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Over 38 000 RR Lyrae Stars in the OGLE Galactic Bulge Fields*

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ABSTRACT

We present the most comprehensive picture ever obtained of the central parts of the Milky Way probed with RR Lyr variable stars. This is a collection of 38 257 RR Lyr stars detected over 182 square degrees monitored photometrically by the Optical Gravitational Lensing Experiment (OGLE) in the most central regions of the Galactic bulge. The sample consists of 16 804 variables found and published by the OGLE collaboration in 2011 and 21 453 RR Lyr stars newly detected in the photometric databases of the fourth phase of the OGLE survey (OGLE-IV). 93% of the OGLE-IV variables were previously unknown. The total sample consists of 27 258 RRab, 10 825 RRc, and 174 RRd stars. We provide OGLE-IV *I*- and *V*-band light curves of the variables along with their basic parameters.

About 300 RR Lyr stars in our collection are plausible members of 15 globular clusters. Among others, we found the first pulsating variables that may belong to the globular cluster Terzan 1 and the first RRd star in the globular cluster M54. Our survey also covers the center and outskirts of the Sagittarius Dwarf Spheroidal Galaxy enabling studies of the spatial distribution of the old stellar population from this galaxy.

A group of double-mode RR Lyr stars with period ratios around 0.740 forms a stream in the sky that may be a relic of a cluster or a dwarf galaxy tidally disrupted by the Milky Way. Three of our RR Lyr stars experienced a pulsation mode switching from double-mode to single fundamental mode or *vice versa*. We also present the first known RRd stars with large-amplitude Blazhko effect.

Key words: *Stars: variables: RR Lyrae – Stars: oscillations (including pulsations) – Stars: Population II – Galaxy: center – Galaxies: individual: Sagittarius Dwarf Spheroidal Galaxy*

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

1. Introduction

RR Lyr stars are an invaluable source of knowledge about the oldest stellar population. They are numerous, present in various stellar environments, and are relatively easy to detect due to their short periods, characteristic light curves and large amplitudes. RR Lyr stars are standard candles which makes them important distance indicators and tracers of the structure of the Milky Way and other galaxies. RR Lyr variables are radially pulsating horizontal branch stars, with periods in the range of 0.2–1.0 d. They are classified into three main types according to the mode in which they pulsate: fundamental-mode RRab stars, first-overtone RRc stars and double-mode RRd stars.

Based on the observations carried out during the second and the third phases of the Optical Gravitational Lensing Experiment (OGLE-II and OGLE-III projects), we have compiled the largest ever collection of RR Lyr stars, consisting in total of over 44 000 objects. It includes RR Lyr stars from the Magellanic Clouds (Soszyński *et al.* 2009, 2010), the Galactic bulge (Soszyński *et al.* 2011, hereafter S11) and the Galactic disk (Pietrukowicz *et al.* 2013).

The OGLE-discovered RR Lyr stars have been the base of many research projects: studies of the structure of the Magellanic Clouds and Galactic bulge (*e.g.,* Subramaniam and Subramanian 2009, Pejcha and Stanek 2009, Feast *et al.* 2010, Kapakos and Hatzidimitriou 2012, Pietrukowicz *et al.* 2012, Dékány *et al.* 2013, Wagner-Kaiser and Sarajedini 2013, Deb and Singh 2014, Sans Fuentes and De Ridder 2014), measurements of distances (*e.g.,* Haschke *et al.* 2012, Pietrukowicz *et al.* 2012), preparation of the reddening maps (*e.g.,* Haschke *et al.* 2011, Nataf *et al.* 2013, Wagner-Kaiser and Sarajedini 2013), studies of the Blazhko modulation in the well-sampled OGLE light curves of RR Lyr stars (*e.g.,* Chen *et al.* 2013, Welch 2014), applications as a training set for automated methods of classification of variable stars (*e.g.,* Long *et al.* 2012). One of the objects included in the OGLE-III Catalog of Variable Stars – OGLE-BLG-RRLYR-02792 – initially classified as an RR Lyr star in an eclipsing binary system, turned out to be a representative of a new class of variable stars, called binary evolution pulsators (Pietrzyński *et al.* 2012, Smolec *et al.* 2013). Such stars have masses much smaller than expected for RR Lyr variables, but their light curves mimic those of classical pulsators.

OGLE-III RR Lyr stars were also extensively followed-up in different wavelength ranges. For example, they served as input list objects for infrared surveys like the Vista Variables in the Vıa Láctea (VVV, Dékány *et al.* 2013) or the Carnegie RR Lyrae Program. Many of these stars will also be input targets for the large spectroscopic survey – APOGEE-II.

In this work – first of a series presenting variable stars detected from the observations collected by the fourth phase of the OGLE survey (OGLE-IV) – we expand the OGLE collection of RR Lyr stars in the central regions of the Galaxy by a factor of more than two and present the most comprehensive picture ever obtained of the central parts of the Galactic bulge as seen *via* RR Lyr stars. The number of newly detected pulsators exceeds 21 000 and now the whole OGLE sample of RR Lyr variables toward the Galactic bulge lines-of-sight consists of 38 257 stars. This is the largest sample of RR Lyr stars discovered so far in one stellar environment. We also provide OGLE-IV light curves of the RR Lyr stars detected during the previous stages of the OGLE project.

The paper is organized as follows. In Section 2 we discuss the observations used in this study and how these data were reduced. Section 3 presents how RR Lyr stars were selected and classified. In Section 4 we compare OGLE-III and OGLE-IV photometry of RR Lyr stars. Section 5 describes the structure of the new catalog of RR Lyr stars. In Section 6 we estimate the completeness of our sample. In Section 7 we discuss possible applications of our collection of RR Lyr stars and show the most interesting individual objects. Finally, Section 8 summarizes the conclusions drawn from this work.

2. Observational Data

The OGLE-IV survey conducts long-term, continuous observations of the fields toward the Galactic bulge using the 1.3 m Warsaw telescope located at the Las Campanas Observatory (LCO) in Chile. The observatory is operated by the Carnegie Institution for Science. OGLE-IV began observations of the Galactic bulge in March 2010 and regular monitoring has been continued up to now. The latest observations used in this study were collected in October 2013, with the exception of several fields with a relatively small number of points, for which we used observations collected up to September 2014.

During the OGLE-IV survey the Warsaw telescope is equipped with a 32-detector mosaic CCD camera covering a field of about 1.4 square degrees in one image. In total, 121 OGLE-IV fields toward the Galactic center were searched for RR Lyr stars (*cf.* the OGLE sky coverage maps on the OGLE project WWW page: *http://ogle.astrouw.edu.pl*). Together with the OGLE-II and OGLE-III fields analyzed by S11, the bulge area of 182 square degrees was covered. Because the OGLE-IV observing strategy has been optimized to detect and study microlensing events hosting exoplanets, the number of collected epochs varies significantly from field to field – from about 80 to over eight thousand. Most of the observations were made through the Cousins *I*-band filter with a standard integration time of 100 s. Additionally from ten to a few dozen epochs, depending on the field, were also collected in the Johnson *V*-band with the exposure time of 150 s for color information. The *I*-band magnitudes in the OGLE-IV databases range from about 13 mag to 20.5 mag.

The photometric reductions were performed using the OGLE real time photometric pipeline (Udalski 2003) implemented for OGLE-IV observing set-up. The pipeline is based on Difference Image Analysis technique (DIA, Alard and Lupton 1998, Woźniak 2000). The instrumental photometry was then stored in the standard OGLE databases.

The final photometry of selected variables was calibrated to the standard *VI* system. Generally, the OGLE-IV photometry has been tied to precisely calibrated OGLE-III Photometric Maps of the Galactic Bulge (Szymański *et al.* 2011). These calibrations are based on observations collected on hundreds of photometric nights. The accuracy of the zero points of OGLE-IV photometry in the Galactic bulge is at the level of 0.02 mag.

3. Selection and Classification of RR Lyr Stars

In order to detect RR Lyr variables, we performed an extensive period search for all discrete sources observed by OGLE-IV toward the Galactic bulge. For nearly 400 million *I*-band light curves with more than 30 data points, we calculated Fourier amplitude spectra in the frequency range from 0 d^{-1} to 24 d^{-1}. For each star we recorded a period corresponding to the highest peak in the spectrum along with its amplitude and signal-to-noise ratio.

