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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. IX. RR Lyr Stars in the Small Magellanic Cloud*

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ABSTRACT

The ninth part of the OGLE-III Catalog of Variable Stars (OIII-CVS) comprises RR Lyr stars in the Small Magellanic Cloud (SMC). Our sample consists of 2475 variable stars, of which 1933 pulsate in the fundamental mode (RRab), 175 are the first overtone pulsators (RRc), 258 oscillate simultaneously in both modes (RRd) and 109 stars are suspected second-overtone pulsators (RRe). 30 objects are Galactic RR Lyr stars seen in the foreground of the SMC.

We discuss some statistical features of the sample. Period distributions show distinct differences between SMC and LMC populations of RR Lyr variable stars, with the SMC stars having on average longer periods. The mean periods for RRab, RRc and RRe stars are 0.596, 0.366 and 0.293 days, respectively. The mean apparent magnitudes of RRab stars are equal to 19.70 mag in the *V*-band and 19.12 mag in the *I*-band. Spatial distribution of RR Lyr stars shows that the halo of the SMC is roughly round in the sky, however the density map reveals two maxima near the center of the SMC.

For each object the multi-epoch *V*- and *I*-band photometry collected over 8 or 13 years of observations and finding charts are available to the astronomical community from the OGLE Internet archive.

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

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

1. Introduction

RR Lyr variable stars are low-mass radially pulsating stars with periods in the range of 0.2–1 day. They appear in the galactic halos, thick disks and globular clusters. RR Lyr stars populate a narrow region in the H-R diagram, where the horizontal branch intersects the pulsational instability strip. Relatively small range of absolute mean magnitudes makes them useful distance indicators. RR Lyr stars are also excellent tracers of the oldest observable population of stars. In account on the pulsation modes, RR Lyr stars can be divided into fundamental-mode (RRab), first-overtone (RRc) and double-mode (RRd) pulsators. An existence of the second-overtone pulsators among RR Lyr stars (RRe) is a matter of controversy (Bono *et al.* 1997).

The first attempt to detect RR Lyr stars in the Small Magellanic Cloud (SMC) was made by Shapley (1922). He suggested that 13 variable stars in this galaxy with periods below 1 day were cluster-type variable stars (the historical name of RR Lyr stars). The mean magnitude of these stars was 16.1, which was in excellent agreement with the Shapley's calibration of the Cepheid and RR Lyr distance scales. Years later, Payne-Gaposchkin and Gaposchkin (1966) showed that the periods provided by Shapley (1922) for these 13 stars were spurious, and most of these objects were classical Cepheids. Also three short-period variable stars discovered in the SMC by Dertayed and Landi Dessy (1952), and suggested to be RR Lyr stars, appeared to be classical Cepheids.

The discovery of the first actual RR Lyr stars in the SMC was reported by Thackeray (1951). Three RR Lyr variable stars in the SMC cluster NGC 121 and four more in the vicinity of that cluster turned out to be of about 19 mag, which was the first independent confirmation of the revised distance scale proposed by Baade (1952). Then, the extensive survey for RR Lyr stars in the SMC was performed by Graham (1975), who discovered 76 RR Lyr stars in the field centered on NGC 121. Smith *et al.* (1992) found 22 certain and 20 suspected (with no period determination) RR Lyr stars in the Northeast Arm of the SMC. Kaluzny (1998) discovered 12 SMC RR Lyr variable stars behind the Galactic globular cluster 47 Tuc. At the end of the twentieth century more than about one hundred RR Lyr stars in the SMC were known.

This number was significantly increased by the Optical Gravitational Lensing Experiment (OGLE). Soszyński *et al.* (2002) published the catalog of 571 RR Lyr stars in the central 2.4 square degrees of the SMC. These objects were discovered using the photometric material collected during the second stage of the OGLE survey (OGLE-II). In this paper we use the OGLE-III data to increase by several times the number of known RR Lyr stars in the SMC. Our catalog contains 2475 variable stars, including 30 Galactic RR Lyr stars in the foreground of the SMC. This is a part of the OGLE-III Catalog of Variable Stars (OIII-CVS) which assembled so far about 130 000 variable stars in both Magellanic Clouds. Among others, we published the catalog of 24 906 RR Lyr stars in the Large Magellanic Cloud (LMC;

Soszyński *et al.* 2009), and the catalogs of classical (4630 objects) and type II (43 objects) Cepheids in the SMC (Soszyński *et al.* 2010ab).

The paper is structured as follows. In Section 2 we present the photometric data and the reduction methods. Section 3 describes the variable stars selection process. Section 4 presents the catalog itself. Section 5 is devoted to the comparison of our sample with the previously published catalogs of RR Lyr stars in the SMC. Finally, we discuss some features of our sample of RR Lyr stars in Section 6.

2. Observational Data

The catalog is based on the observations carried out with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile. 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 OGLE-III project obtained time-series observations of the SMC during about 800 nights between June 2001 and May 2009. About 90% of the observations were made with the *I*-band filter, the remaining measurements were obtained in the *V* photometric band. The exposure time was 180 sec and 225 sec in the *I*- and *V*-bands, respectively. The total area regularly observed by the OGLE-III project was about 14 square degrees distributed over 41 fields. The OGLE data reduction pipeline was developed by Udalski (2003) on the basis of the Difference Image Analysis (DIA; Alard and Lupton 1998, Alard 2000, Woźniak 2000). Full description of the reduction techniques, photometric calibration and astrometric transformations can be found in Udalski *et al.* (2008a).

