

**The OGLE Collection of Variable Stars.
Over 45 000 RR Lyrae Stars in the Magellanic System***

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Received June 21, 2016

ABSTRACT

We present the largest collection of RR Lyrae stars in the Magellanic System and in its foreground. The sample consists of 45 451 RR Lyr stars, of which 39 082 were detected toward the Large Magellanic Cloud and 6369 toward the Small Magellanic Cloud. We provide long-term time-series photometric measurements collected during the fourth phase of the Optical Gravitational Lensing Experiment (OGLE-IV).

We discuss several potential astrophysical applications of our collection: investigation of the structure of the Magellanic Clouds and the Galactic halo, studies of the globular clusters in the Magellanic System, analysis of double-mode RR Lyr stars, and search for RR Lyr stars in eclipsing binary systems.

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

1. Introduction

RR Lyrae stars are a powerful tool to trace the oldest (≥ 10 Gyr) stellar component in our and other galaxies. These radially pulsating stars are numerous, easily identifiable, and present in all Local Group galaxies, irrespective of their morphological type. RR Lyr stars are standard candles making them important distance

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

indicators, probes of the three-dimensional structures of their parent galaxies, and tracers of the star formation history. Large samples of RR Lyr variables have proven useful in investigating the metallicity distribution in galaxies and in determination of the interstellar extinction maps.

The Optical Gravitational Lensing Experiment (OGLE, Udalski, Szymański and Szymański 2015) has already released catalogs of RR Lyr stars in the Large (LMC) and Small Magellanic Clouds (SMC) based on the observations obtained in 1997–2000 during the OGLE-II (Soszyński *et al.* 2002, 2003) and in 2001–2009 during the OGLE-III phases (Soszyński *et al.* 2009, 2010). The latter release contained a total of 27 381 RR Lyr stars detected in 54 square degrees of the sky covering central regions of the LMC and SMC. These catalogs found many astrophysical applications. They were used by various authors to investigate three-dimensional structure of the Magellanic Clouds (Pejcha and Stanek 2009, Subramanian and Subramanian 2009, Haschke *et al.* 2012b, Kapakos and Hatzidimitriou 2012, Subramanian and Subramanian 2012, Wagner-Kaiser and Sarajedini 2013, Moretti *et al.* 2014, Deb and Singh 2014, Deb *et al.* 2015), to examine metallicity gradients in both galaxies (Feast *et al.* 2010, Kapakos *et al.* 2011, Kapakos and Hatzidimitriou 2012, Haschke *et al.* 2012a, Wagner-Kaiser and Sarajedini 2013), to construct reddening maps toward both Clouds (Pejcha and Stanek 2009, Haschke *et al.* 2011, Wagner-Kaiser and Sarajedini 2013), to study the RR Lyr light curve morphology in various passbands (Chen *et al.* 2013, Gavrilchenko *et al.* 2014, Moretti *et al.* 2014), and to analyze relations between periods, luminosities, colors, amplitudes, and metallicities of RR Lyr stars (Ripepi *et al.* 2012, Bhardwaj *et al.* 2014, Muraveva *et al.* 2015). The OGLE samples were also used as training sets for the automatic systems of the variable star classification (Long *et al.* 2012, Kim *et al.* 2014, Kim and Bailer-Jones 2016).

In this paper, we present a new OGLE collection of RR Lyr stars in the Magellanic System being an extension of the OGLE-III catalog to the regions covered by the OGLE-IV fields. About 650 square degrees of the sky regularly monitored by the OGLE-IV survey cover a large part of the Magellanic System, including the outskirts of the two galaxies and the Magellanic Bridge connecting them. The new OGLE release of RR Lyr variables in the Magellanic System contains 45 451 objects in total. This is the largest set of RR Lyr stars published to date in any stellar environment.

The paper is organized as follows. Section 2 presents observational data used in this investigation. Methods used in the selection and classification of RR Lyr stars are detailed in Section 3. The collection itself is described in Section 4. In Section 5, we estimate the completeness of our sample and compare it with other catalogs of RR Lyr stars in the Magellanic Clouds. In Section 6, we discuss some possible applications of our collection. Finally, conclusions are presented in Section 7.

2. Observations and Data Reduction

The time-series photometry used in this study has been obtained with the 1.3-m Warsaw telescope at Las Campanas Observatory (operated by the Carnegie Institution for Science), Chile, between March 2010 and July 2015. The telescope is equipped with a mosaic camera composed of 32 CCDs, each with 2048 by 4096 pixels, providing a field of view of 1.4 square degrees on the sky. Most of the observations were obtained through the Cousins *I* filter – typically from 100 to 750 points, depending on the field. In the Johnson *V*-band we secured from several to 260 observations for color information.

Altogether 475 OGLE-IV fields cover about 650 square degrees in the Magellanic System, including the Magellanic Bridge between the LMC and SMC and selected peripheral areas, up to 20 degrees from the centers of the galaxies. The total number of point sources in the Magellanic Cloud OGLE-IV database exceeds 75 million. The OGLE data reduction pipeline is based on the Difference Image Analysis technique (Alard and Lupton 1998, Woźniak 2000). The reduction procedures, photometric calibrations and astrometric transformations have been described by Udalski *et al.* (2015a).

3. Selection and Classification of RR Lyrae Stars

We performed a period search for nearly all *I*-band light curves stored in the OGLE database. The only cut was done on the number of data points that had to be larger than 30. We used the FNPEAKS code[†] which calculates the Fourier amplitude spectra and provides the best periods with their signal-to-noise ratios. For each star we derived two periods, the second one on the residual light curve obtained by the subtraction of the primary periodicity.

A search for RR Lyr stars was conducted on light curves with periods between 0.2 and 1 day. The preselection of the candidates was based on the Fourier decomposition of the light curves (Simon and Lee 1981) and the template fitting to the *I*-band light curves. Double-mode RR Lyr stars were identified on the basis of their period ratios, which fall in a narrow range of 0.72–0.75. However, the automatic algorithms played only a supporting role in the process of the manual selection and classification of RR Lyr stars. The final decision on each object was made after a visual inspection of its light curve. In doubtful cases we took into account the position of the star in the color–magnitude diagram, as well as period–luminosity, period–amplitude, and other diagrams.