The identification of RR Lyr stars was performed in two ways, but in both approaches the final decision was made based on the visual inspection of the light curves. In the first method, each light curve with a period between 0.2 d and 1.0 d was fitted with a Fourier cosine series and the Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} (Simon and Lee 1981) were derived. We visually checked the light curves with the Fourier coefficients and amplitudes typical for RR Lyr stars. The second algorithm was based on the template light curve fitting. First, we prepared templates of typical light curves of RRab and RRc stars. Then we correlated the real observations with the templates and visually examined the best fit light curves.

If the same star was identified twice, in two overlapping fields, only one entry in our final RR Lyr star list was left. We have chosen the detection with larger number of data points in the light curve. Objects with double detections were used to estimate the completeness of the catalog (see Section 6).

In this way we found 21 453 RR Lyr stars that were not recorded by the previous stages of the OGLE survey. The sample was divided into three groups: RRab, RRc and RRd stars. In most cases our classification was based on the morphology of the light curves. RRd stars were found based on their characteristic period ratios. We did our best to minimize contamination of our RR Lyr sample from other types of variables. RRab stars are usually easy to distinguish from non-pulsating variable stars (although sometimes spotted variables may mimic pulsating stars). On the other hand, RRc stars have much more symmetric light curves and can be easily confused with close binary systems or rotating stars. In the OGLE databases we found at least a few thousand sinusoidal light curves with periods in the range of 0.2–0.5 days. Many of these objects may be first-overtone RR Lyr stars, but they are not included in our sample. We required at least a small asymmetry of the light curves to classify stars as RRc variables. A number of multi-mode δ Sct stars contaminating our RR Lyr sample were filtered out based on their position in the Petersen diagram (period ratio *vs.* period diagram). However, despite our efforts, we expect that a limited number of single-mode δ Sct stars and variable stars of other types may be hidden among RR Lyr stars in our collection. Some questionable cases are flagged as "uncertain" in the Remarks file.

4. Comparison with the OGLE-III Catalog

Despite the fact that OGLE-IV fields cover most of the OGLE-II and OGLE-III fields in the Galactic bulge, the vast majority of the newly detected RR Lyr stars (more than 97%) were found in the regions outside the previously searched area. This confirms high completeness of the OGLE catalogs of variable stars. One should be aware that due to the technical gaps between CCD detectors of the OGLE-IV mosaic camera which have been only partially filled in the reference images of a given field (being a stack of a few individual somewhat shifted images) a few percent of the area of each OGLE-IV field remained unobserved. However, in the fields overlapping with our previous studies (S11) these OGLE-IV "dead zones" were usually filled by OGLE-III observations.

Table 1

Reclassified objects from the OGLE-III Catalog of RR Lyr stars (S11)

ID	New classification	ID	New classification
OGLE-BLG-RRLYR-01594	Eclipsing	OGLE-BLG-RRLYR-09947	Other
OGLE-BLG-RRLYR-01929	Cepheid	OGLE-BLG-RRLYR-10243	Spotted
OGLE-BLG-RRLYR-02159	Other	OGLE-BLG-RRLYR-10938	Cepheid
OGLE-BLG-RRLYR-02251	Cepheid	OGLE-BLG-RRLYR-11514	Other
OGLE-BLG-RRLYR-02674	Other	OGLE-BLG-RRLYR-11616	Other
OGLE-BLG-RRLYR-02676	Other	OGLE-BLG-RRLYR-11907	Other
OGLE-BLG-RRLYR-02974	Other	OGLE-BLG-RRLYR-11947	Other
OGLE-BLG-RRLYR-03385	Eclipsing	OGLE-BLG-RRLYR-13883	Other
OGLE-BLG-RRLYR-03439	Other	OGLE-BLG-RRLYR-14003	Eclipsing
OGLE-BLG-RRLYR-03929	Other	OGLE-BLG-RRLYR-14084	Eclipsing
OGLE-BLG-RRLYR-04475	Other	OGLE-BLG-RRLYR-14183	Other
OGLE-BLG-RRLYR-04864	Cepheid	OGLE-BLG-RRLYR-14754	Spotted
OGLE-BLG-RRLYR-04897	Other	OGLE-BLG-RRLYR-15159	Other
OGLE-BLG-RRLYR-08477	Other	OGLE-BLG-RRLYR-15476	Eclipsing
OGLE-BLG-RRLYR-09105	Cepheid	OGLE-BLG-RRLYR-16120	Other
OGLE-BLG-RRLYR-09326	Other	OGLE-BLG-RRLYR-16833	Other

We extracted and visually inspected OGLE-IV light curves of RR Lyr stars from the OGLE-III catalog (S11). We recalculated their periods and other parameters, such as their mean magnitudes, amplitudes and Fourier coefficients. During the inspection we reclassified 32 objects from S11 as classical Cepheids, eclipsing binaries, spotted variables or other (usually unknown) types of variable stars. Table 1 lists all these stars along with their new classification. We removed these objects from the present version of our RR Lyr sample. The binary evolution pulsator OGLE-BLG-RRLYR-02792 (Pietrzyński *et al.* 2012) is not a classical RR Lyr star, but we decided to leave it on the list, so that the astronomical community has an access to the current photometry of this unique object.

For several RR Lyr stars we corrected their mode of pulsation. At least three variables evidently switched their pulsation modes, from RRd to RRab or *vice versa* (see Section 7.4). In other cases, the OGLE-III light curves were affected by a small number of points, which resulted in erroneous classifications by S11. Four other RR Lyr stars in the OGLE-III catalog had incorrect periods – one-day aliases of the real ones.

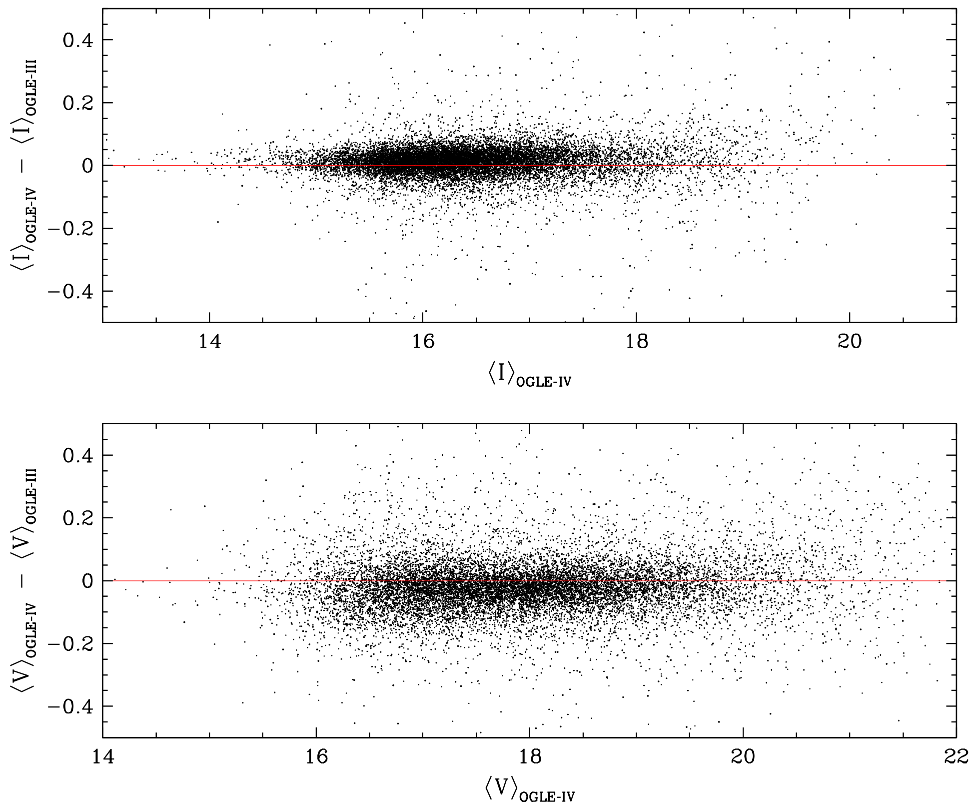

Fig. 1. Comparison between OGLE-III and OGLE-IV *I*-band (*upper panel*) and *V*-band (*lower panel*) mean magnitudes of RR Lyr stars in the Galactic bulge.