Some stars were detected twice, because they were located in the overlapping regions of adjacent fields. The photometry of these objects was compiled from all available sources. For the stars in the central 2.4 square degrees of the SMC the OGLE-III photometry was supplemented with the OGLE-II observations (Szymański 2005) collected between 1997 and 2000. Both datasets were tied by shifting the OGLE-II photometry to agree with the OGLE-III light curves.

3. Selection and Classification of RR Lyr Stars

All *I*-band light curves collected by the OGLE-III survey were searched for periodicity with the FNPEAKS code kindly provided by Z. Kołaczkowski. The software used Discrete Fourier Transform to output the most significant periodicities with amplitudes and signal-to-noise ratios (S/N) for a given light curve. The Fourier spectra were calculated up to 24 d^{-1} for each star. All light curves with $S/N > 5$ and primary periods between 0.2 and 1 day were visually examined and divided into pulsating-like, eclipsing-like and other variable objects. Then, the stars tentatively classified as possible pulsating variable stars were classified by means of the detected periods, colors, magnitudes, amplitudes, light curve shapes, period ratios (for multiperiodic stars), etc.

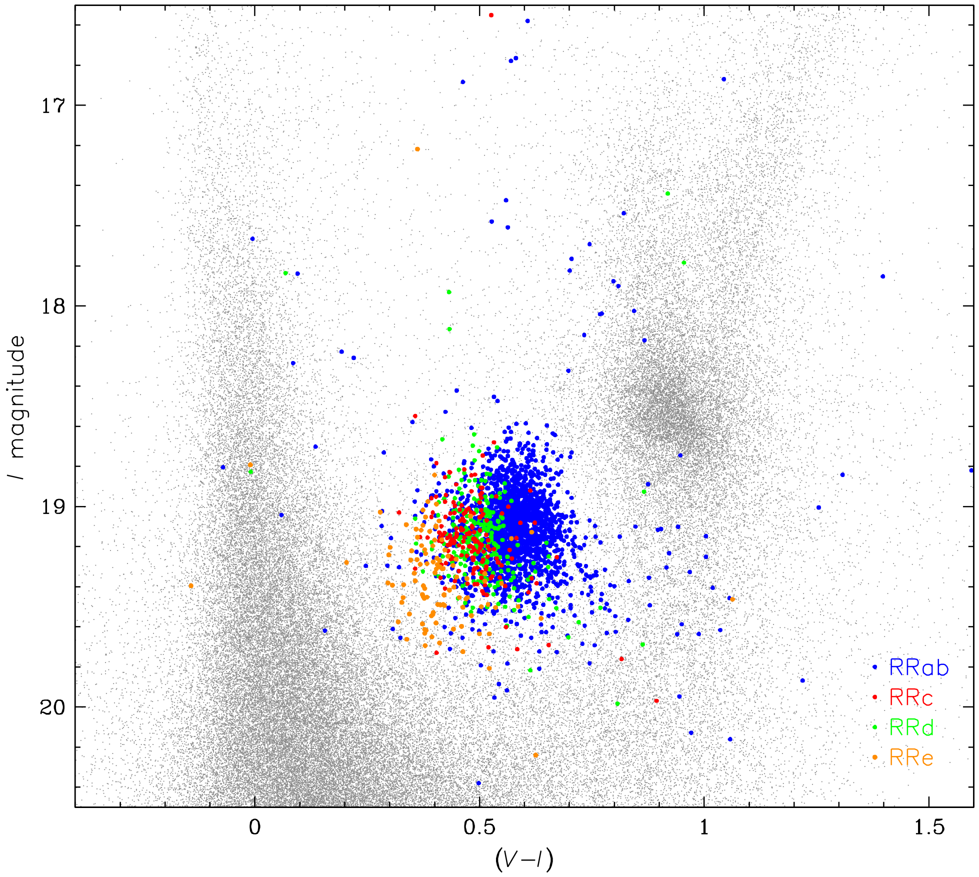

Fig. 1. Color–magnitude diagram for RR Lyr stars in the SMC. Blue points represent RRab stars, red – RRc stars, green – RRd stars, yellow – RRe stars. Grey dots show all stars from the fields SMC100.1 and SMC100.2.

Our search revealed a number of δ Sct stars, which lie at the extension of the period–luminosity relation for first-overtone classical Cepheids, so they are generally brighter than RR Lyr stars with the same periods. The list of δ Sct stars in the SMC will be published elsewhere. Some of the stars categorized in our catalog as RR Lyr stars have atypical $(V-I)$ colors and magnitudes in one or both filters. These objects are visible as outliers in the $(V-I)$ *vs.* I color–magnitude diagram plotted in Fig. 1. The amplitudes of these variable stars are usually reduced compared to typical RR Lyr stars with the same periods. We assumed that these objects are unresolved blends of RR Lyr variable stars with other stars. In these cases our classification is based on their light curve morphology. Our sample includes also

30 variable stars brighter than SMC RR Lyr stars that are likely Galactic RR Lyr stars in the foreground of the SMC. For several of the brightest (*i.e.*, the nearest) objects from that group proper motions are detectable in the OGLE data. One of the foreground RR Lyr stars (OGLE-SMC-RRLYR-0051 = V9 = HV 810) belongs to 47 Tuc cluster (Storm *et al.* 1994).

