phases of the stellar evolution. Explaining the evolution of such a system could be a real challenge for the theory.

4. The Catalog

The OGLE-III catalog of RR Lyr stars in the LMC contains 24 906 objects, of which 17 693 are RRab, 4958 – RRc, 986 – RRd, and 1269 – RRe stars. The list of objects with their multi-epoch *VI* photometry and finding charts is available on-line through the WWW interface or *via* anonymous FTP site:

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

In the FTP site the full list of RR Lyr stars is given in the file ident.dat. The stars are listed in order of increasing right ascension and designated with symbols

OGLE-LMC-RRLYR-NNNNN, where NNNNN is a five digit consecutive number. The file ident.dat contains the following information about each RR Lyr star: the object designation, OGLE-III field and internal database number of a star, mode of pulsation (RRab, RRc, RRd or RRe), equinox J2000.0 right ascension and declination, cross-identifications with the OGLE-II catalog of RR Lyr stars in the LMC (Soszyński *et al.* 2003), with the MACHO catalog (Alcock *et al.* 1996, 1997a, 2000) and with the extragalactic part of the General Catalogue of Variable Stars (GCVS – Artyukhina *et al.* 1995). In the last column there are other designations taken from the GCVS.

Basic parameters of the RR Lyr stars are provided in the files RRab.dat, RRc.dat, RRd.dat and RRe.dat. For single-mode objects the consecutive columns contain: object designation, intensity mean magnitudes in the I and V bands, periods in days and their uncertainties, epochs of maximum light, peak-to-peak I-band amplitudes, and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} derived for the I-band light curves. For RRd stars the format of the table is longer including secondary periodicities. Periods and their uncertainties were derived using program TATRY by Schwarzenberg-Czerny (1996).

The file remarks.txt contains additional information on some RR Lyr stars. The subdirectory phot/ contains multi-epoch I- and V-band OGLE photometry of the stars. If available, OGLE-II data are 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.

To test the completeness of our catalog we matched our initially selected sample with two large selections of RR Lyr stars in the LMC – the OGLE-II and the MACHO catalogs. The OGLE-II project released the catalog of 7612 RR Lyr variables (Soszyński *et al.* 2003). In the present sample, we found no counterparts for 205 of them. From that number 50 stars were reclassified in the present investigation as classical or anomalous Cepheids, HADS or eclipsing binary systems. Most of the remaining 155 stars were located close to the edges of the OGLE-III fields and were affected by a small number of observations. We included these missing objects in the present catalog.

The list of RR Lyr stars in the LMC detected by the MACHO project was retrieved from the web-page of the survey[†]. After removing double detections and stars lying outside the OGLE-III fields we found 8745 stars in the list. In the preliminary version of our catalog we missed 151 of them. However, only 39 of these missing stars seem to be RR Lyr variables. The remaining objects usually belong to different types of variable stars, most of them being eclipsing binaries. It is worth noting that for about 220 positively cross-identified RR Lyr stars the periods provided in the MACHO list seemed to be aliases of the periods derived here.