The OGLE-III and OGLE-IV light curves have been obtained with different instrumental configurations, in particular with different filters and CCD detectors. Although both instrumental systems were transformed to the standard photometric system, the systematic uncertainties of the calibration zero point may reach 0.02 mag. In Fig. 1 we compare *I*- and *V*-band mean luminosities of RR Lyr stars derived from the OGLE-III (S11) and OGLE-IV light curves. The agreement between both data sets for most of the stars is reasonably good. The mean difference between *I*-band magnitudes measured from the OGLE-IV and OGLE-III photometry is 0.012 mag with the standard deviation of 0.043 mag. There is also a number of individual variables for which OGLE-III and OGLE-IV luminosities differ much more considerably. For 6% of RR Lyr stars observed in both phases of the survey, $|I_{\rm OGLE-IV} - I_{\rm OGLE-III}|$ is larger than 0.1 mag, and for 2% this difference is larger than 0.2 mag. We found that in most such cases the offset between magnitudes was caused by crowding and blending by unresolved stars that randomly affected the reference image fluxes of the DIA photometry.

In the *V*-band there is a systematic difference between OGLE-IV and OGLE-III datasets at the level of -0.020 mag with the standard deviation of 0.079 mag. The offset is well within the expected uncertainty of the photometric calibrations. The larger scatter of the points in the lower panel of Fig. 1 can be explained by a much smaller number of observations in the *V*-band than in *I*-band, which affected the accuracy of the derived mean luminosities. The OGLE-III *V*-band light curves contained typically only a few points. In the OGLE-IV databases the median number of the *V*-band epochs is 22, so we expect that the accuracy of the calculated mean magnitudes is on average much better.

5. Catalog of RR Lyr Stars Toward the Galactic Bulge

The sample of newly detected RR Lyr stars toward the Galactic bulge was combined with the OGLE-III catalog (S11). The total number of RR Lyr variables in our collection is now 38 257, including 27 258 RRab, 10 825 RRc and 174 RRd stars. There are 32 objects reclassified in the present investigation (Section 4) that were removed from the collection. We kept the identifiers of RR Lyr variables from S11. The identifiers from OGLE-BLG-RRLYR-00001 to OGLE-BLG-RRLYR-16836 are occupied by the RR Lyr stars from the OGLE-III catalog. The newly detected variables are named starting from OGLE-BLG-RRLYR-16837 to OGLE-BLG-RRLYR-38289 and are ordered by increasing right ascension.

The whole catalog is available *via* anonymous FTP or the WWW site:

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/blg/rrlyr/
http://ogle.astrouw.edu.pl/

The format of the files in the FTP archive follows that of S11. For each star we provide its identifier, J2000 equatorial coordinates, mode of pulsation, fields and internal numbers in the OGLE-IV, OGLE-III, and OGLE-II photometric databases (if available) and the cross-matches with the International Variable Star Index (VSX, Watson *et al.* 2006), which is currently the most complete database of known variable stars. Observational parameters of the RR Lyr stars: periods, intensity mean magnitudes in the *I*- and *V*-bands, *I*-band peak-to-peak amplitudes, and Fourier coefficients R_{21}, ϕ_{21}, R_{31} and ϕ_{31} derived for the *I*-band light curves are listed in separate files. The periods with uncertainties were found with the TATRY code kindly provided by A. Schwarzenberg-Czerny (1996).

Note that all the observational parameters were computed using solely the OGLE-IV photometry collected in the years 2010–2013. This refers also to the OGLE-III RR Lyr variables, if only the OGLE-IV light curves were available. For stars with no OGLE-IV photometry we copied the parameters from the OGLE-III catalog (S11). We recalculated the periods because many RR Lyr stars (especially RRc variables) significantly changed periods in the time that passed between previous and present phases of the OGLE project. For strictly periodic variables we recommend to merge OGLE-III and OGLE-IV light curves and to find the pulsation period using the whole OGLE photometry spanning up to 17 years. While merging the light curves one should keep in mind that in individual cases the OGLE-III and OGLE-IV observations may be somewhat shifted in magnitudes (*cf.* Fig. 1), so an additional magnitude alignment may be necessary.

The files with the OGLE-IV time-series photometry of each star are stored in the phot/ directory. Finding charts for all stars can be downloaded from the directory fcharts/. These are $60'' \times 60''$ subframes of the *I*-band DIA reference images. The file gc.dat lists RR Lyr stars that are candidates for the globular cluster members. The file remarks.txt contains remarks about some RR Lyr stars. See the README file for more details.

In Fig. 2 we present the 2-D spatial map of our collection. This is the most complete view of the central parts of the Galactic bulge ever obtained with RR Lyr variables as the stellar structure probes. Brightness of variables is color-coded. It is clearly seen that the RR Lyr stars become gradually fainter in the lines-of-sight closer to the Galactic plane. This is obviously due to dramatically increasing interstellar extinction in the optical bands toward these regions, moving the brightness of RR Lyr below the OGLE detection limit. However, it is worth noting that the empty area around the Galactic plane in Fig. 2 was also searched for RR Lyr but no foreground objects were found. In the future near infrared surveys, *e.g.,* the VVV survey (Minniti *et al.* 2010, Catelan *et al.* 2013), may complement the OGLE picture presented in Fig. 2 in this highly obscured region of the Galactic plane, unreachable for the OGLE optical survey.

In the isolated region at the Galactic latitudes $b < -10^\circ$, most of the RR Lyr stars have apparent *I*-band luminosities between 17 mag and 18 mag – much fainter than expected for the bulge members. This is because these stars belong to the Sagittarius Dwarf Spheroidal Galaxy (Sgr dSph) which is located behind the Galactic bulge (see Section 7.2).

Lower panels of Fig. 2 show possible applications of our sample of RR Lyr stars. The density map (left panel) traces the structure of the bulge, while the color map (right panel) reflects the spatial distribution of the interstellar extinction toward the Milky Way center. More detailed study of the bulge structure will be presented in Pietrukowicz *et al.* (2014, in preparation).