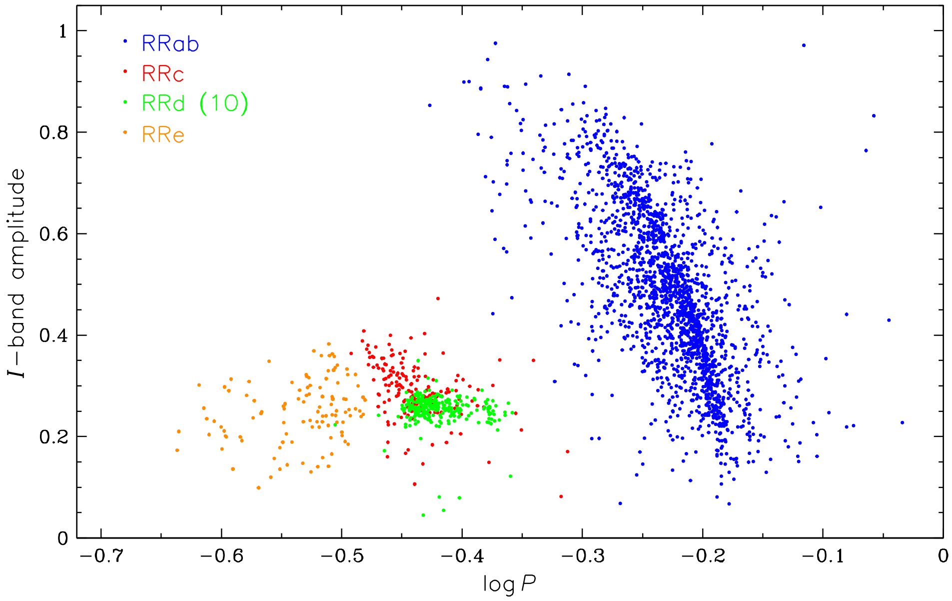

Fig. 2. Period–amplitude diagram for RR Lyr stars in the SMC. Color symbols denote the same type of stars as in Fig. 1. RRd stars are represented by the first-overtone periods.

Single-mode RR Lyr stars were divided into three groups: RRab, RRc and RRe variable stars. Distinguishing between fundamental-mode and overtone pulsators was a relatively easy task, thanks to the very different shapes of the light curves in both classes. In several questionable cases we also used the amplitudes of variations (Fig. 2), positions in the period–luminosity diagrams and parameters of the Fourier light curve decomposition. We decided to separate RRc and RRe variable stars, because, like in the LMC (Soszyński *et al.* 2009), we noticed additional peak in the period distribution for the shortest-period RR Lyr stars (Fig. 3). The peak is centered at $P \approx 0.31$ days. Similar secondary maximum was observed also in the Sculptor dwarf spheroidal galaxy (Kaluzny *et al.* 1995). This peak is usually attributed to the second-overtone RR Lyr stars (*e.g.*, Alcock *et al.* 1996), although other explanations are also possible (*e.g.*, Bono *et al.* 1997 suggested that this peak is a signature of a metal-rich population of RR Lyr stars). We separated RRe stars from RRc variable stars using their positions in the period–amplitude diagram (Fig. 2). The limiting maximum period of RRe stars was adopted at $P = 0.33$ days. Such an approach certainly has only statistical meaning. In individual cases our distinction between RRc and RRe stars may be wrong.