[†]http://wwwmacho.mcmaster.ca/

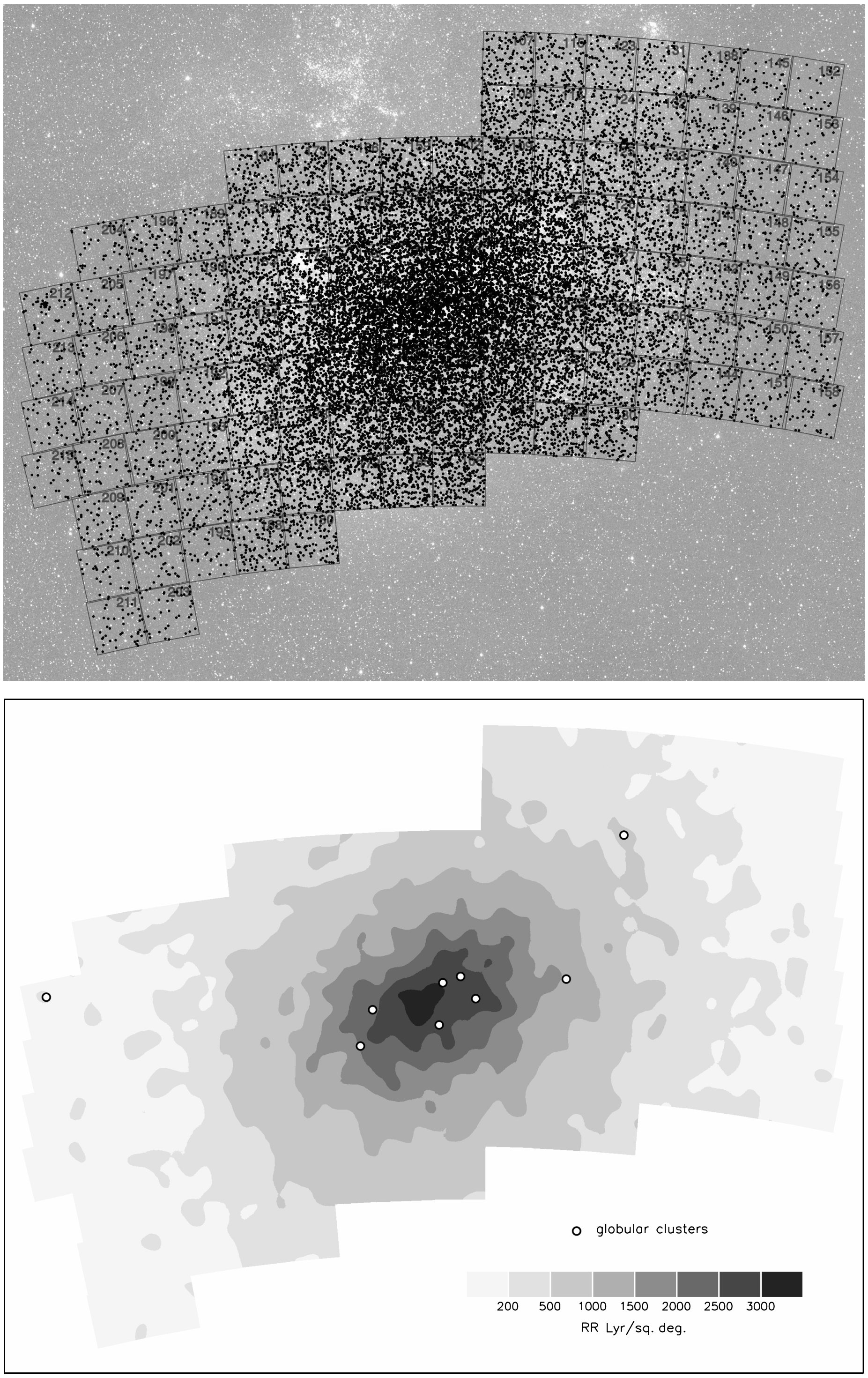

Fig. 6. *Upper panel*: spatial distribution of RR Lyr stars in the LMC. The background image of the LMC is originated from the ASAS sky survey. *Lower panel*: surface density map of RR Lyr stars in the LMC. White circles show positions of globular clusters.

Our sample was also compared with the LMC RR Lyr stars listed in the GCVS (Artyukhina *et al.* 1995). Unfortunately, 151 of the 197 LMC stars classified as RR Lyr stars in the GCVS were located outside the OGLE-III fields. From the remaining variables our catalog includes 42 objects. Two stars (LMC V0588, LMC V4498) turned out to be classical Cepheids (Paper I), one (LMC V0464) was classified as an anomalous Cepheid (Paper II). We found no counterpart for one star (LMC V0546) classified in the GCVS as "RRAB:".

5. Discussion

The upper panel of Fig. 6 displays the position of OGLE-III RR Lyr stars overplotted on the image originated in the ASAS-3 survey (Pojmański 1997). After smoothing this distribution with the Gaussian filter we obtained a surface density map visualized in the lower panel of Fig. 6. It is evident that the distribution of field RR Lyr stars in the LMC is elongated along the LMC bar. This result confirms the conclusion of Subramaniam (2006) drawn on a basis of the OGLE-II catalog of RR Lyr stars.

In the lower panel of Fig. 6 we also marked globular clusters in which RR Lyr stars were found. The catalog of extended objects in the Magellanic System recently published by Bica *et al.* (2008) lists 16 genuine globular clusters in the LMC. Five of these objects are out of the OGLE-III fields. We used the coordinates and angular sizes for the remaining 11 clusters provided by Bica *et al.* (2008) to select RR Lyr stars located inside the area outlined by the cluster radii.