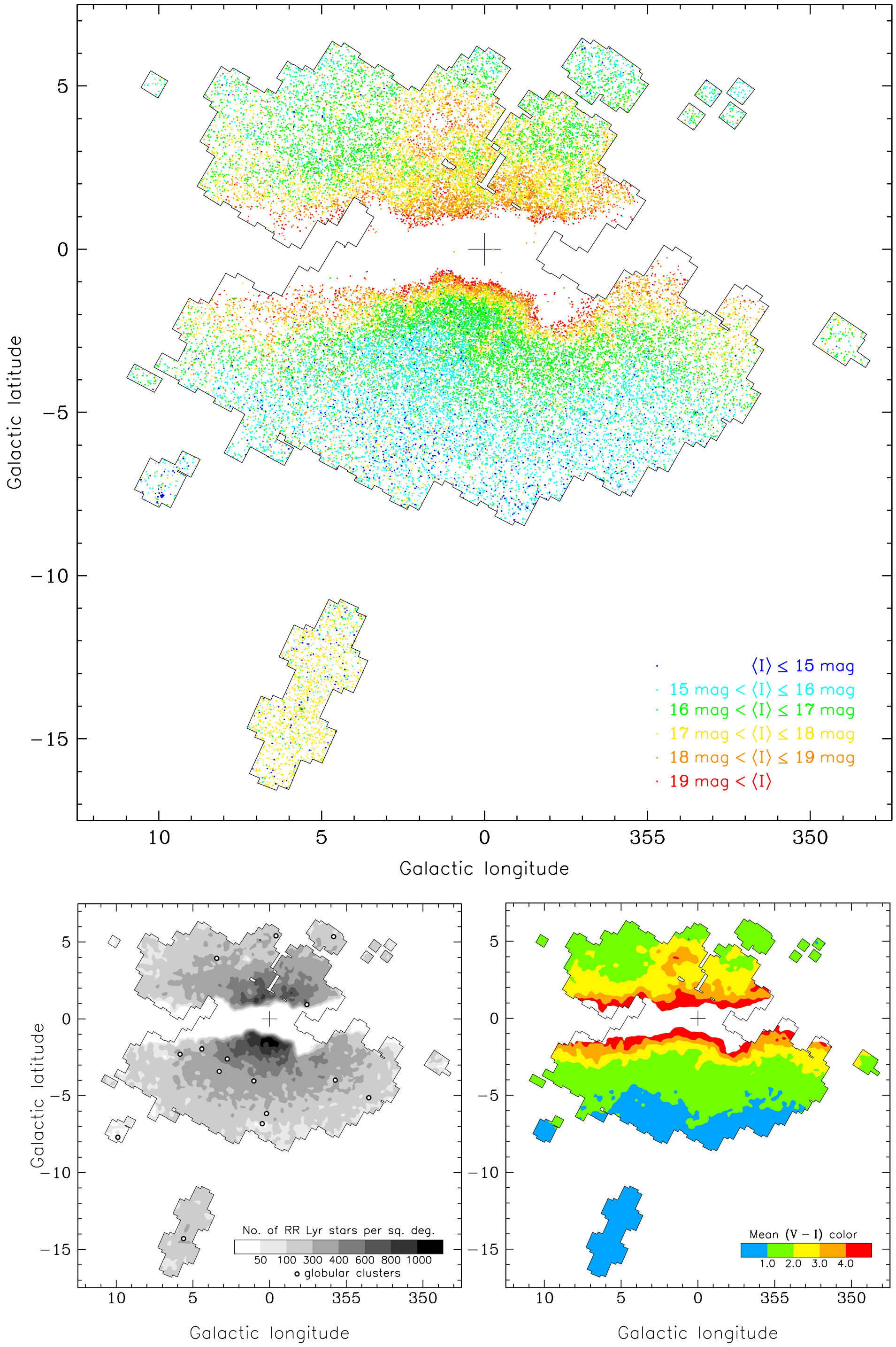

Fig. 2. Spatial distribution of RR Lyr stars in the OGLE fields toward the Galactic bulge. In the *upper panel* points of different colors represent individual RR Lyr stars of different mean magnitudes. *Lower left panel*: surface density map of RR Lyr stars. White circles indicate the positions of globular clusters likely hosting RR Lyr stars. *Lower right panel*: spatial distribution of the mean apparent $(V-I)$ colors of RR Lyr stars that increase toward the Galactic plane due to dust extinction.

6. Completeness of the Sample

The completeness of our list of RR Lyr stars in the Galactic bulge depends on many factors, such as the pulsation modes, brightness of the stars, amplitudes of variations, positions in the sky and number of points in the light curves. Undoubtedly, the greatest completeness and the least contamination is in the regions covered by both, OGLE-III and OGLE-IV, surveys, since we performed two independent searches for RR Lyr stars in this area.

The completeness in the regions covered only by the OGLE-IV fields is reduced by gaps between CCD detectors of the OGLE-IV mosaic camera. We estimate that about 7% of RR Lyr stars fell into these gaps. On the other hand, some RR Lyr stars were detected twice, in the overlapping regions between adjacent OGLE-IV fields. We used such objects to estimate the completeness in the area covered by the CCD detectors (outside the gaps). We checked how many variables from our list could be potentially detected in the neighboring fields and we compared this with the number of independently identified objects. Assuming that the minimum number of data points in the light curves must be larger than 100, in total 460 RR Lyr stars from our catalog were recorded in the OGLE-IV databases twice, so we had an opportunity to identify 920 counterparts. We independently detected 864 of them, which gives the general completeness equal to 94%.

We expect that the completeness will be larger for RRab stars, due to their characteristic, asymmetric light curves. Indeed, using the same method we estimate that our collection of RRab stars is complete to 97%, while for RRc stars it is only 84%. Many RRc stars, especially fainter ones, were not recognized as pulsators due to their nearly sinusoidal light curves. We also estimated how the completeness depends on the brightness of stars and the number of epochs. For RR Lyr stars fainter then $I = 19$ mag the completeness drops down to 82%, while for variables brighter than $I = 17$ mag it is above 95%. When the number of data points in the light curves is below 100, but larger than 50, the completeness decreases to 77%.

7. Discussion

7.1. RR Lyr Stars in Globular Clusters

More than 300 RR Lyr stars in our collection are plausible members of globular clusters. Cluster variables (the historical name of RR Lyr stars) are not only used as distance indicators, but they also play an important role in unraveling the early history of globular clusters. The mere presence of RR Lyr stars in the cluster suggests that its age is at least 10 Gyr. Furthermore, the distribution of pulsation periods and the morphology of the light curves of RR Lyr stars can be used to estimate the metallicity of the cluster without spectroscopic measurements.

In S11 we listed seven globular clusters that likely host from 3 to 43 RR Lyr stars. In the present work we increase this list to 15 globular clusters (Table 2). In

T a b l e 2

Globular clusters containing RR Lyr star candidates

Cluster name	RA (J2000)	Dec (J2000)	Cluster radius [′]	$N_{\rm RR}$	$N_{\rm fieldRR}$ (estimated)
NGC 6304	$17^h14^m32^s$	$-29°27'44''$	4.0	5	2.0
NGC 6355	$17^h23^m59^s$	$-26°21'13''$	2.1	5	0.3
Terzan 1	$17^h35^m48^s$	$-30°28'11''$	1.2	9	2.0
NGC 6401	$17^h38^m37^s$	$-23°54'32''$	2.4	30	1.8
NGC 6441	$17^h50^m13^s$	$-37°03'04''$	4.8	44	2.8
NGC 6453	$17^h50^m52^s$	$-34°35'55''$	3.8	10	2.5
Djorg 2	$18^h01^m49^s$	$-27°49'33''$	5.0	17	11.0
Terzan 10	$18^h02^m57^s$	$-26°04'00''$	0.8	3	1.0
NGC 6522	$18^h03^m34^s$	$-30°02'02''$	4.7	17	6.5
NGC 6540	$18^h06^m09^s$	$-27°45'55''$	0.8	3	0.5
NGC 6544	$18^h07^m21^s$	$-24°59'51''$	4.6	6	2.2
NGC 6558	$18^h10^m18^s$	$-31°45'49''$	2.1	7	0.3
NGC 6569	$18^h13^m39^s$	$-31°49'35''$	3.2	21	0.8
M22 (NGC 6656)	$18^h36^m24^s$	$-23°54'12''$	16.0	26	4.5
M54 (NGC 6715)	$18^h55^m03^s$	$-30°28'42''$	6.0	128	6.5

column 5 of Table 2 we provide the number of RR Lyr stars lying within one cluster angular radius from the cluster center[†]. In the last column we also provide the estimated number of field RR Lyr stars that fall by chance inside the area outlined by the cluster radii (we counted RR Lyr stars lying in the rings from 1.5 to 2.5 radii from the cluster centers and rescaled the number of detected stars to the area occupied by the clusters). It should be, however, stressed that our RR Lyr stars are only candidates for cluster members, selected based on purely statistical arguments. Spectroscopic and/or astrometric follow-up observations of these candidates should provide the ultimate confirmation of their cluster membership. In the FTP site we provide the file gc.dat with the list of RR Lyr stars located within the radii of the globular clusters.

As can be seen in Table 2, globular clusters Terzan 10 and NGC 6540 host only three RR Lyr star candidates each and it is possible that all of them are field variables. In the highly-reddened globular cluster Terzan 1 we found nine RR Lyr star candidates of which seven objects may belong to the cluster. To our knowledge, these are the first pulsating stars found along the cluster's line-of-sight. Most of these variables have V-band apparent magnitudes shifted below our detection limit due to high interstellar extinction.

The largest sample of RR Lyr stars (128) was found in the globular cluster M54 (NGC 6715) that resides at the center of the Sgr dSph. Most of these vari-

[†]The list of the Milky Way globular clusters is available at the web page *http://messier.obspm.fr/xtra/supp/mw_gc.html*

ables were already discovered by Rosino and Nobili (1959), Layden and Sarajedini (2000) and Sollima *et al*. (2010), however, we also discovered over a dozen new RR Lyr stars in M54, including the first known RRd star in this cluster: OGLE-BLG-RRLYR-37594. Another newly detected RR Lyr star located close to the center of M54 – OGLE-BLG-RRLYR-37582 – exhibits two periodicities: 0.508058 d and 0.623940 d. After separation of these two modes, it turned out that both periods are associated with the fundamental-mode pulsations. Thus, we have discovered two unresolved RRab star lying along the same line-of-sight.