The selected sample of RR Lyr variables has been divided into three classes: fundamental-mode RRab stars, first-overtone RRc stars, and double-mode RRd stars. Our classification was based on the periods, amplitudes, and light curve shapes of the stars. In several dozen cases we corrected the pulsation modes provided by Soszyński *et al.* (2009, 2010). All objects classified in the OGLE-III

[†]<http://helas.astro.uni.wroc.pl/deliverables.php?lang=en&active=fnpeaks>

catalogs as RRe stars (second-overtone pulsators) have been incorporated to the RRc group. The second-overtone RR Lyr stars have not been separated from the first-overtone variables because of the doubts whether the RRe stars exist at all. We did not find any natural boundary, which could be used for an unambiguous separation of the first- and second-overtone RR Lyr stars.

As a result, we found 18 158 RR Lyr stars in both Clouds that were not recorded during previous stages of the OGLE survey. Only 227 of them (less than 1% of the OGLE-III sample) were found in the region covered by the OGLE-III fields, confirming the high completeness of the OGLE collection of variable stars. Other newly detected variables lie in the outer regions of the two galaxies. We also verified the OGLE-III samples of RR Lyr stars (Soszyński *et al.* 2009, 2010) with the OGLE-IV photometry and we decided to remove 88 of the sources previously classified as RR Lyr stars (0.3% of the original sample). The detailed list of these objects is given in Table 1. Most of them turned out to be eclipsing or ellipsoidal binary systems or their variability type could not be unambiguously identified from the OGLE photometry (they are designated in Table 1 as “Other”). Another ≈ 200 stars in our collection should be treated with caution, because their classification is uncertain. These stars are flagged in appropriate data files of our collection.

4. RR Lyrae Stars in the Magellanic System

The current version of the OGLE collection of RR Lyr stars in the Magellanic System contains variables detected during the previous stages of the OGLE project (Soszyński *et al.* 2002, 2003, 2009, 2010) and during the current, fourth phase of the survey. The whole sample consists of 45 451 RR Lyr stars (32 581 RRab, 10 246 RRc, and 2624 RRd stars, including 22 anomalous RRd stars, Soszyński *et al.* 2016, in preparation), of which 39 082 and 6369 variables were found toward the LMC and SMC, respectively. The on-sky boundary between both Clouds may be established only approximately, because the halos of the two galaxies overlap with each other. In our collection, we adopted celestial meridian of $2^{\text{h}} 8$ to separate the LMC and SMC samples, because we found a local minimum in the number of RR Lyr variables around this value of right ascension. Our collection also includes RR Lyr stars from the halo of the Milky Way. It is impossible to unambiguously separate Galactic and Magellanic Cloud old stellar populations, since the Clouds are immersed in the halo of our Galaxy. There is no a natural luminosity boundary that separates RR Lyr stars from the Magellanic Clouds and the Milky Way.

The entire collection can be downloaded from the OGLE Internet Archive through anonymous FTP sites or via a web interface:

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/lmc/rrlyr/
ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/smc/rrlyr/
<http://ogle.astrouw.edu.pl>

Table 1

Reclassified variables from the OGLE-III catalogs of RR Lyr stars in the Magellanic Clouds

Identifier	New classification	Identifier	New classification
OGLE-LMC-RRLYR-00077	Other	OGLE-LMC-RRLYR-13259	Eclipsing
OGLE-LMC-RRLYR-00485	Other	OGLE-LMC-RRLYR-13512	Eclipsing
OGLE-LMC-RRLYR-00803	Spotted	OGLE-LMC-RRLYR-15806	Other
OGLE-LMC-RRLYR-00824	Other	OGLE-LMC-RRLYR-16124	Eclipsing
OGLE-LMC-RRLYR-00961	Eclipsing	OGLE-LMC-RRLYR-16210	Eclipsing
OGLE-LMC-RRLYR-01104	Eclipsing	OGLE-LMC-RRLYR-16426	Other
OGLE-LMC-RRLYR-01257	Other	OGLE-LMC-RRLYR-16656	Eclipsing
OGLE-LMC-RRLYR-01802	Eclipsing	OGLE-LMC-RRLYR-16795	Eclipsing
OGLE-LMC-RRLYR-02171	Other	OGLE-LMC-RRLYR-17073	Eclipsing
OGLE-LMC-RRLYR-02376	Other	OGLE-LMC-RRLYR-17117	Eclipsing
OGLE-LMC-RRLYR-02390	Eclipsing	OGLE-LMC-RRLYR-17396	Eclipsing
OGLE-LMC-RRLYR-02548	Eclipsing	OGLE-LMC-RRLYR-17584	Eclipsing
OGLE-LMC-RRLYR-03158	Eclipsing	OGLE-LMC-RRLYR-17847	Other
OGLE-LMC-RRLYR-03802	Eclipsing	OGLE-LMC-RRLYR-18086	Other
OGLE-LMC-RRLYR-04103	Eclipsing	OGLE-LMC-RRLYR-18360	Other
OGLE-LMC-RRLYR-04426	Classical Cep.	OGLE-LMC-RRLYR-18854	Other
OGLE-LMC-RRLYR-04733	Other	OGLE-LMC-RRLYR-19067	Eclipsing
OGLE-LMC-RRLYR-04862	Eclipsing	OGLE-LMC-RRLYR-19207	Other
OGLE-LMC-RRLYR-04892	Eclipsing	OGLE-LMC-RRLYR-19243	Eclipsing
OGLE-LMC-RRLYR-05128	Eclipsing	OGLE-LMC-RRLYR-19258	Other
OGLE-LMC-RRLYR-05282	Other	OGLE-LMC-RRLYR-19438	Eclipsing
OGLE-LMC-RRLYR-05305	Eclipsing	OGLE-LMC-RRLYR-20089	Other
OGLE-LMC-RRLYR-05784	Eclipsing	OGLE-LMC-RRLYR-20767	Eclipsing
OGLE-LMC-RRLYR-06232	Eclipsing	OGLE-LMC-RRLYR-20781	Other
OGLE-LMC-RRLYR-06645	Other	OGLE-LMC-RRLYR-20821	Eclipsing
OGLE-LMC-RRLYR-07073	Other	OGLE-LMC-RRLYR-21161	Eclipsing
OGLE-LMC-RRLYR-07569	Eclipsing	OGLE-LMC-RRLYR-21207	Other
OGLE-LMC-RRLYR-07905	Eclipsing	OGLE-LMC-RRLYR-21255	Eclipsing
OGLE-LMC-RRLYR-07935	Other	OGLE-LMC-RRLYR-21285	Eclipsing
OGLE-LMC-RRLYR-08281	Other	OGLE-LMC-RRLYR-21455	Eclipsing
OGLE-LMC-RRLYR-08457	Other	OGLE-LMC-RRLYR-22035	Other
OGLE-LMC-RRLYR-09009	Eclipsing	OGLE-LMC-RRLYR-22482	Eclipsing
OGLE-LMC-RRLYR-09044	Eclipsing	OGLE-LMC-RRLYR-22492	Other
OGLE-LMC-RRLYR-09614	Other	OGLE-LMC-RRLYR-23055	Other
OGLE-LMC-RRLYR-10747	Other	OGLE-LMC-RRLYR-23485	Other
OGLE-LMC-RRLYR-10933	Eclipsing	OGLE-LMC-RRLYR-23513	Eclipsing
OGLE-LMC-RRLYR-10994	Eclipsing	OGLE-LMC-RRLYR-23517	Eclipsing
OGLE-LMC-RRLYR-11143	Other	OGLE-LMC-RRLYR-23685	Other
OGLE-LMC-RRLYR-11169	Eclipsing	OGLE-LMC-RRLYR-23868	Other
OGLE-LMC-RRLYR-11606	Other	OGLE-LMC-RRLYR-24247	Other
OGLE-LMC-RRLYR-12072	Eclipsing	OGLE-LMC-RRLYR-24338	Other
OGLE-LMC-RRLYR-12151	Eclipsing	OGLE-LMC-RRLYR-24428	Eclipsing
OGLE-LMC-RRLYR-12343	Other	OGLE-SMC-RRLYR-0251	Other
OGLE-LMC-RRLYR-12875	Eclipsing	OGLE-SMC-RRLYR-0720	Other