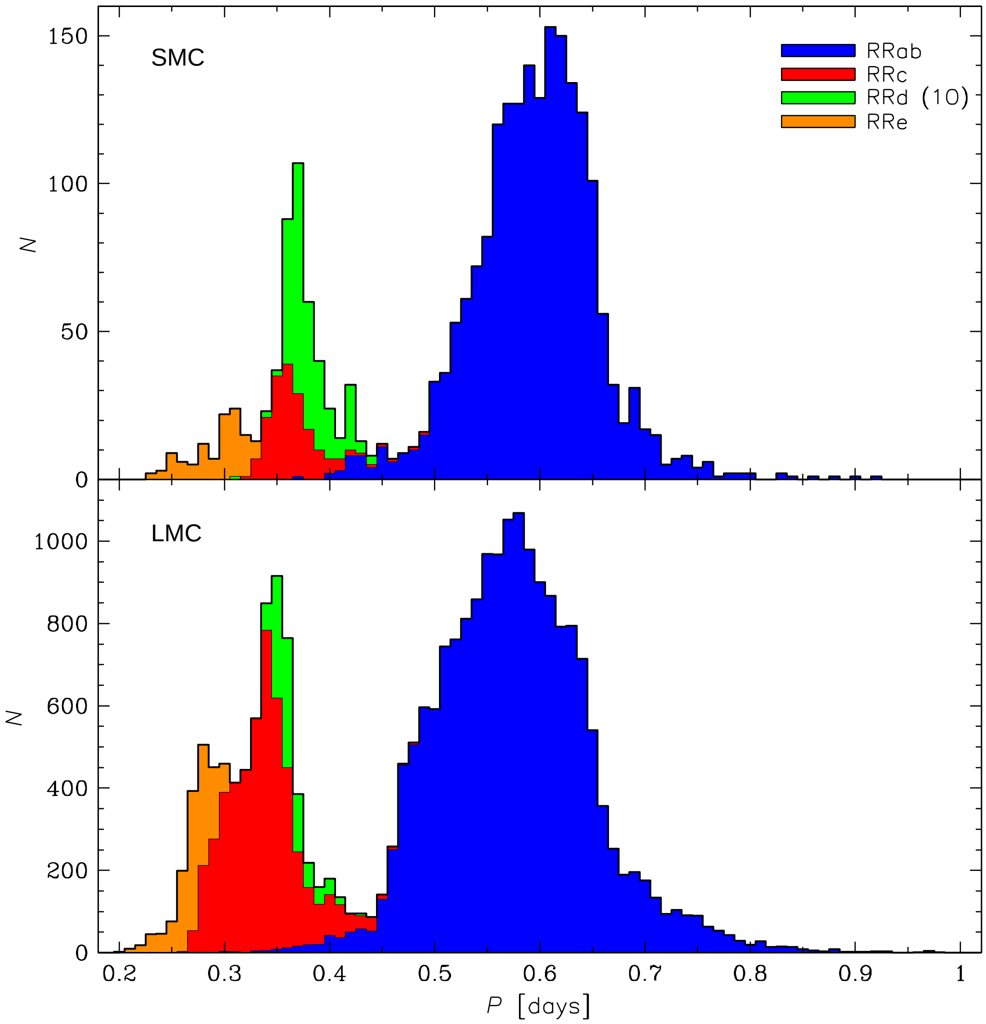

Fig. 3. Period distribution for RR Lyr stars in the SMC and LMC: cumulative histogram with different types of RR Lyr stars shown with different colors. Blue regions show RRab stars, red – RRc stars, green – the first-overtone period of RRd stars, and orange – RRe stars. The width of bins is 0.01 day.

We performed a search for double-mode RR Lyr stars (RRd) in two ways. First, we carried out a search for the secondary periods for all previously identified RR Lyr stars. Each light curve was fitted with a Fourier series with a number of harmonics minimizing the χ^2 per degree of freedom, the function was subtracted from the observational data and the period search was performed on the residual data. Then, the stars with periods and period ratios characteristic for RRd variable stars (*i.e.*, with longer periods in the range 0.42–0.6 days and shorter-to-longer period ratios between 0.74 and 0.75) were subjected for visual inspection. From that group we selected stars with significant secondary periods ($S/N > 4$).

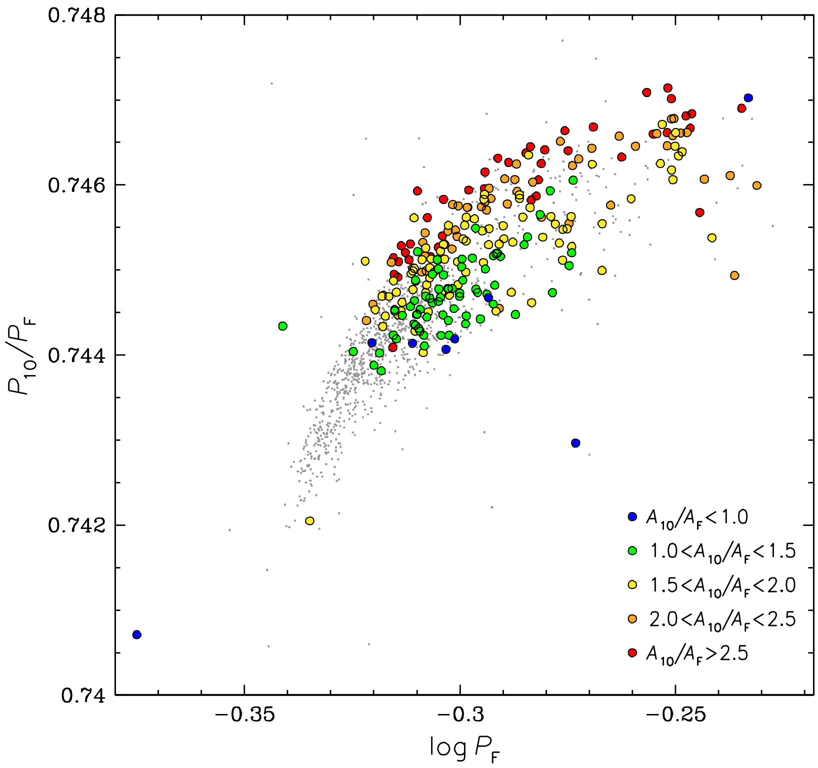

Fig. 4. Petersen diagram for RRd stars in the SMC. Different colors represent different amplitude ratios between the first overtone and fundamental mode. Grey small dots show RRd stars in the LMC (Soszyński *et al.* 2009).