7.2. RR Lyr Stars in the Sagittarius Dwarf Spheroidal Galaxy

More than 2000 RR Lyr stars from our sample are located far behind the Galactic bulge. Most of them belong to the Sgr dSph – a satellite of the Milky Way that is currently being disrupted by the tidal forces of our Galaxy. Actually, seven

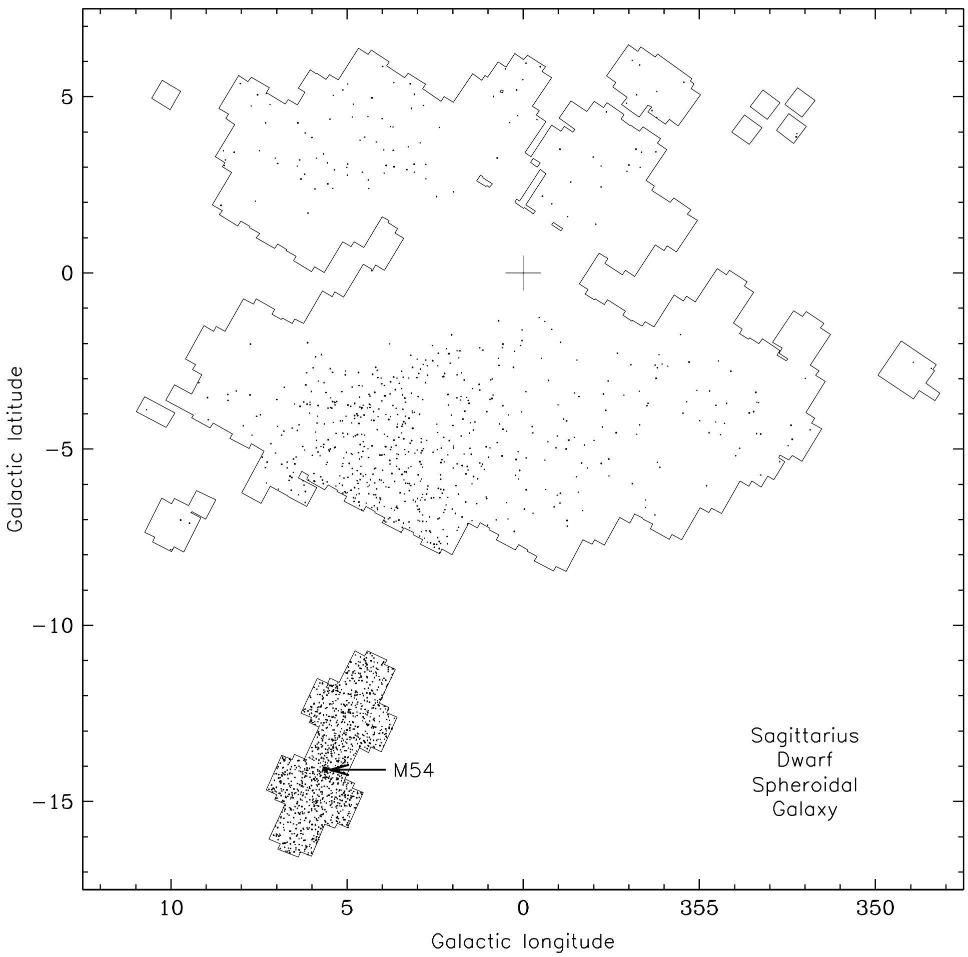

Fig. 3. Spatial distribution of RR Lyr stars in the Sagittarius Dwarf Spheroidal Galaxy. The arrow indicates the position of the globular cluster M54 at the center of the galaxy.

OGLE-IV fields – BLG705 to BLG711 (the fields located at the Galactic latitudes $b < -10°$) – were selected primarily for observations of the central regions of this dwarf galaxy. Indeed, over 80% of RR Lyr stars detected in these fields (about 1300 out of 1600 objects) are members of the Sgr dSph, including 128 cluster variables in M54.

Obviously, RR Lyr stars behind the bulge are affected by different interstellar extinction, depending on their position in the sky. We separated RR Lyr stars behind the bulge using the same arbitrary criterion as in S11: $I > 1.2(V - I) + 16.2$ mag. The spatial distribution of RR Lyr stars in the Sgr dSph is shown in Fig. 3. A pronounced gradient in the number of stars is clearly visible.

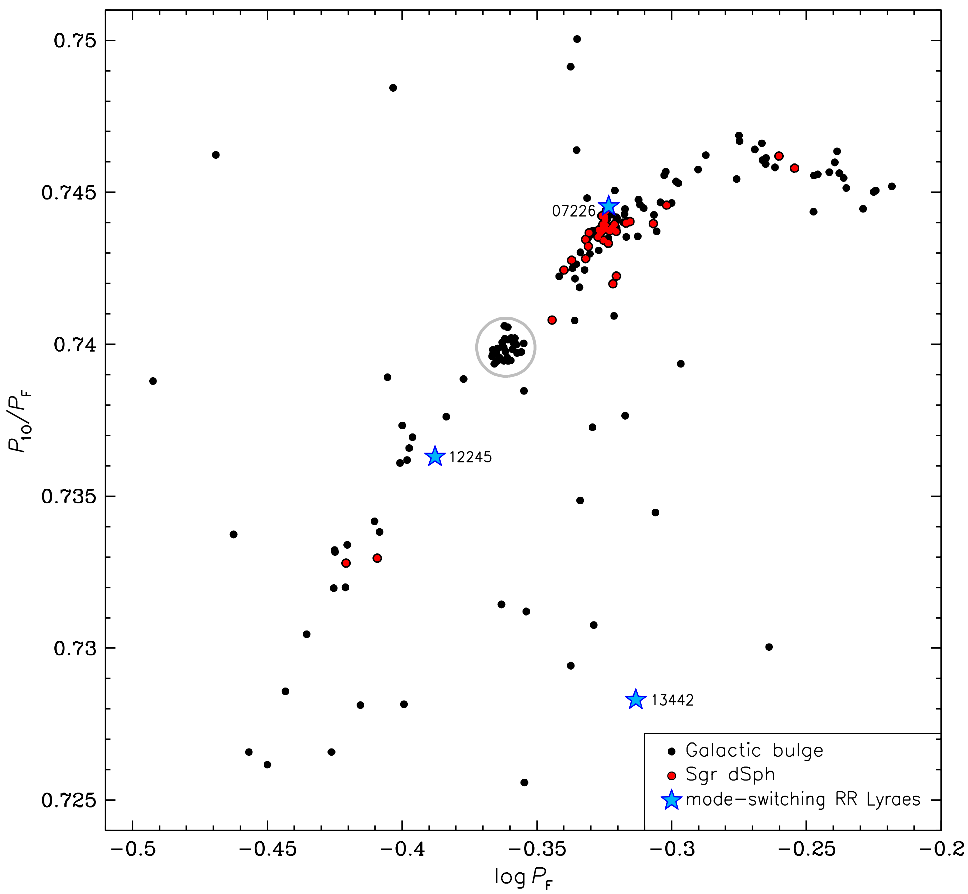

Fig. 4. Petersen diagram for RRd stars in our collection. Black points indicate objects from the Galactic bulge, red points represent variables from the Sgr dSph, blue stars show positions of three RR Lyr stars that switched pulsation modes. Large gray circle marks the position of a group of 28 RRd stars with $\log P_F \approx -0.36$ and $P_{1O}/P_F \approx 0.740$.

7.3. Double-mode RR Lyr Stars

Double-mode RR Lyr variables (RRd stars) are very rare objects in the Galactic bulge. They exhibit unique features, different than RRd stars known in any other stellar environment. The number of RRd variables in our collection almost doubled, compared to our previous study (S11). The Petersen diagram for this sample is shown in Fig. 4. The extended sample confirms that some RRd stars in the bulge have exceptionally small P_{1O}/P_{F} period ratios, down to 0.726, which can be explained by high metallicity values in these objects (S11).

Our sample of RR Lyr stars also contains a number of double-periodic variables with the period ratios lower than the above limit. At least seven of these objects may be RRd stars with the period ratios, between 0.69 and 0.72. The secondary periods of double-periodic RR Lyr stars are given in the Remarks of the catalog.