Each RR Lyr star has a unique identifier which follows the scheme introduced in the OGLE-III catalogs. The identifiers from OGLE-LMC-RRLYR-00001 to OGLE-LMC-RRLYR-24906 (in the LMC) and from OGLE-SMC-RRLYR-0001 to OGLE-SMC-RRLYR-2475 (in the SMC) are reserved for the RR Lyr stars presented by Soszyński *et al.* (2009, 2010). The identifiers with higher numbers are assigned to the newly detected RR Lyr stars in order of increasing right ascension.

Our collection contains not only the most important parameters of the sources (their coordinates, modes of pulsation, periods, mean magnitudes in the *I*- and *V*-bands, amplitudes, and Fourier coefficients of the light curve decomposition), but also the time-series *VI* photometry collected from the beginning of the OGLE-IV survey. This photometry can be combined with the OGLE-III and OGLE-II light curves (if available) from the Soszyński *et al.* (2009, 2010) catalogs, however in individual cases one should compensate possible differences in the mean brightness and amplitudes between the previous and present stages of the OGLE project. About 8% of the RR Lyr stars included in the OGLE-III catalogs do not have OGLE-IV photometry, mostly because they fell in technical gaps between CCD chips of the OGLE-IV mosaic camera. The parameters of these variables were copied from the OGLE-III catalog. In the future, we plan to obtain the OGLE-IV time-series photometry also for the stars in the gaps, since these regions are observed from time to time due to imperfections of the telescope pointing.

5. Completeness of the Sample

Due to a partial overlap of the adjacent OGLE-IV fields, some of the sources were recorded twice, independently in both fields. However, our collection contains only one entry per star – in the case of the double detections we usually chose the one with the larger number of observing points in its light curve. These independent identifications of the same RR Lyr stars may be used to estimate the completeness of our sample.

We expect that the OGLE collection of RR Lyr variables is practically complete in the central regions of the LMC and SMC, that were monitored since 2001 by the OGLE-III and OGLE-IV surveys. The outer regions are affected by the gaps between CCD detectors of the mosaic camera, which reduce the completeness by about 7%. The efficiency of our search for RR Lyr stars in the area covered by the pixels may be judged on the basis of the double detections. Outside the OGLE-III fields, 1284 variables from our sample had two entries in the OGLE-IV database (assuming that both light curves must have at least 100 points), so we had a chance to find 2568 counterparts. We independently identified 2480 of them, which implies the completeness of about 96%.

The highest completeness is expected for RRab stars, due to their characteristic sawtooth-like light curves. Indeed, the same method applied to the fundamental-mode pulsators gives the completeness well above 98%. For RRc and RRd stars

we obtained the completeness of about 92%, which reflects the difficulties to distinguish between the overtone pulsators and close binary systems.

We compared the OGLE collection with the sample of 9722 RR Lyr stars in the LMC published by Alcock *et al.* (2001). Our sample does not include 131 of these objects, of which 40 are not present in the OGLE-IV database (most of them lies in the gaps between the CCD chips). The remaining 91 stars classified by MACHO as RR Lyr stars either clearly belong to other types of variable sources or are constant stars.

Kim *et al.* (2014) published a list of periodic variable star candidates detected from the EROS-2 LMC photometric database. These objects were classified using an automatic random forest algorithm. The list of potential RR Lyr stars contains 6607 sources not discovered during the previous stages of the OGLE survey or the MACHO project. We cross-matched an early version of our collection of RR Lyr stars in the LMC with the sample published by Kim *et al.* (2014) and we found that as many as 4408 object were missed in our list. For 3234 of these stars we found their counterparts in the OGLE-IV database within 1 arcsec search radius. We carefully analyzed the light curves of these objects and found that 149 of them indeed are probable RR Lyr stars. Most of these overlooked variables turned out to be RRc stars with noisy, nearly sinusoidal light curves, sometimes affected by a small number of points in their light curves. We supplemented our collection with these newly identified RR Lyr variables. In turn, we do not confirm the Kim *et al.* (2014) classification for the remaining 3085 sources. For the majority of these objects we had no doubt that we deal with eclipsing binaries, δ Sct stars, Cepheids, or simply just constant stars. There is also a number of sources in this group for which the OGLE light curves are too noisy to unambiguously categorize their type of variability.

6. Discussion

The present version of the OGLE collection of RR Lyr stars in the Magellanic Clouds is larger and purer than any other catalog of these pulsators detected in any other environment. Therefore, our sample is an ideal tool to study RR Lyr stars themselves, as well as the structure of the Magellanic Clouds and their interactions with each other and our Galaxy. Below we present a few possible applications of our collection, however we are far from being exhaustive.