The second method used to select double-mode RR Lyr stars based on the massive period search performed for all stars observed in the SMC by the OGLE-III project. We checked two dominant periods obtained from this analysis, searching for objects with periods and period ratios typical for RRd stars. After careful visual inspection of the light curves we extended the previously selected sample of RRd stars by a few objects. In total, we found 258 RRd stars. Fig. 4 shows the Petersen diagram (*i.e.*, a plot of the period ratio *vs.* logarithm of the fundamental period) for our sample. For comparison we also present here the LMC RRd stars from the catalog of Soszyński *et al.* (2009). Different colors of the points show different amplitude ratio of both pulsation modes ($A_{1O}/A_{\rm F}$). It is clear that the ratio of amplitudes is strongly correlated with the position of a double-mode RR Lyr star in the Petersen diagram.

During the search for RRd stars we noticed objects with the secondary periods very similar to the primary ones. Such a phenomenon can be related to the Blazhko effect or to the changes of the primary period. The time baseline of the OGLE data span up to 13 years, so the period changes are detectable for some RR Lyr stars. We detected closely-spaced secondary frequencies for about 22% of RRab stars, and 14% of the (single-mode) overtone variables.

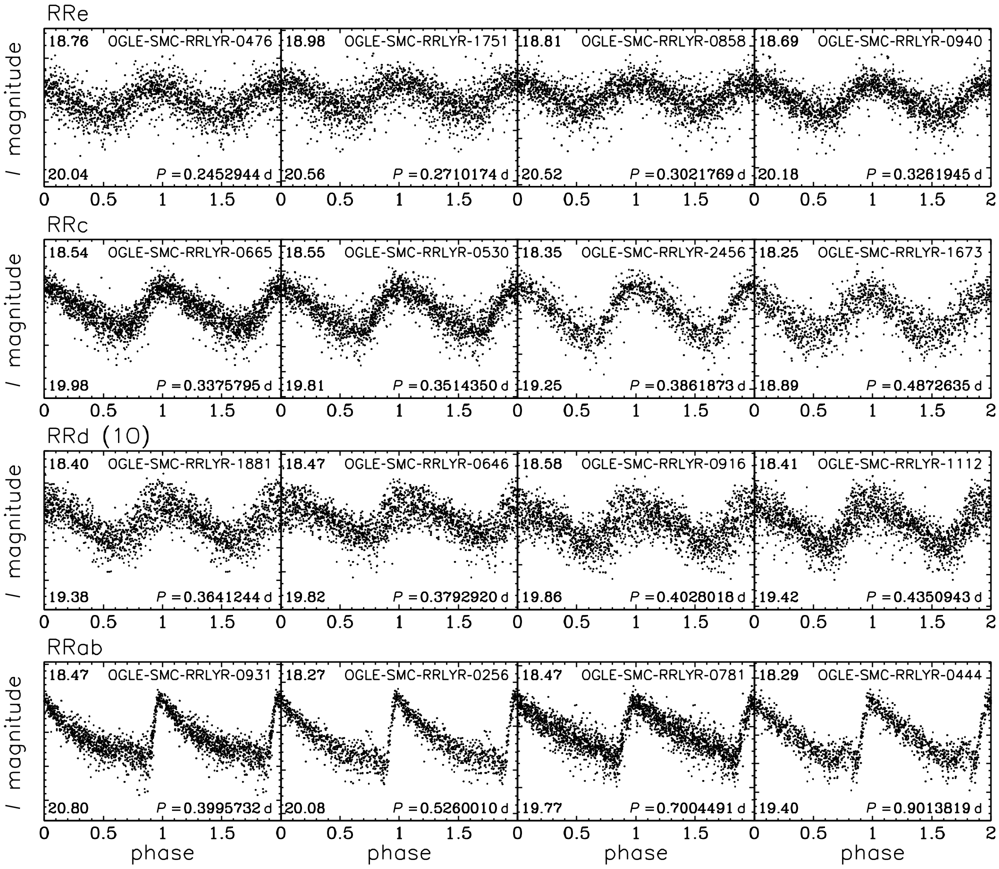

Fig. 5. Representative light curves of RR Lyr stars from our catalog. First row presents four RRe variable stars, second row – RRc stars, third row – RRd stars phased with the first-overtone period, and the last row shows light curves of RRab star. The range of magnitudes varies from panel to panel. Numbers in the left corners show the lower and the upper limits of magnitudes.

Representative light curves of RR Lyr variable stars of various types are presented in Fig. 5. The scatter of the light curves caused by the photometric errors is substantial, as RR Lyr stars in the SMC are close to the detection limit of the OGLE-III SMC photometry. However, generally there are no problems with the variability type identification. Some stars with uncertain classification are flagged in the remarks of the catalog.