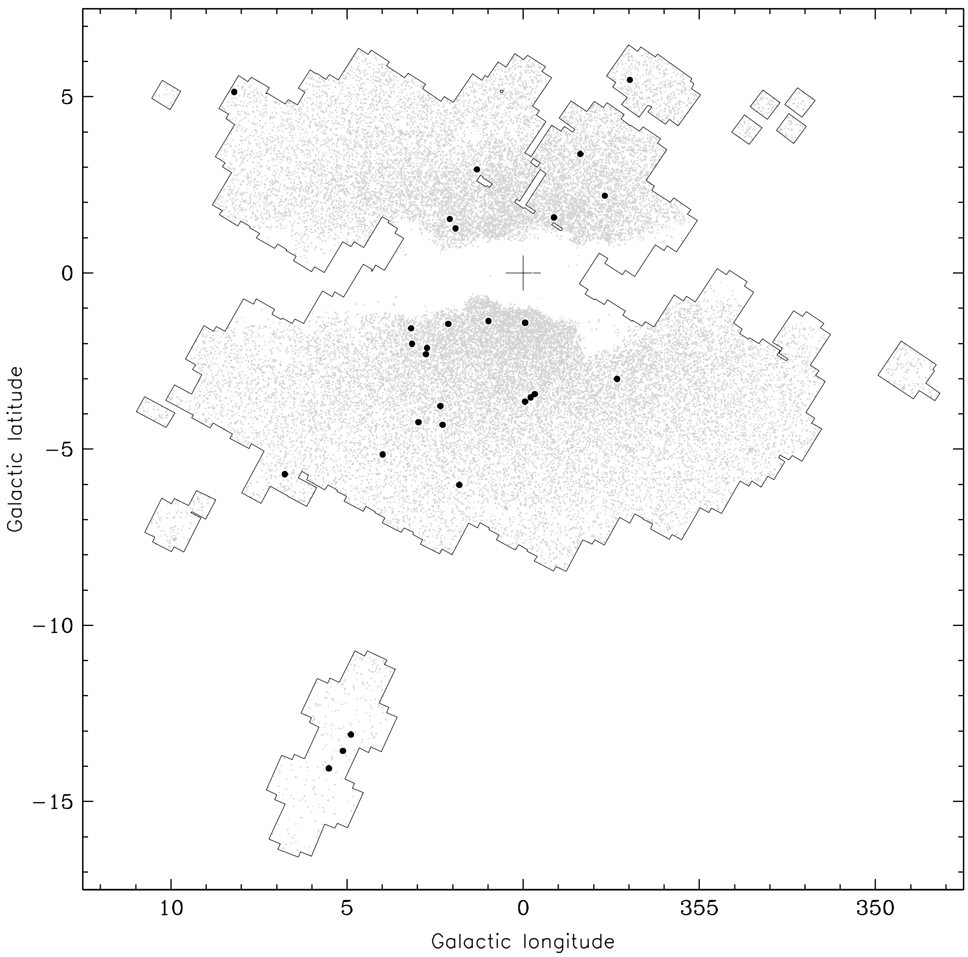

Fig. 5. Spatial distribution of RRd stars encircled in Fig. 4 (black points). Gray points show the positions of the remaining RR Lyr stars from the Galactic bulge (the Sgr dSph variables have been removed).

In S11 we noticed a group of 16 RRd stars with a very narrow range of periods ($-0.366 < \log P_{\rm F} < -0.354$) and period ratios ($0.739 < P_{\rm 1O}/P_{\rm F} < 0.741$). After adding OGLE-IV-discovered objects this group increased to 28 stars, which constitutes over 20% of all RRd stars detected in the Galactic bulge. In Fig. 4 these stars are marked with a gray circle. Fig. 5 presents the position of these double-mode pulsators in the sky. It seems that most of these objects are associated with a stellar stream that nearly vertically crosses the bulge. We performed a two dimensional Kolmogorov-Smirnov test (Fasano and Franceschini 1987) in the (l,b) plane. There is only a 1.1% chance that our group of 28 RRd stars and all other bulge RR Lyr stars in our collection are drawn from the same general population. Thus, we suspect that this well-defined group of RRd stars is a relic of a stellar cluster or a dwarf galaxy disrupted by tidal interactions with the Milky Way. The stream is similar to the tidal stream of the Sgr dSph, but it is closer and located roughly at the same distance as the Galactic center.

7.4. RR Lyrae Stars With Mode Switching

The long-term extensive OGLE photometry of variable stars offers an opportunity to study various stellar behaviors, including very rare phenomena such as mode switching in RR Lyr stars. Until recently, only one case of an RR Lyr star that changed the pulsation mode was known. It was V79 in the globular cluster M3, which switched from a single-mode RRab star to a double-mode RRd star in 1992 (Kaluzny *et al.* 1998) and returned to a single-mode fundamental-mode pulsation in 2007 (Goranskij *et al.* 2010).

Soszyński *et al.* (2014) presented a second example of a mode-switching RR Lyr star – OGLE-BLG-RRLYR-12245 – that spectacularly changed from a double- to single-mode pulsation in a one-year time-span. The third object of that type – OGLE-LMC-RRLYR-13308 – was recently reported by Poleski (2014), who compared EROS-II (Kim *et al.* 2014) and OGLE photometry of RR Lyr stars in the Large Magellanic Cloud (LMC). Drake *et al.* (2014) announced the discovery of six mode-changing RR Lyr stars in the sample observed by the Catalina survey, however the example of such an object presented in their Fig. 31 definitely is not an RRc star that switched to an RRab star. The nature of the behaviors detected by the Catalina survey in these six RR Lyr stars remains an open question.

We compared the OGLE-III and OGLE-IV light curves of RRd stars in the bulge and we found two additional RR Lyr stars that changed their pulsation modes: OGLE-BLG-RRLYR-07226 that switched from an RRd to RRab star and OGLE-BLG-RRLYR-13442 that underwent a reverse change. Table 3 summarizes the pulsation characteristics of the three mode-switching RR Lyr stars in the bulge. Fig. 6 presents changes of the periods and amplitudes of OGLE-BLG-RRLYR-07226 during the mode switching.

It seems that all known mode-switching RR Lyr variables have similar properties. All these stars switched from a double-mode 1O/F pulsation (RRd) to a

