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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. XI. RR Lyrae Stars in the Galactic Bulge*

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ABSTRACT

The eleventh part of the OGLE-III Catalog of Variable Stars (OIII-CVS) contains 16 836 RR Lyr stars detected in the OGLE fields toward the Galactic bulge. The total sample is composed of 11 756 RR Lyr stars pulsating in the fundamental mode (RRab), 4989 overtone pulsators (RRc), and 91 double-mode (RRd) stars. About 400 RR Lyr stars are members of the Sagittarius Dwarf Spheroidal Galaxy. The catalog includes the time-series photometry collected in the course of the OGLE survey, basic parameters of the stars, finding charts, and cross-identifications with other catalogs of RR Lyr stars toward the Milky Way center.

We notice that some RRd stars in the Galactic bulge show unusually short periods and small ratio of periods, down to $P_{\rm F} \approx 0.35$ days and $P_{\rm 1O}/P_{\rm F} \approx 0.726$. In the Petersen diagram double-mode RR Lyr stars form a parabola-like structure, which connects shorter- and longer-period RRd stars. We show that the unique properties of the bulge RRd stars may be explained by allowing for the wide range of the metal abundance extending up to [Fe/H] ≈ -0.36.

We report the discovery of an RR Lyr star with additional eclipsing variability with the orbital period of 15.2447 days. Some statistical features of the RR Lyr sample are presented. We discuss potential applications of our catalog in studying the structure and history of the central region of the Galaxy, mapping the interstellar extinction toward the bulge, studying globular clusters and the Sagittarius Dwarf Galaxy.

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 of Washington.

1. Introduction

RR Lyrae stars are of particular interest to astronomers for several reasons. First, they are useful indicators of old, metal-poor population of stars. Second, they are standard candles, enabling an estimate of their distances to be made. Third, they are very numerous and bright enough that they can be easily observed in our and nearby galaxies. Thus, RR Lyr stars play an essential role in our understanding of the formation and evolution of the Galaxy, as well as the internal constitution and evolution of stars. RR Lyr stars in the Galactic bulge are an important source of information on the distance to the center of the Milky Way, the geometry of the bar and the bulge and the interstellar extinction in these regions. The properties of these stars give us an insight into the earliest history of our Galaxy.

First significant sample of RR Lyr stars close to the central regions of the Milky Way was discovered by van Gent (1932, 1933). He noticed that cluster type variables (the historical name of RR Lyr stars) strongly concentrate toward the Galaxy center. The fields located closer to the Galactic center were observed under a survey conducted by the Harvard Observatory (*e.g.*, Swope 1936, 1938). Baade (1946, 1951) observed the relatively unobscured area today called Baade's Window[†] which yielded over 100 newly identified RR Lyr stars (Gaposchkin 1956).

Each of the many other efforts to detect variable stars in the Galactic bulge (*e.g.*, Plaut 1948, 1973, Fokker 1951, Oosterhoff and Horikx 1952, Oosterhoff *et al.* 1954, 1967, Ponsen 1955, Oosterhoff and Ponsen 1968, Hartwick *et al.* 1981, Blanco 1984) gave additionally from a few to a few dozen new RR Lyr stars. As a result, in the early nineties of the twentieth century about one thousand RR Lyr variables inhomogeneously distributed over the Galactic bulge were known.

In the nineties, large and homogeneous samples of variable stars were published as by-products of microlensing sky surveys. Udalski *et al.* (1994, 1995ab, 1996, 1997) published a catalog of over 3000 periodic variable stars in the Galactic bulge detected in the fields covered by the first phase of the Optical Gravitational Lensing Experiment (OGLE-I). In total, 215 of these stars were classified as RR Lyr variables. The next stage of the OGLE project (OGLE-II) resulted in much larger samples of RR Lyr stars in the central regions of the Milky Way. Mizerski (2003) detected and analyzed over 2700 RR Lyr stars in the bulge. He noticed very high incident rate of Blazhko stars, and very low percentage of RRd stars. The OGLE-II data were also used by Collinge *et al.* (2006) to prepare a catalog of 1888 fundamental-mode RR Lyr stars (RRab).

Also the MACHO microlensing project observed a numerous sample of RR Lyr stars toward the Galactic center (Alcock *et al.* 1997, 1998). The largest to date catalog of these variables in the bulge was constructed by Kunder *et al.* (2008) on the basis of the MACHO database. Their sample contains 3525 RR Lyr stars of ab type.

[†]It is interesting to note that Baade called this region "van Tulder's pole".