4. Catalog of RR Lyr Stars in the SMC

We identified in total 2475 RR Lyr stars in the SMC OGLE-III fields. The sample consists of 1933 RRab, 175 RRc, 258 RRd and 109 RRe stars. 30 objects are Galactic foreground RR Lyr stars, of which 22 pulsate in the fundamental mode, one was classified as an RRc star, three as RRe stars and four are double-mode

RR Lyr variable stars. The catalog data are available through the WWW interface or from the anonymous FTP site:

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

The stars arranged in order of right ascension are listed in the file ident.dat at the FTP site. The object designation (in the form OGLE-SMC-RRLYR-NNNN, where NNNN is a four-digit consecutive number), OGLE-III field and internal database number (consistent with the photometric maps of the SMC by Udalski *et al.* 2008b), mode of pulsation (RRab, RRc, RRd, RRe), equinox J2000.0 right ascension and declination, cross-identifications with the OGLE-II photometric database (Szymański 2005), cross-identifications with the extragalactic part of the General Catalogue of Variable Stars (GCVS; Artyukhina *et al.* 1995), and other designations are given in the file ident.dat.

Observational parameters of the stars – intensity-averaged $\langle I\rangle$ and $\langle V\rangle$ magnitudes, periods with uncertainties (derived with the TATRY code developed by Schwarzenberg-Czerny 1996), peak-to-peak *I*-band amplitudes and parameters of the Fourier light curve decomposition (Simon and Lee 1981) – are provided in the files RRab.dat, RRc.dat, RRd.dat and RRe.dat. Additional information on some objects can be found in the file remarks.txt. The OGLE-II and OGLE-III multi-epoch *VI* photometry can be downloaded from the directory phot/. Finding charts for each star are stored in the directory fcharts/. These are $60'' \times 60''$ subframes of the *I*-band DIA reference images.

5. Cross-Identification with Other Catalogs

To test the completeness of our catalog we cross-matched our sample with the previously released lists of RR Lyr variable stars in the SMC. The largest catalog of these objects published heretofore was the OGLE-II catalog (Soszyński *et al.* 2002). We independently identified 558 stars from 571 objects classified as RR Lyr variable stars in the OGLE-II catalog of RR Lyr stars in the SMC. We checked the missed 13 objects and noticed that eight of them have been reclassified as δ Sct stars, short-period classical Cepheids or artifacts. The remaining five stars turned out to be RR Lyr stars, usually of RRc type. They were not classified as RR Lyr stars in the initial classification procedure due to a small number of observing points in the OGLE-III database or atypical colors. We included all the missing RR Lyr stars in the present catalog.

Most of the RR Lyr stars in the SMC provided by the GCVS Vol. V (Artyukhina *et al.* 1995) originate from the paper by Graham (1975). Unfortunately, the majority of these objects lie outside the OGLE-III fields. From 27 RR Lyr stars that may be potentially found in the region monitored by the OGLE-III survey, we identified practically all objects. Only one star – BV Tuc – was reclassified as a classical