Table 1

Globular clusters containing RR Lyr stars

Cluster name	RA (J2000)	Dec (J2000)	Cluster radius [$'$]	$N_{\rm RR}$	$N_{\rm ab}$	$N_{\rm c}$	$N_{\rm d}$	$N_{\rm e}$
NGC 1754	$4^h54^m17^s$	$-70°26'29''$	1.6	36	20	15	0	1
NGC 1786	$4^h59^m06^s$	$-67°44'42''$	2.0	55	28	18	9	0
NGC 1835	$5^h05^m06^s$	$-69°24'14''$	2.3	109	63	30	10	6
NGC 1898	$5^h16^m41^s$	$-69°39'23''$	1.6	49	31	16	0	2
NGC 1916	$5^h18^m38^s$	$-69°24'23''$	2.1	25	15	10	0	0
NGC 1928	$5^h20^m57^s$	$-69°28'40''$	1.3	8	7	1	0	0
NGC 1939	$5^h21^m26^s$	$-69°56'59''$	1.4	7	3	4	0	0
NGC 2005	$5^h30^m10^s$	$-69°45'10''$	1.6	18	9	9	0	0
NGC 2019	$5^h31^m56^s$	$-70°09'33''$	1.5	61	36	15	4	6
NGC 2210	$6^h11^m31^s$	$-69°07'18''$	3.3	58	34	21	0	3

In the cluster Hodge 11 we found only one RR Lyr variable and it is probably a field star. Toward the clusters NGC 1939 and NGC 1928 we detected seven and eight RR Lyr stars, respectively. These numbers are somewhat larger than the expected numbers of field RR Lyr stars in the regions occupied by clusters, but the possibility that all these variables belong to a field cannot be ruled out. For the remaining eight globular clusters there are no doubts that the bulk of RR Lyr stars identified around them belong to these clusters. Table 1 summarizes the information about RR Lyr stars in the star clusters in the LMC. This table lists, from the left to right, designation of the cluster, coordinates of the cluster center and cluster radius (from Bica *et al.* 2008), the total number of RR Lyr stars detected within the cluster radius and the number of RRab, RRc, RRd and RRe stars in each cluster.

Three of the clusters presented in Table 1 host RRd stars. In Fig. 4 we highlighted these objects in colors to show that the cluster RRd stars occupy relatively limited area in the Petersen diagram compared to the field variables. This is related to a much smaller range of metal abundances in the LMC clusters than in the field.

The period–luminosity (PL) diagrams for RR Lyr stars in the LMC in V, I and extinction insensitive Wesenheit index $W_I = I - 1.55(V - I)$ are plotted in Fig. 7. The magnitudes shown in the two upper panels are not compensated for interstellar extinction. The PL relations are clearly visible with the slopes which depend on the waveband. One can notice that many objects in our catalog are significantly brighter or fainter than typical RR Lyr stars with a given period. Most of the RR Lyr stars above the PL relations (in case of the $\log P$–W_I diagram also below the relation) are blended objects. Their amplitudes are usually reduced compared to unblended RR Lyr variables with the same periods.

However, among these bright stars we detected 66 Galactic RR Lyr stars lying in the front of the LMC. Their light curves, amplitudes and $(V - I)$ colors are similar to the LMC RR Lyr stars. 55 of these foreground RR Lyr stars are RRab variables, 8 were classified as RRc stars, 1 as RRe, and 2 of them are double mode RRd stars. The distances to the Galactic RR Lyr stars derived on the basis of their magnitudes seem to be almost uniformly distributed, with no concentration toward any particular distance between us and the LMC. It is in agreement with the result presented by Alcock *et al.* (1997b) who used the MACHO database to select 20 RR Lyr stars lying in the front of the LMC.

The bulk of RR Lyr stars significantly fainter than the PL relations are highly reddened objects. They are well visible in the color–magnitude diagram plotted in Fig. 8. The tail of points in the lower right part of the diagram outlines the reddening vector.

The apparent V-band magnitudes of RRab stars have the modal value at 19.36 mag. The overtone RR Lyr stars (RRc, RRd and RRe stars) are somewhat brighter in this filter – the most preferred V-band magnitude for these stars is about 19.32 mag. In the I-band fundamental-mode RR Lyr variables are on average brighter (18.78 mag) than overtone pulsators (18.88 mag).