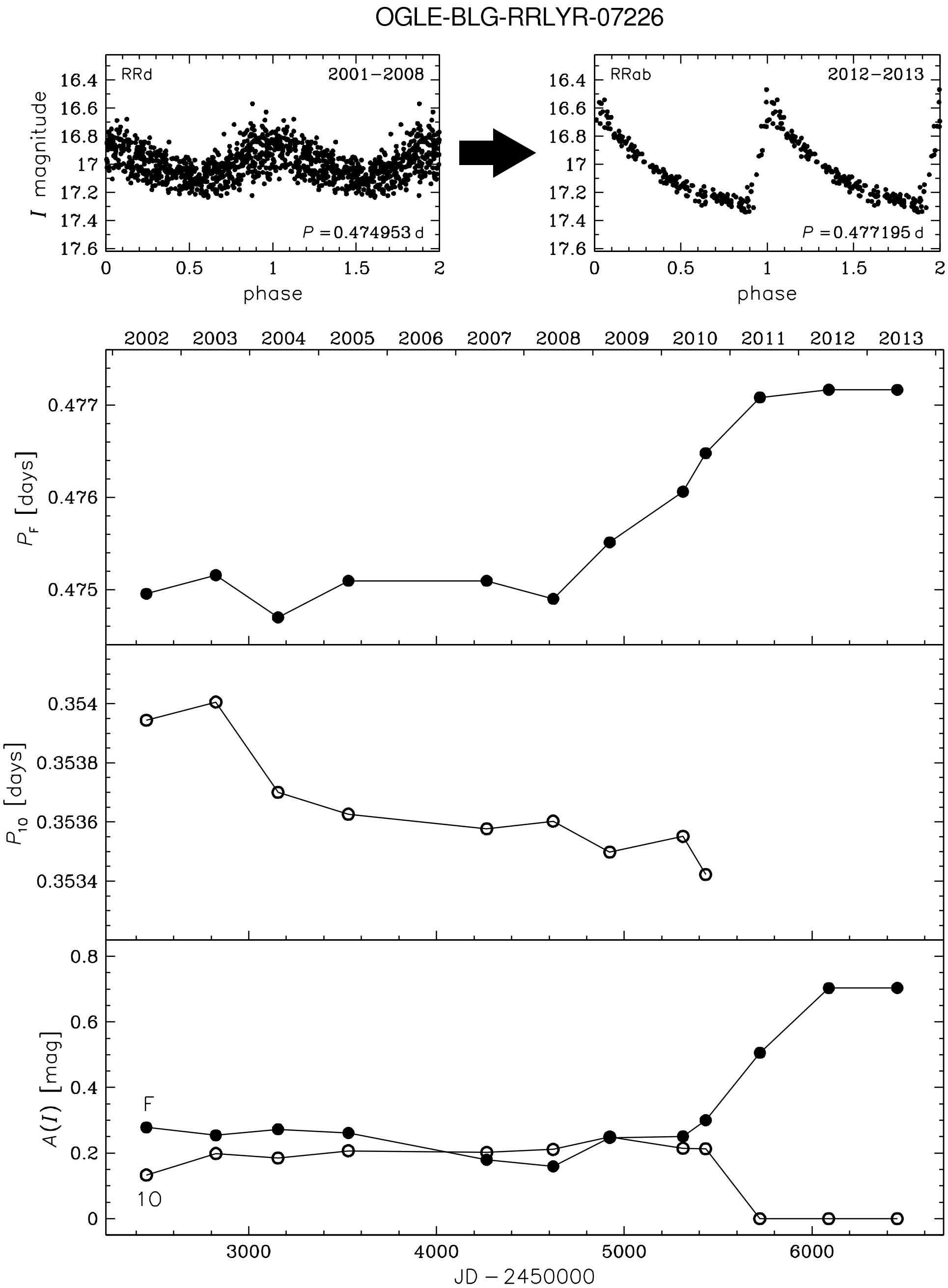

Fig. 6. OGLE-BLG-RRLYR-07226 – an RR Lyr star that switched from a double- to single-mode pulsation. *Upper panels* show the light curves of OGLE-BLG-RRLYR-07226 collected in the years 2001–2008 (*upper left panel*) and 2012–1013 (*upper right panel*). Both light curves are folded with the fundamental-mode periods, however note the difference between both periods. *Lower panels* present: changes of the fundamental-mode period in time, changes of the first-overtone period in time, changes of the peak-to-peak *I*-band amplitudes of both modes.

Table 3

Mode-switching RR Lyr stars in the Galactic bulge

ID	Mode change	P_F (initial) [d]	P_F (final) [d]	ΔP_F [d]
OGLE-BLG-RRLYR-07226	RRd → RRab	0.474953	0.477195	0.002242
OGLE-BLG-RRLYR-12245	RRd → RRab	0.409486	0.409975	0.000489
OGLE-BLG-RRLYR-13442	RRab → RRd	0.486202	0.486074	−0.000128

sole fundamental mode (RRab) or *vice versa*. In each case the mode change was a relatively rapid process, lasting about one year. Every change from a double- to a single-mode pulsation was connected with the increase of the fundamental-mode period and the reverse change of modes was associated with the fundamental period decrease.

7.5. Unique RR Lyr Stars

Our sample of 38 257 RR Lyr stars should contain many exceptional objects. Some of them were presented in the previous sections. In this section we show a few other potentially interesting RR Lyr stars in our collection.

OGLE-BLG-RRLYR-14277 underwent an episode of increased luminosity in 2013 due to gravitational microlensing. Its light curve is shown in Fig. 7. As a microlensing event, OGLE-BLG-RRLYR-14277 was included in the microlensing alert databases of the large microlensing surveys: MOA (Bond *et al.* 2001; as MOA-2013-BLG-300) and OGLE (Udalski 2003; as OGLE-2013-BLG-0665). Such objects are a powerful tool for constraining the nature of the gravitational lenses, because the regular variability of a microlensed star may break the degeneracy between the parallax and blended light (Wyrzykowski *et al.* 2006, Assef *et al.* 2006).

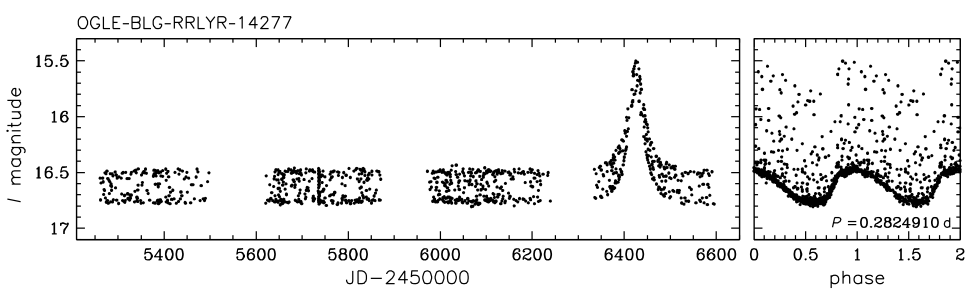

Fig. 7. Light curve of OGLE-BLG-RRLYR-14277 – an RRc star that experienced a gravitational microlensing episode. *Left panel* presents unfolded light curve collected in the years 2010–2013. *Right panel* shows the same light curve folded with the pulsation period.

Many RR Lyr stars in our sample exhibit large-amplitude Blazhko modulation. This also applies to several RRd stars. In Fig. 8 we present an example light curve of such object – OGLE-BLG-RRLYR-05762. To our knowledge these are the first known classical RRd stars with Blazhko effect. A detailed analysis of these stars will be presented in a forthcoming paper (Smolec *et al.* 2014, in preparation).

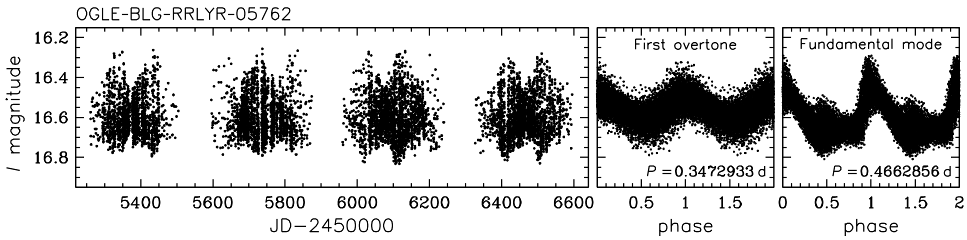

Fig. 8. Light curve of OGLE-BLG-RRLYR-05762 – an RRd star with the Blazhko effect. *Left panel* presents unfolded light curve collected in the years 2010–2013. Note the modulations of the pulsation amplitudes. *Right panels* show the pre-whitened light curves of the first-overtone and fundamental modes.

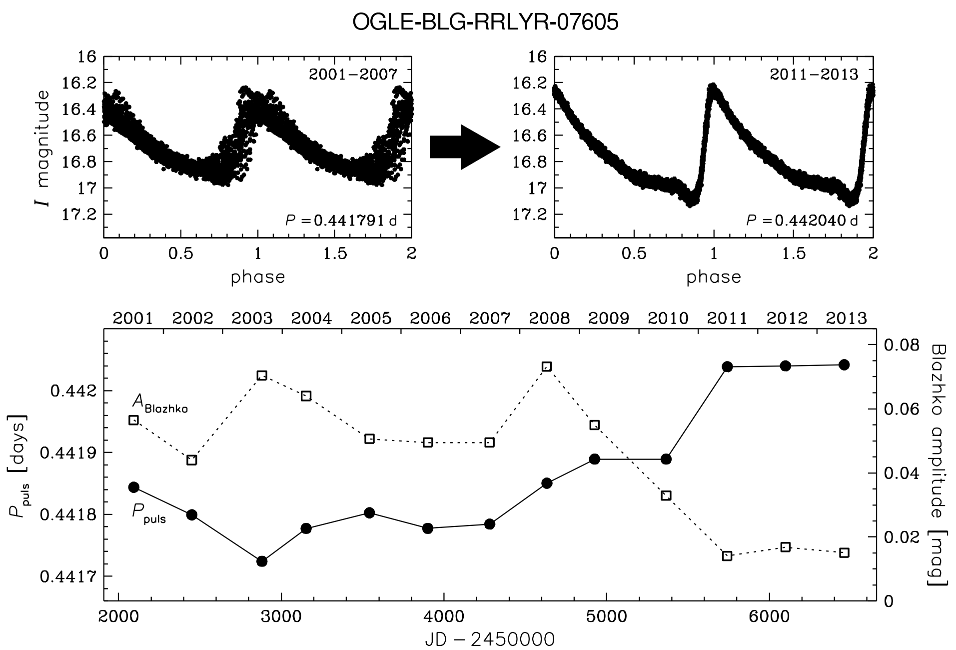

Fig. 9. OGLE-BLG-RRLYR-07605 – a Blazhko period-changing RRab star. *Upper panels* present light curves of OGLE-BLG-RRLYR-07605 collected in the years 2001–2007 (*upper left panel*) and 2011–2013 (*upper right panel*). *Lower panel* shows changes of the pulsation period in time (filled circles and solid line) and changes of the Blazhko amplitudes (empty squares and dotted line).