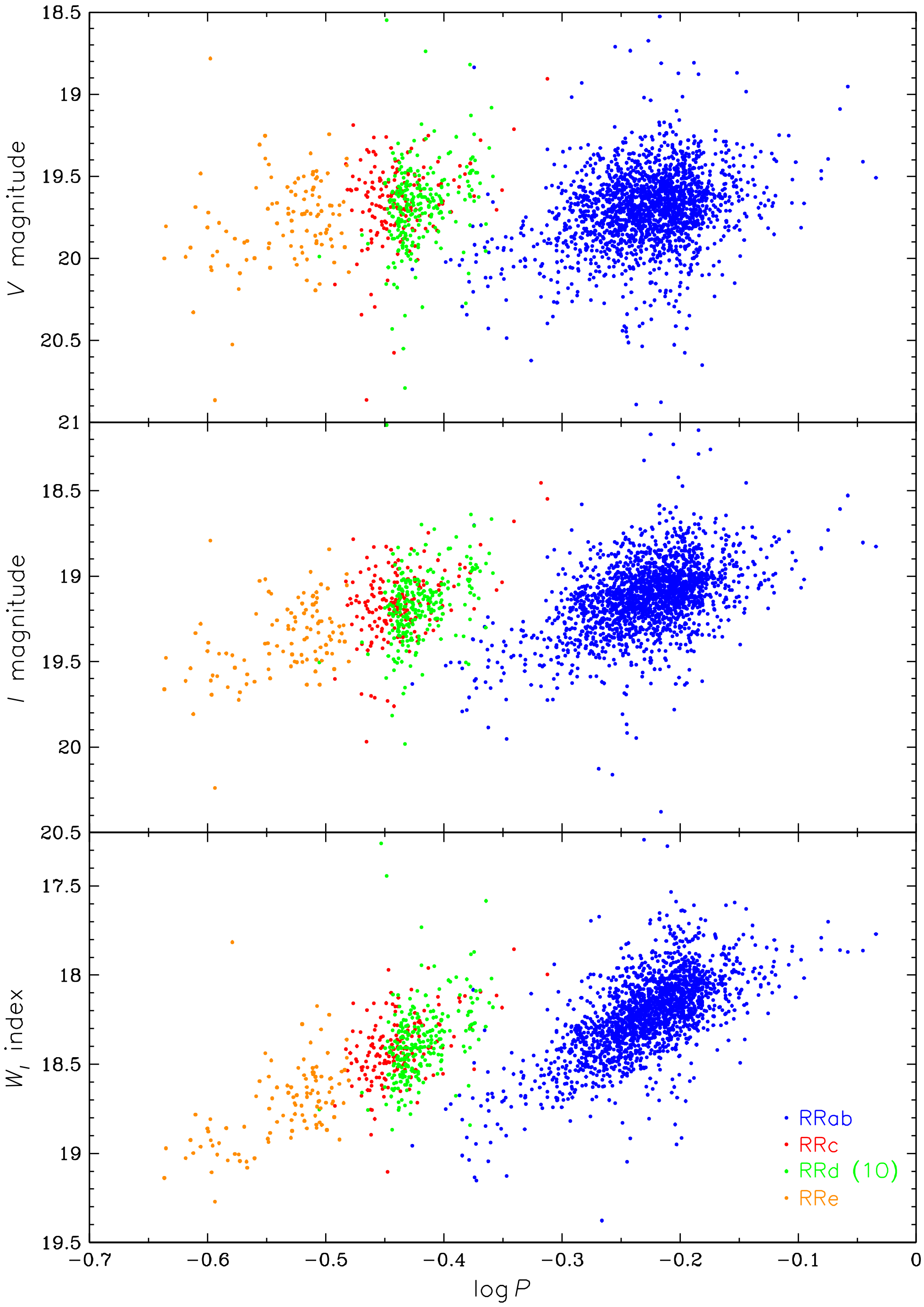

Fig. 6. Period–luminosity relations for RR Lyr in the SMC. Color symbols represent the same type of stars as in Fig. 1. *Upper panel* presents $\log P$ *vs.* V diagram, *middle panel* – $\log P$ *vs.* I diagram, *lower panel* – $\log P$ *vs.* W_I diagram, where $W_I = I - 1.55(V - I)$ is the extinction insensitive Wesenheit index.

Cepheid. Our catalog includes also six Galactic RR Lyr stars that were incorrectly classified in the GCVS as BL Boo type stars (*i.e.*, anomalous Cepheids). From the list of RR Lyr stars in the vicinity of 47 Tuc published by Weldrake *et al.* (2004), we identified 19 objects, *i.e.*, all stars covered by the OGLE-III fields.

6. Discussion

A large number of RR Lyr stars in the SMC allows us to perform a preliminary analysis of their statistical properties, and to compare them to a huge sample of RR Lyr variable stars in the LMC identified by the OGLE project (Soszyński *et al.* 2009). Period–amplitude diagram for the SMC sample is shown in Fig. 2. Comparing to the LMC and the field of the Galaxy, RR Lyr stars in the SMC seem to constitute much more homogeneous group in terms of metallicity, history of star formation and reddening. In particular, Galactic field RR Lyr stars manifest clear Oosterhoff dichotomy (Suntzeff *et al.* 1991, Szczygieł *et al.* 2009), which is not detectable in the SMC.

Fig. 3 presents the period distribution of the SMC and LMC RR Lyr stars. These are cumulative histograms with different types of RR Lyr stars plotted in different colors. It is striking that both galaxies host different proportion of variable stars pulsating in various modes. In the LMC, RRc and RRe stars constitute together 25% of all RR Lyr stars, but the whole population comprises only 4% of RRd stars. In the SMC single-mode overtone pulsators (RRc and RRe stars) constitute only 11.5% of the RR Lyr sample, and there is a similar number of RRd stars. Such a discrepancy cannot be explained by a possible incompleteness of the SMC catalog relative to the LMC sample.

Table 1

Mean and Modal Periods of RR Lyr Stars in the SMC and LMC.

	SMC		LMC	
	mean period [days]	modal period [days]	mean period [days]	modal period [days]
RRab	0.596	0.615	0.576	0.580
RRc	0.366	0.366	0.337	0.341
RRd (1O)	0.380	0.369	0.363	0.357
RRe	0.293	0.309	0.270	0.272

Fig. 3 shows that RR Lyr stars in the Large and Small Magellanic Clouds reveal different mean and modal periods. Table 1 compares the typical periods for various types of RR Lyr variable stars in both environments. The SMC variable stars have average periods by 0.02–0.03 days longer than the LMC RR Lyr stars.