Among variables classified as RRab stars the shortest periods are below 0.3 days, the longest periods are around 1 day, but more than 95% of fundamental-mode RR Lyr stars have periods in the range of 0.45–0.75 days. Mean period of RRab

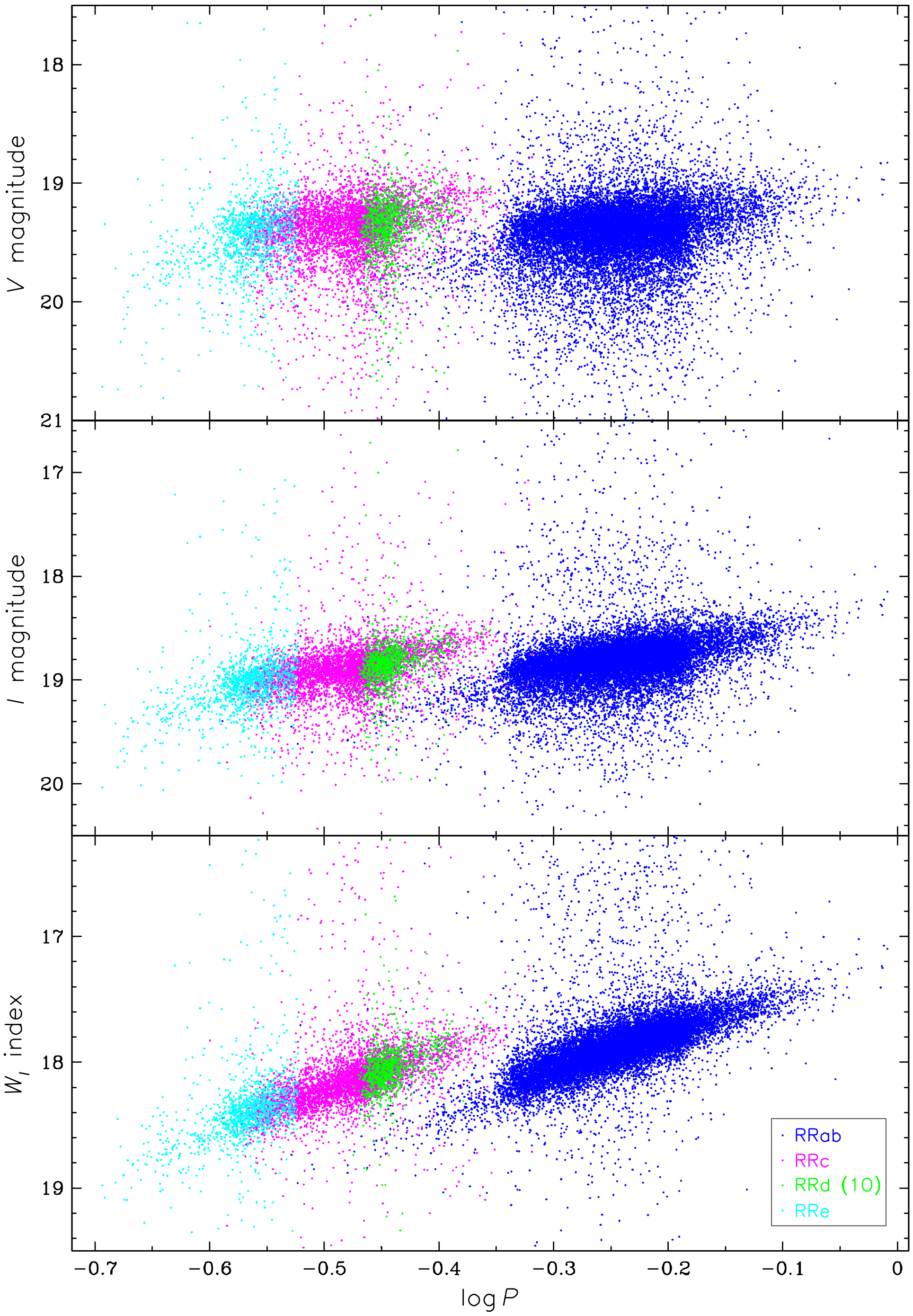

Fig. 7. Period–luminosity diagrams for RR Lyr stars in the LMC. The color symbols are the same as in Fig. 2.