Finally, we draw the attention to other RR Lyr stars with the Blazhko effect. The huge number of stars and long-term light curves offer an opportunity to shed some light on this mysterious phenomenon. As an example, we present in Fig. 9 an RRab star – OGLE-BLG-RRLYR-07605. This is a Blazhko variable which underwent a significant period change in the years 2007–2011. Since 2011 the light curve of OGLE-BLG-RRLYR-07605 has been much more stable than in the previous years, and the amplitude of the Blazhko modulation significantly decreased. This is clearly visible in the lower panel of Fig. 9, where we present the changes of the pulsation period together with the changes of the Blazhko amplitudes. Note the anti-correlation of both quantities. Such a period–Blazhko amplitude feedback may be an important constraint for the physical explanation of the Blazhko effect.

8. Conclusions

In this paper, we have presented the most complete picture of the central parts of the Galactic bulge probed *via* RR Lyr variable stars – the OGLE collection of RR Lyr variables in the Galactic center. Compared to our previous study (S11), the OGLE sample of RR Lyr stars has grown by a factor of 2.3 in the area of the sky larger by a factor of 2.6. With 21 453 RR Lyr stars identified from the OGLE-IV data, only 1484 objects (7%) have been cataloged so far in the International Variable Star Index. In total, the OGLE collection of the Galactic bulge RR Lyr stars contains now 38 257 objects.

The list of possible astrophysical applications of the OGLE RR Lyr collection is very long. For example, it can be used for distance determinations and mapping the 3-D structures of the bulge and Sgr dSph, examining the early history of the star formation in the Galaxy, exploring properties of globular clusters, tracing metallicity gradients or mapping the interstellar extinction toward the Milky Way center – to mention just the basic ones. A huge number of RR Lyr stars with long-term light curves is also an ideal laboratory to study various aspects of stellar pulsations: multi-mode radial and non-radial oscillations, mode switching, period changes, and the Blazhko effect.

The OGLE picture of the Galactic bulge probed with RR Lyr stars will be significantly extended in the coming years. The OGLE-IV project has recently started another large scale program – the OGLE Galaxy Variability Survey which will photometrically cover practically entire Galactic bulge – additional 550 square degrees in the sky – and a fair fraction of the Galactic disk.

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REFERENCES

Alard, C., and Lupton, R.H. 1998, *ApJ*, **503**, 325.
Assef, R.J., *et al.* 2006, *ApJ*, **649**, 954.

Bond, I.A., *et al.* 2001, *MNRAS*, **327**, 868.
Catelan, M., *et al.* 2013, "Regional Variable Star Conference: Physics and Astronomy Dept, Michigan State University: 40 Years of Variables Stars: A Celebration of Contributions by Horace A. Smith", Eds. K. Kinemuchi *et al.* (arXiv:1310.1996).
Chen, B.-Q., Jiang, B.-W., and Yang, M. 2013, *Research in Astronomy and Astrophysics*, **13**, 290.
Deb, S., and Singh, H.P. 2014, *MNRAS*, **438**, 2440.
Dékány, I., Minniti, D., Catelan, M., Zoccali, M., Saito, R.K., Hempel, M., and Gonzalez, O.A. 2013, *ApJ*, **776**, L19.
Drake, A.J., *et al.* 2014, *ApJS*, **213**, 9.
Fasano, G., and Franceschini, A. 1987, *MNRAS*, **225**, 155.
Feast, M.W., Abedigamba, O.P., and Whitelock, P.A. 2010, *MNRAS*, **408**, L76.
Goranskij, V.P., Clement, C.M., and Thompson, M. 2010, in "Variable Stars, the Galactic halo and Galaxy Formation", Eds. Sterken, C., Samus, N., and Szabados, L. (Moscow: Sternberg Astronomical Institute of Moscow Univ.), p. 115.
Haschke, R., Grebel, E.K., and Duffau, S. 2011, *AJ*, **141**, 158.
Haschke, R., Grebel, E.K., and Duffau, S. 2012, *AJ*, **144**, 106.
Kaluzny, J., Hilditch, R.W., Clement, C., and Rucinski, S.M. 1998, *MNRAS*, **296**, 347.
Kapakos, E., and Hatzidimitriou, D. 2012, *MNRAS*, **426**, 2063.
Kim, D.-W., Protopapas, P., Bailer-Jones, C.A.L., Byun, Y.-I., Chang, S.-W., Marquette, J.-B., and Shin, M.-S. 2014, *A&A*, **566**, A43.
Layden, A.C., and Sarajedini, A. 2000, *AJ*, **119**, 1760.
Long, J.P., Karoui, N.E., Rice, J.A., Richards, J.W., and Bloom, J.S. 2012, *PASP*, **124**, 280.
Minniti, D., *et al.* 2010, *New Astronomy*, **15**, 433.
Nataf, D.M., *et al.* 2013, *ApJ*, **769**, 88.
Pejcha, O., and Stanek, K.Z. 2009, *ApJ*, **704**, 1730.
Pietrukowicz, P., *et al.* 2013, *Acta Astron.*, **63**, 379.
Pietrukowicz, P., *et al.* 2012, *ApJ*, **750**, 169.
Pietrzyński, G., *et al.* 2012, *Nature*, **484**, 75.
Poleski, R. 2014, *PASP*, **126**, 509.
Rosino L., and Nobili F. 1959, *Asiago Contrib.*, **97**, 1.
Sans Fuentes, S.A., and De Ridder, J. 2014, arXiv:1409.2278.
Schwarzenberg-Czerny, A. 1996, *ApJ*, **460**, L107.
Simon, N.R., and Lee, A.S. 1981, *ApJ*, **248**, 291.
Smolec, R., *et al.* 2013, *MNRAS*, **428**, 3034.
Sollima, A., Cacciari, C., Bellazzini, M., and Colucci, S. 2010, *MNRAS*, **406**, 329.
Soszyński, I., *et al.* 2009, *Acta Astron.*, **59**, 1.
Soszyński, I., Udalski, A., Szymański, M.K., Kubiak, M., Pietrzyński, G., Wyrzykowski, Ł., Ulaczyk, K., and Poleski, R. 2010, *Acta Astron.*, **60**, 165.
Soszyński, I., *et al.* 2011, *Acta Astron.*, **61**, 1 (S11).
Soszyński, I., *et al.* 2014, *Acta Astron.*, **64**, 1.
Subramaniam, A., and Subramanian, S. 2009, *A&A*, **503**, L9.
Szymański, M.K., Udalski, A., Soszyński, I., Kubiak, M., Pietrzyński, G., Poleski, R., Wyrzykowski, Ł., and Ulaczyk, K. 2011, *Acta Astron.*, **61**, 83.
Udalski, A. 2003, *Acta Astron.*, **53**, 291.
Wagner-Kaiser, R., and Sarajedini, A. 2013, *MNRAS*, **431**, 1565.
Watson, C.L., Henden, A.A., and Price, A. 2006, in: "Society for Astronomical Sciences 25th Annual Symposium on Telescope Science", Eds. B. Warner, *et al.*, Soc. Astron. Sci., Big Bear, California, 47.
Welch, D.L. 2014, *JAAVSO*, **42**, 236.
Woźniak, P.R. 2000, *Acta Astron.*, **50**, 421.
Wyrzykowski, Ł., Udalski, A., Mao, S., Kubiak, M., Szymański, M.K., Pietrzyński, G., Soszyński, I., and Szewczyk, O. 2006, *Acta Astron.*, **56**, 145.