6.1. *Spatial Distribution of RR Lyr Stars in the Magellanic System*

RR Lyr stars are primary tracers of the ancient stellar population. These pulsating stars are common in various environments, can be easily identified in time-series sky surveys, and are standard candles, so can be used to study the distribution of the old population in three dimensions. The OGLE-III catalogs of RR Lyr stars (Soszyński *et al.* 2009, 2010) were extensively used to investigate the structure of

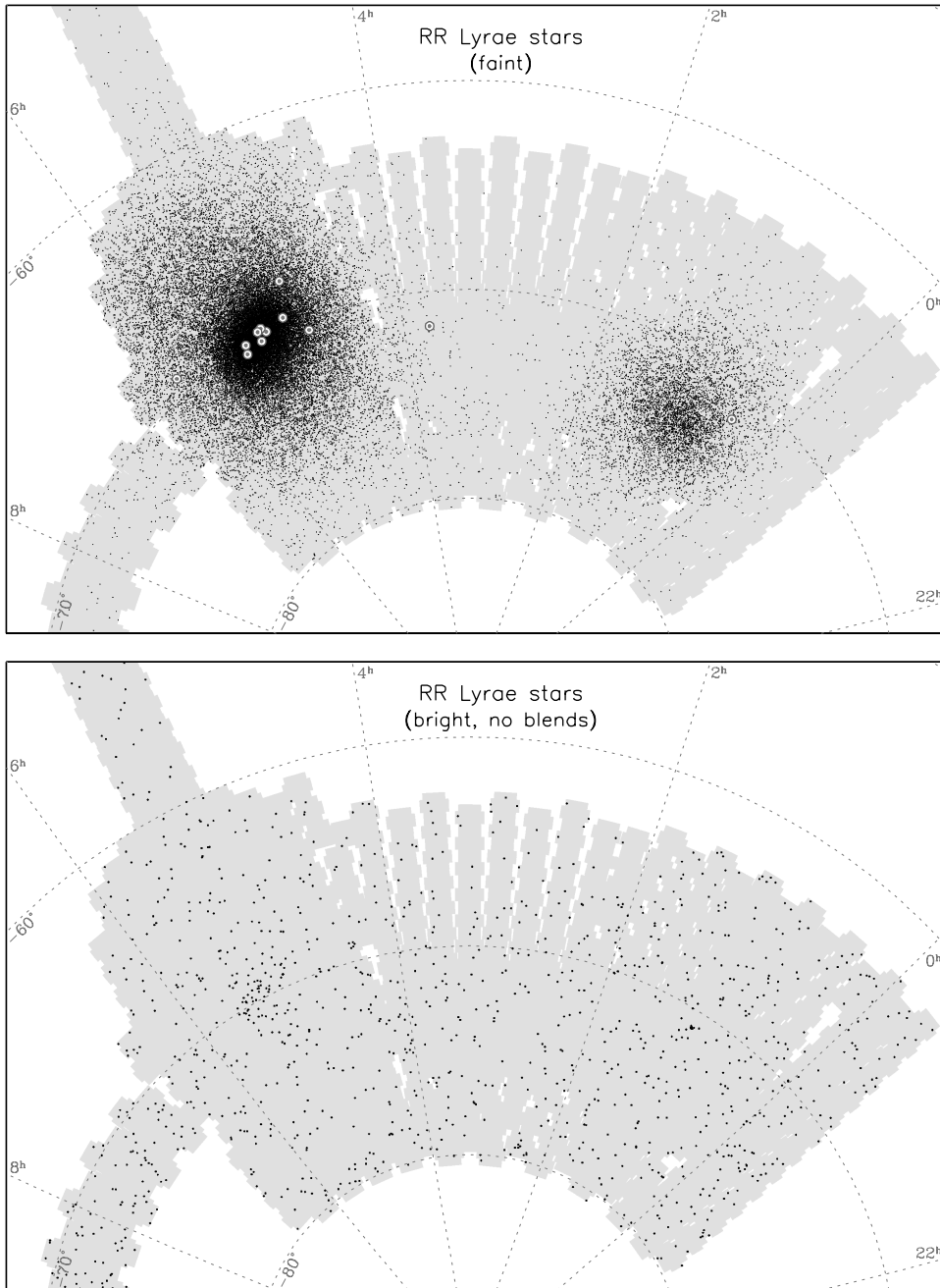


Fig. 1. Spatial distribution of RR Lyr stars in the OGLE fields toward the Magellanic Clouds. *Upper panel* presents members of the Magellanic Clouds (fainter group). Gray circles indicate positions of twelve globular clusters that host RR Lyr stars. *Lower panel* shows positions of the brighter group of RR Lyr stars – consisting mostly of the Milky Way members. The boundary between fainter and brighter groups has been adopted at 1 magnitude above the mean period–luminosity relations for RRab, RRc, and RRd stars, separately for the LMC and SMC. Additionally, blended stars have been removed from the bright group. Gray area shows the sky coverage of the OGLE fields.

the Magellanic Clouds (Pejcha and Stanek 2009, Subramanian and Subramanian 2009, Haschke *et al.* 2012b, Kapakos and Hatzidimitriou 2012, Subramanian and Subramanian 2012, Wagner-Kaiser and Sarajedini 2013, Moretti *et al.* 2014, Deb and Singh 2014, Deb *et al.* 2015). Now we extend the OGLE-III set to the peripheral areas of the Clouds, which offers the opportunity to investigate the history of interactions between the LMC, SMC, and Milky Way.

In Fig. 1, we present two-dimensional maps of RR Lyr stars from our collection. We divided our sample into fainter (upper panel of Fig. 1) and brighter variables (lower panel), wherein the dividing lines were arbitrarily defined at 1 magnitude above the mean period–luminosity relations in the reddening-free Wesenheit index, $W_I = I - 1.55(V - I)$, separately for RRab, RRC, and RRd stars in the LMC and SMC. In the case of the brighter group, we also cleaned the sample from blended variables. In this procedure we relied on the light curve amplitudes, which are smaller in blended variables than in typical pulsators with the same periods.

The fainter RR Lyr stars belong mainly to the Magellanic Clouds, while the brighter group is populated mostly by members of the Milky Way halo, although there is no clear boundary between outer regions of these three galaxies. This is seen in the distribution of the brighter RR Lyr stars, which is roughly uniform over the OGLE fields with the exception of the center of the LMC. The excess of bright RR Lyr stars in this region may be partially explained by the contamination of not removed blends, but the majority of these RR Lyr stars have typical amplitudes of their light curves, so they do not seem to be substantially blended. Thus, these stars are likely located in the outskirts of the LMC stellar halo tidally stretched toward our Galaxy.

The fainter group (upper panel of Fig. 1) mostly belong to the Magellanic Clouds. The projection of the SMC halo on the celestial sphere seem to be round, while the LMC halo is obviously elongated. Moreover, the distribution of the LMC RR Lyr stars probably cannot be described by a simple ellipsoid, because the number of RR Lyr stars in the North-East part of the LMC seems to be larger than in the opposite side. A detailed analysis of the three-dimensional distribution of RR Lyr stars in the Magellanic Clouds on the basis of our collection will be presented in the forthcoming paper (Jacyszyn-Dobrzyniecka *et al.* in preparation).