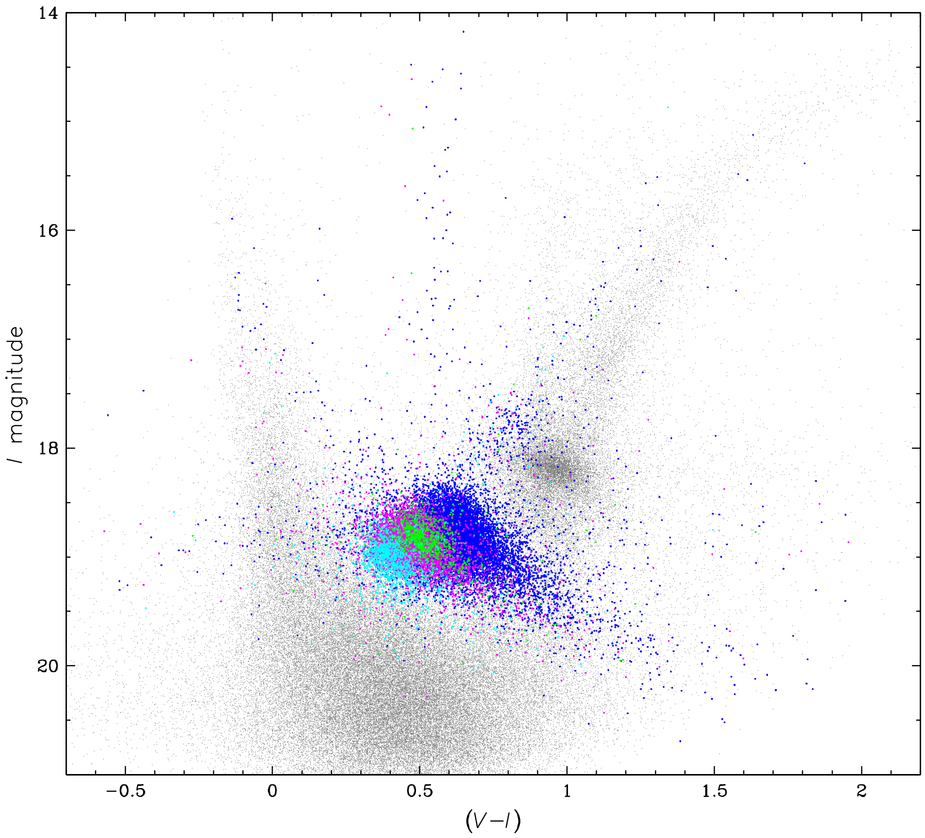

Fig. 8. Color–magnitude diagram for RR Lyr stars in the LMC. The color symbols are the same as in Fig. 2. In the background stars from the subfield LMC100.1 are plotted.

stars in the LMC is $\langle P_{ab} \rangle = 0.576$ days, and it is close to the most preferred period (Fig. 1) for these objects: 0.580 days. The periods of RRc stars range from 0.25 to 0.49 days with a mean value of $\langle P_c \rangle = 0.337$ days, and a modal period of 0.341 days. The first-overtone periods of RRd stars are between 0.33 and 0.44 days with a mean value of $\langle P_d^{1O} \rangle = 0.363$ days and the most likely period of 0.357 days. Finally, for RRe stars $\langle P_e \rangle = 0.270$ days and the most frequent period is 0.272 days.

6. Conclusions

In this part of the OIII-CVS we presented a selection of almost 25 000 RR Lyr stars in the LMC – almost three times larger than the largest sample of RR Lyr stars published to date. This is the largest set of RR Lyr stars identified so far in any environment.

This huge sample provides a unique opportunity to investigate in detail various statistical features of these objects, like relations between observational and physical parameters of RR Lyr stars (*e.g.*, Jurcsik and Kovács 1996, Morgan *et al.* 2007), incidence rates of the Blazhko variables, or spatial distribution of RR Lyr stars in the LMC. Long-term OGLE photometry can be also used for examining secular changes in RR Lyr stars.

Acknowledgements. We are grateful to Prof. W.A. Dziembowski for critical reading of the paper and clearing up the problem of pulsating stars in eclipsing binary systems. We thank Drs. Z. Kołaczkowski, T. Mizerski, G. Pojmański, A. Schwarzenberg-Czerny and J. Skowron for providing the software which enabled us to prepare this study.

This work has been supported by the Foundation for Polish Science through the Homing (Powroty) Program and by MNiSW grants: NN203293533 to IS and N20303032/4275 to AU.

The massive period search was performed at the Interdisciplinary Centre for Mathematical and Computational Modeling of Warsaw University (ICM UW), project no. G32-3. We are grateful to Dr. M. Cytowski for helping us in this analysis.

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