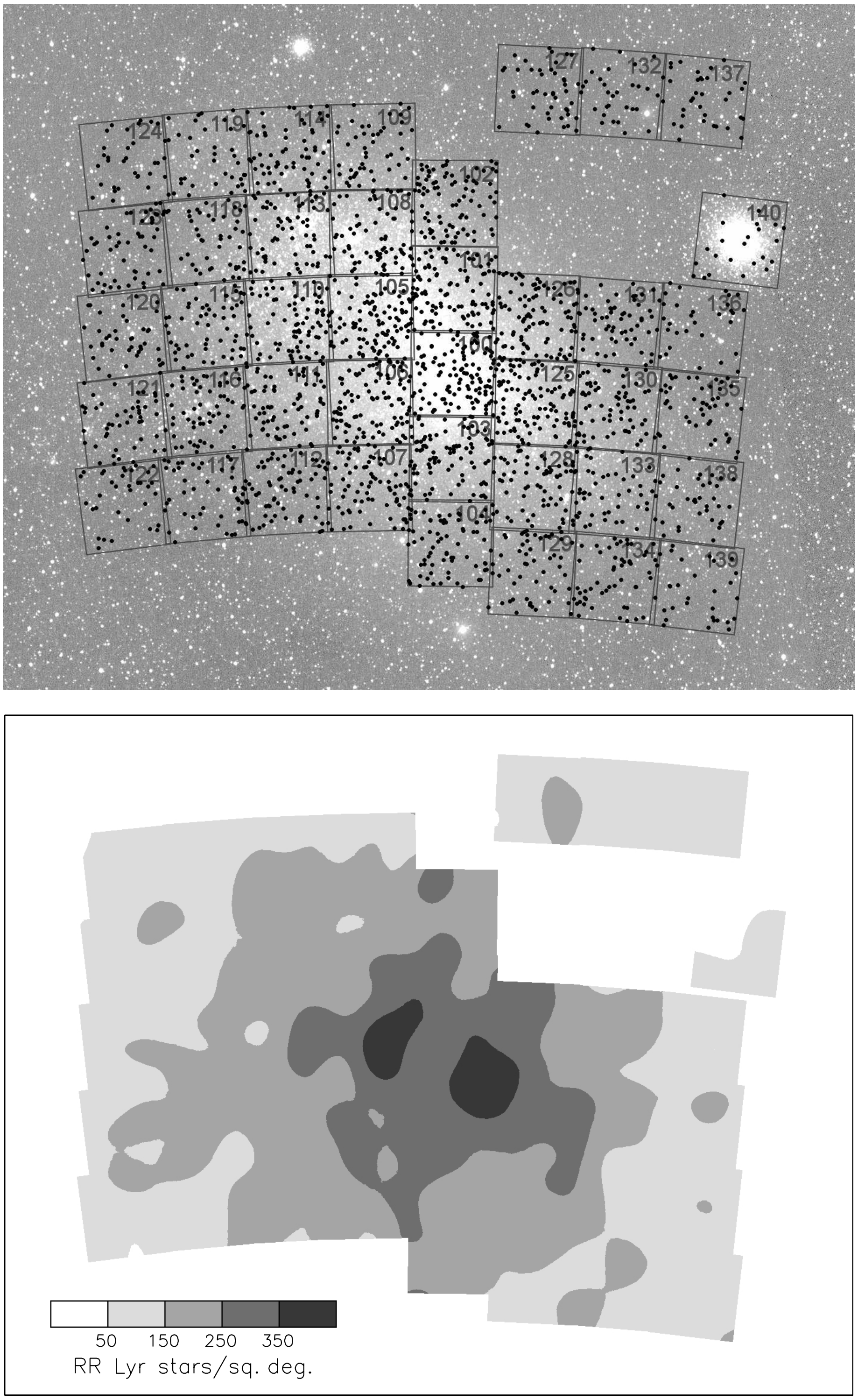

Fig. 7. *Upper panel*: spatial distribution of RR Lyr stars in the SMC. The background image of the SMC originates from the ASAS sky survey (Pojmański 1997). *Lower panel*: surface density map of RR Lyr stars in the SMC.

Mean apparent unreddened magnitudes of RRab stars (after removing Galactic and blended objects) are equal to 19.12 mag in the *I*-band and 19.70 mag in the *V*-band, however a weak period–luminosity relation is visible in both filters (Fig. 6).

In Fig. 7 we present the spatial distribution of RR Lyr stars in the SMC. Upper panel shows the position of individual objects overplotted on the image of the SMC obtained by the ASAS project (Pojmański 1997). Lower panel displays the density map of the SMC RR Lyr stars derived by smoothing the above distribution with the Gaussian filter. It is clear that the population of RR Lyr stars in the SMC is distributed over large area, much larger than 14 square degrees covered by the OGLE-III fields. We expect that the current phase of the OGLE project (OGLE-IV) will cover virtually all RR Lyr stars in both Magellanic Clouds.

RR Lyr in the SMC form roughly a round structure in the sky, in contrast to the LMC (Soszyński *et al.* 2009), where the spatial distribution of RR Lyr stars is not spherical and is elongated in the same direction as the LMC bar. Pejcha and Stanek (2009) used our catalog to study 3D structure of the LMC halo. They noticed that the RR Lyr distribution can be approximated by a triaxial ellipsoid with the longest axis almost parallel to the line of sight. The scatter of points in the reddening-free period–Wesenheit index diagram (Fig. 6) is considerably larger for RR Lyr stars in the SMC than in the LMC, so the SMC stellar halo is probably more extended along the line of sight than in the LMC. The standard deviation of residuals after subtracting the least-square fit to the $\log P - W_I$ relation is equal to 0.11 mag in the LMC, while in the SMC it exceeds 0.14 mag. It is interesting that the spatial distribution of RR Lyr stars in the SMC (Fig. 7) seems to have two maxima, around the coordinates $\alpha_{\rm J2000} = 00^{\rm h}47^{\rm m}\!\!.4$, $\beta_{\rm J2000} = -73^\circ 12'$ and $\alpha_{\rm J2000} = 00^{\rm h}56^{\rm m}\!\!.7$, $\beta_{\rm J2000} = -72^\circ 54'$.

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