6.2. RR Lyr Stars in Globular Clusters

The Oosterhoff dichotomy observed in Galactic globular clusters is not present among the globular clusters in nearby dwarf galaxies, in particular in the LMC. Five of the LMC clusters (NGC 1466, NGC 1853, NGC 2019, NGC 2210, and NGC 2257) have properties that place them inside the zone of avoidance between the two Oosterhoff groups in the Milky Way. This fact poses a significant challenge to the models assuming hierarchical merger formation of the Galactic halo.

The catalog of extended objects in the Magellanic System by Bica *et al.* (2008) lists 18 globular clusters in the Magellanic Clouds, 14 of which are currently mon-

itored by OGLE. We found RR Lyr stars in all but two of the observed globular clusters. We found no RR Lyr stars in Hodge 11 in the LMC and Lindsay 1 in the SMC (strictly speaking we identified one RR Lyr star in Hodge 11, but it is probably a field variable located by chance in the area outlined by the cluster radius). The simplest explanation for the lack of RR Lyr stars in Hodge 11 and Lindsay 1 is that these clusters are younger than ≈ 10 Gyr.

Table 2

Globular clusters containing RR Lyr stars

Cluster name	RA (J2000)	Dec (J2000)	Cluster radius [$'$]	N_{RR}	N_{fieldRR} (estimated)
NGC 121	00 ^h 26 ^m 47 ^s	-71°32'12"	3.8	15	1.2
NGC 1466	03 ^h 44 ^m 33 ^s	-71°40'17"	3.5	92	0.1
NGC 1754	04 ^h 54 ^m 17 ^s	-70°26'29"	1.6	37	0.4
NGC 1786	04 ^h 59 ^m 06 ^s	-67°44'42"	2.0	57	2.5
NGC 1835	05 ^h 05 ^m 06 ^s	-69°24'14"	2.3	125	6.4
NGC 1898	05 ^h 16 ^m 41 ^s	-69°39'23"	1.6	49	6.8
NGC 1916	05 ^h 18 ^m 38 ^s	-69°24'23"	2.1	25	10.5
NGC 1928	05 ^h 20 ^m 57 ^s	-69°28'40"	1.3	8	4.7
NGC 1939	05 ^h 21 ^m 26 ^s	-69°56'59"	1.4	7	4.9
NGC 2005	05 ^h 30 ^m 10 ^s	-69°45'10"	1.6	19	5.2
NGC 2019	05 ^h 31 ^m 56 ^s	-70°09'33"	1.5	61	4.6
NGC 2210	06 ^h 11 ^m 31 ^s	-69°07'18"	3.3	59	1.0

Table 2 summarizes the properties of twelve globular clusters in the LMC and SMC that host RR Lyr stars. The coordinates and angular radii of the clusters are taken from Bica *et al.* (2008). In the last two columns we provide numbers of RR Lyr stars detected within one radius from the clusters' centers and estimated numbers of field RR Lyr stars that are expected to fall inside the same area. We estimated the number of field variables counting RR Lyr stars in the rings from 1.5 to 2.5 radii around the cluster centers and rescaling these numbers to the area occupied by clusters. The full lists of RR Lyr stars found within the cluster radii are provided in the FTP site in the file `gc.dat`.

In two clusters – NGC 1928 and NGC 1939 – we found only eight and seven RR Lyr stars, respectively, while the expected number of field variables is about five in both cases. Therefore, it cannot be excluded that all RR Lyr stars detected inside the area outlined by the radii of these clusters are field variables. Spectroscopic and astrometric follow-up observations of these stars should give a definitive answer to the question of their membership. In other globular clusters listed in Table 2 the identification of a significant number of RR Lyr stars is firm, although in most cases cluster members and field variables cannot be unambiguously distinguished.

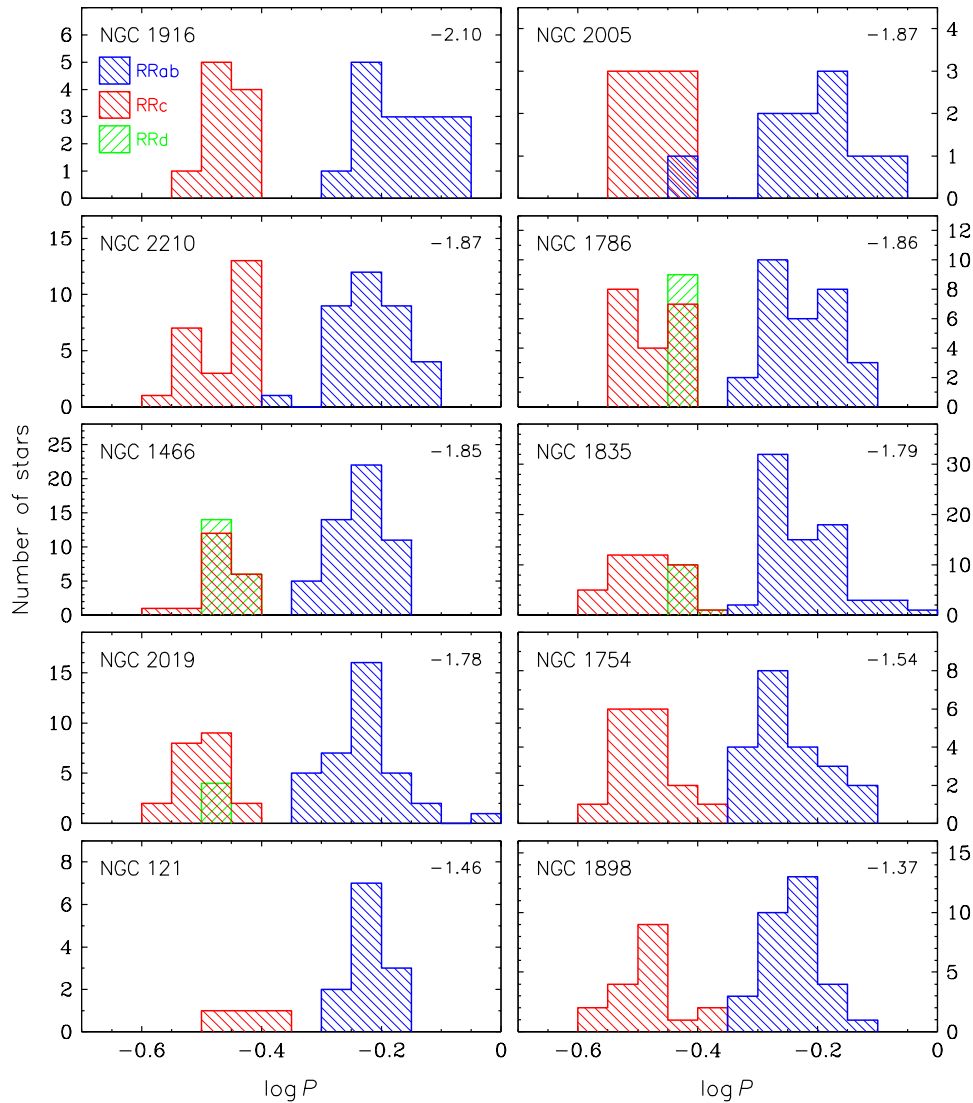


Fig. 2. Period distributions of RR Lyr stars in the Magellanic Clouds' globular clusters. Blue, red, and green contours show histograms for RRab, RRc, and RRd (first-overtone periods) stars. Globular clusters are arranged by increasing metallicities, $[\text{Fe}/\text{H}]$, given in the top right corner of *each panel*.

The distribution of pulsation periods of RR Lyr stars in ten the richest clusters are presented in Fig. 2. The clusters are arranged by increasing metallicities to show the progression of the period distribution with metallicity. RRd stars have been detected in four globular clusters and it is interesting that all of them have intermediate metal abundances $-1.86 \leq [\text{Fe}/\text{H}] \leq -1.78$ and fall in the Oosterhoff gap.

6.3. Double-Mode RR Lyr Stars

RR Lyr stars with two first radial modes simultaneously excited (RRd stars) constitute 5% of the total sample in the LMC and 10% in the SMC. These are the largest sets of RRd stars known in any stellar environment, so they may serve as important testbeds for theories of stellar pulsation. Petersen diagram (period ratios plotted against the longer period) is a sensitive tool widely used in asteroseismology (Popielski *et al.* 2000) and we construct it to analyze RRd stars.

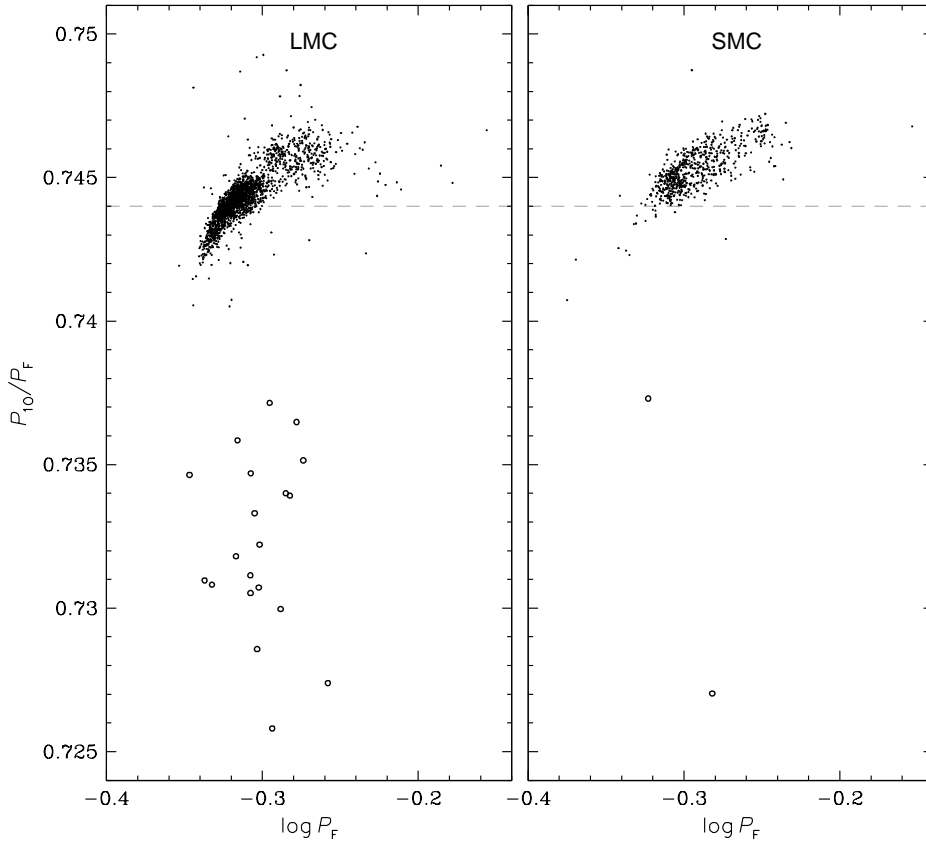


Fig. 3. Petersen diagrams for double-mode RR Lyr variables in the LMC (*left panel*) and SMC (*right panel*). Black dots represent “classical” RRd stars, while empty circles mark anomalous RRd stars (Soszyński *et al.* 2016, in preparation). Gray dashed lines indicate period ratio of 0.744 used to separate RRd stars shown in the two panels of Fig. 4.

Fig. 3 shows the Petersen diagrams for RRd stars in the LMC and SMC. The vast majority of double-mode RR Lyr stars has period ratios within a narrow range of $0.74 < P_{10}/P_F < 0.75$ and forms a curved sequence in the diagram. The sequence is longer in the LMC and reaches smaller period ratios than in the SMC. A simple test shows how the Petersen diagram is sensitive to the chemical composition of the stars. We divided our sample of RRd stars into two groups – with period

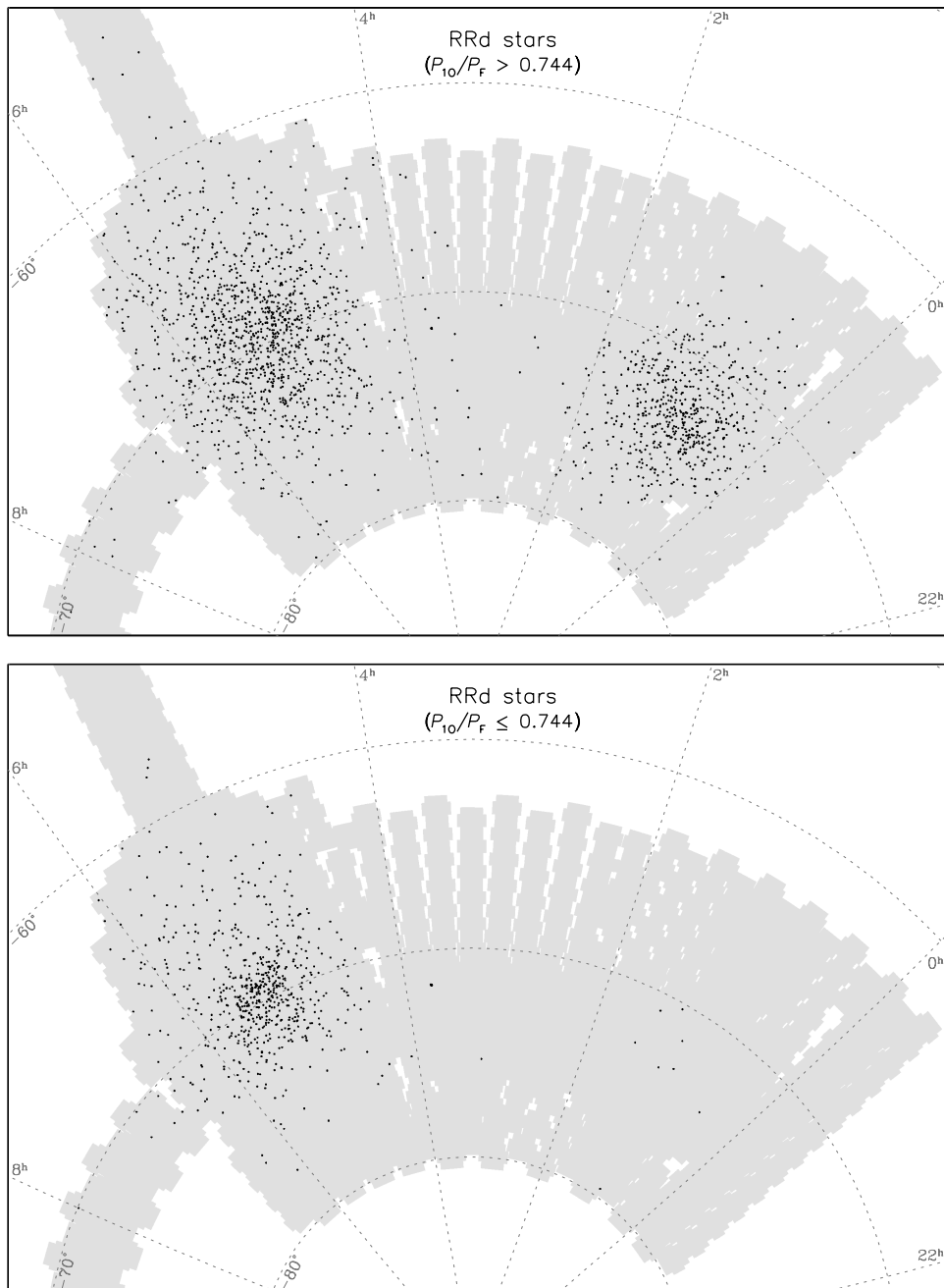


Fig. 4. Spatial distribution of double-mode RR Lyr stars in the OGLE fields toward the Magellanic Clouds. *Upper panel* presents RRd stars with period ratios $P_{10}/P_F > 0.744$. *Lower panel* shows positions of RRd stars with $P_{10}/P_F \leq 0.744$.

ratios above and below 0.744 – and we checked the spatial distribution of both groups. The result is displayed in Fig. 4. The $P_{10}/P_F \leq 0.744$ group is almost absent in the SMC, while in the LMC both groups have clearly different distributions, reflecting different metal abundance of these stars. RRd stars with $P_{10}/P_F \leq 0.744$ are clearly more concentrated toward the LMC center than the other group. This indicates that smaller period ratios are associated with higher metal abundances.

In Fig. 3, we included a new class of double-mode RR Lyr stars with period ratios ranging between 0.725 and 0.738. We call these objects anomalous RRd stars and describe them in the paper by Soszyński *et al.* (2016, in preparation). Anomalous RRd variables are characterized not only by different ratios of periods in comparison to “classical” RRd stars, but also by different amplitude ratios (in the anomalous RRd stars the fundamental mode usually dominates) and different light curve morphology of the fundamental mode component. Also, anomalous RRd stars usually show modulations of the pulsation amplitudes, in other words – the Blazhko effect. First RRd stars exhibiting Blazhko modulation were recently discovered in the Galactic bulge (Soszyński *et al.* 2014, Smolec *et al.* 2015) and these objects also belong to the anomalous subclass.

6.4. RR Lyr Stars with Eclipsing Modulation

In contrast to other types of classical pulsating stars (classical Cepheids – *e.g.*, Udalski *et al.* 2015b – or type II Cepheids), none of RR Lyr stars was confirmed as a member of an eclipsing binary system. In the OGLE-II catalog, Soszyński *et al.* (2003) discovered three RR Lyr stars in the LMC which show additional eclipsing variability superimposed on the pulsation light curves. However, it is not clear whether the pulsating stars are components of the binary systems, or these are physically unrelated blends. Soszyński *et al.* (2009) found one more RR Lyr star with eclipsing modulation. Very similar object – OGLE-BLG-RRLYR-02792 – detected by Soszyński *et al.* (2011) in the Galactic bulge was spectroscopically studied by the Araucaria project (Pietrzyński *et al.* 2012). They confirmed that OGLE-BLG-RRLYR-02792 is indeed a pulsating star in a binary system, but it cannot be a classical RR Lyr star, since its mass is only $0.26 M_{\odot}$. It turned out that OGLE-BLG-RRLYR-02792 is a prototype of a new class of internal variables – binary evolution pulsators – that mimic properties and behavior of RR Lyr stars.

In the present investigation, we report the discovery of one more candidate for an RR Lyr star with eclipsing-like modulation – OGLE-LMC-RRLYR-30844 – and we confirm the four previously announced objects of this kind (Soszyński *et al.* 2003, 2009). All these stars are located in the LMC. Fig. 5 shows the OGLE-IV *I*-band light curves of all five stars.

Based solely on the photometric data it cannot be judged whether these objects are real binary systems with a pulsating star as one of the components or the eclipsing binaries are not related to the RR Lyr stars and are just optical blends. It should be noted that the orbital periods of our candidates are very short compared

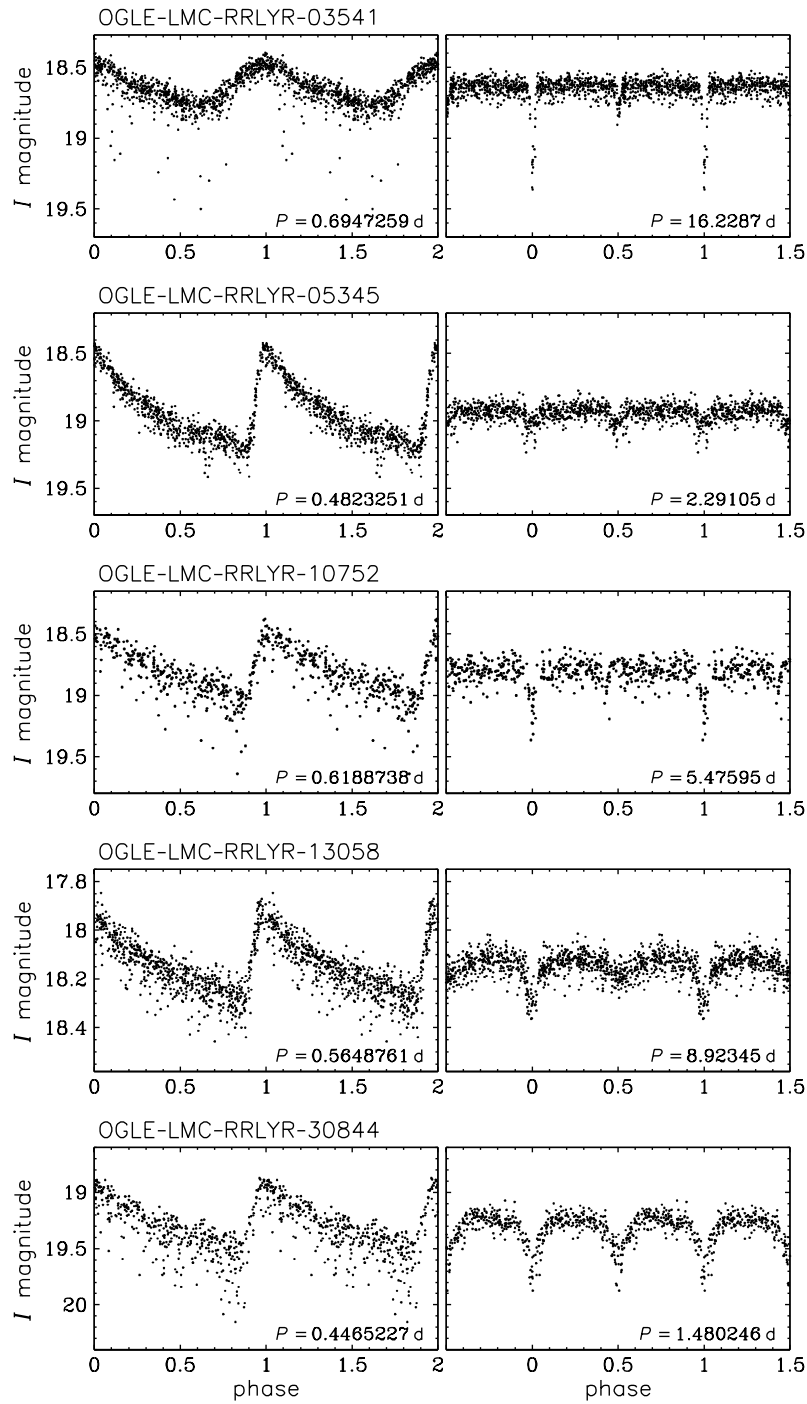


Fig. 5. OGLE-IV *I*-band light curves of RR Lyr stars showing eclipsing variability. *Left panels* show the original photometric data folded with the pulsation periods. *Right panels* show the eclipsing light curves after subtracting the RR Lyr component. The ranges of magnitudes are the same in each pair of the panels.

to the values expected for horizontal branch stars which in the previous stage of their evolution were located at the tip of the red giant branch. Recently, Hajdu *et al.* (2015) conducted a search for binary RR Lyr stars in the Galactic bulge using the OGLE collection (Soszyński *et al.* 2011, 2014) and found 12 firm candidates for (non-eclipsing) binary systems with the RR Lyr components. The orbital periods of all these candidates are longer than 1000 d. Our eclipsing binaries have orbital periods between 1.48 d and 16.23 d, which may suggest that we deal with optical blends.

However, the case of OGLE-BLG-RRLYR-02792 ($P_{\text{orb}} = 15.24$ d) indicates that at least some of the stars shown in Fig. 5 may be binary evolution pulsators – stars that transferred most of their mass to their companions and currently they cross the pulsation instability strip in their fast evolution toward the helium white dwarf branch. In particular, OGLE-LMC-RRLYR-03541 ($P_{\text{orb}} = 16.23$ d) has very similar properties (period, light curve shape) to OGLE-BLG-RRLYR-02792. In turn, OGLE-LMC-RRLYR-10752 exhibits a monotonic decrease of the pulsation period, just as it is expected for fast-evolving binary evolution pulsators (Pietrzyński *et al.* 2012). Using the 18-years-long OGLE light curve of OGLE-LMC-RRLYR-10752 we found the period change rate equal to -0.09 ± 0.01 s/yr.

7. Conclusions

We presented the OGLE collection of over 45 000 RR Lyr stars in the Magellanic System. Our sample contains, in fact, the vast majority of all RR Lyr variables in the Magellanic Clouds. A comparison of the OGLE-IV set to the previous editions of the OGLE collection of variable stars (Soszyński *et al.* 2009, 2010) assures us that our collection is characterized by a very high level of completeness and low contamination. Therefore, it is currently the best suited dataset for studying old stellar population in the Magellanic System. Distance determinations, three-dimensional distribution of the ancient stars, history of interactions between the Magellanic Clouds and the Milky Way, mapping of the interstellar extinction, metallicity gradients in the galaxies, properties of globular clusters – these are just the most obvious applications of the OGLE collection of RR Lyr stars.

The sample of RR Lyr stars itself is also a gold mine for stellar astrophysics. Exotic multimode pulsations, non-radial modes, period changes, mode switching, Blazhko effect, searching for pulsating stars in binary systems – all these studies are possible with the long-term OGLE photometry published with this collection.

Acknowledgements. We would like to thank Profs. M. Kubiak and G. Pietrzyński, former members of the OGLE team, for their contribution to the collection of the OGLE photometric data over the past years. We are grateful to Z. Kołaczowski and A. Schwarzenberg-Czerny for providing software used in this study.

This work has been supported by the Polish Ministry of Science and Higher Ed-

education through the program “Ideas Plus” award No. IdP2012 000162. The OGLE project has received funding from the Polish National Science Centre grant MAE-STRO no. 2014/14/A/ST9/00121 to AU. We acknowledge financial support from the National Science Centre grant No. DEC-2011/03/B/ST9/02573.

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