This paper presents a catalog of 16 836 RR Lyr stars detected in the fields toward the Galactic bulge monitored during the third phase of the OGLE project (OGLE-III). This is the eleventh part of the OGLE-III Catalog of Variable Stars, and the first part of the Catalog containing variable stars detected outside the Magellanic Clouds. So far we published, among others, a huge catalog of almost 25 000 RR Lyr stars in the Large Magellanic Cloud (LMC, Soszyński *et al.* 2009, hereafter Paper I) and a ten times smaller catalog of this type variables in the Small Magellanic Cloud (SMC, Soszyński *et al.* 2010, hereafter Paper II).

This paper is structured as follows. Section 2 presents the data and their reduction. In Section 3, we describe the selection and classification processes. In Section 4, we describe the catalog itself, and Section 5 is devoted to the comparison of our sample with other catalogs of RR Lyr stars in the Galactic bulge. In Section 6 we discuss possible applications of our catalog in the studies of the central parts of the Milky Way and Sagittarius Dwarf Galaxy (hereafter Sgr dSph). Finally, we summarize our results and in Section 7.

2. Observational Data

Our observations of the Galactic bulge were obtained at Las Campanas Observatory with the 1.3-m Warsaw telescope. The observatory is operated by the Carnegie Institution of Washington. During the OGLE-III project (2001–2009), the Warsaw telescope was equipped with an eight-chip mosaic camera covering approximately 35×35 arcmin in the sky with the scale of 0.26 arcsec/pixel. Details of the instrumentation setup can be found in the paper by Udalski (2003).

The time coverage, as well as a number of points obtained by the OGLE project in the bulge varies considerably from field to field. Some fields have been monitored since 1992 and for these fields up to several thousand points per star have been collected until now. Other fields were observed for only one or two seasons and only several dozen observations were collected for them. In this study we used only those OGLE-II and OGLE-III fields for which at least 30 epochs were gathered. These fields range in the Galactic coordinates within approximately $|l| < 11^\circ$ and $|b| < 7^\circ$ and cover an area of 68.7 square degrees.

Observations were obtained through the *I* and *V* filters closely resembling the Johnson-Cousins system. The accuracy of the transformations from the instrumental to the standard magnitudes is better than 0.02 mag (Udalski *et al.* 2008). The vast majority of the observations (from 30 to over 5000 points per star, median: 623) were made with the *I*-band filter, while in the *V*-band we obtained from a few to several dozen points.

The time-series photometry attached to this catalog was compiled from the OGLE-II and OGLE-III observations, so it covers up to 13 years (from March 1997 to May 2009). For individual stars both datasets were tied by shifting the OGLE-II photometry to agree with the OGLE-III light curves. For 279 RR Lyr stars exclu-

sively the OGLE-II photometry is available. We also combined the photometry of stars observed in the overlapping regions of two or more adjacent fields.

The photometry was obtained with the standard OGLE data reduction pipeline (Udalski *et al.* 2008) based on the Difference Image Analysis (DIA, Alard and Lupton 1998, Woźniak 2000). For 40 objects in our catalog there is no *I*-band DIA photometry in the OGLE database, due to saturation or location close to other bright stars. For these objects we provide the photometry measured with the DOPHOT package (Schechter *et al.* 1993). We flag these stars in the remarks of the catalog.

3. Selection and Classification of RR Lyr Stars

3.1. Single-Period Variables

A massive periodicity search was performed for all 3×10^8 stars monitored by the OGLE-III survey in the Galactic bulge. To perform this time-consuming task, we used supercomputers assembled at the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM) of the University of Warsaw. The period-search code FNPEAKS (by Z. Kołaczkowski – private communication) was run on each *I*-band light curve with more than 30 points. Ten the highest peaks in the periodogram were selected and archived with the corresponding amplitudes and signal-to-noise ratios. Then, each light curve was prewhitened with the primary period and the procedure of the period search was repeated on the residual data.

Before we began selection and classification of variable stars, all light curves were fitted with a series of Fourier cosine functions, and the Fourier coefficients R_{21}, ϕ_{21}, R_{31}, ϕ_{31} (Simon and Lee 1981) were calculated. We used the positions of stars in the period–Fourier coefficient planes (Fig. 1) to provisionally divide the sample into pulsating and other stars. However, the main selection procedure was based on the visual inspection of the light curves. We inspected all stars with periods between 0.2 and 1.0 day and amplitudes larger than a limit that depended on the average brightness of the star. For the brightest objects the amplitude limit reached 0.01 mag, which allowed us to select a number of RR Lyr variables blended by other stars.

The selection and classification of variable stars based primarily on the morphology of light curves. Short-period variable stars were divided into two groups: pulsating stars and much more numerous group of eclipsing and ellipsoidal binaries, which will be published in a future part of the OIII-CVS. The vast majority of pulsating stars were categorized as RR Lyr stars, only a small fraction was classified as Cepheids and δ Sct stars due to their characteristic light curve shapes or period ratios in double-mode pulsators. Note, that our catalog may still contain a small fraction of δ Sct stars, which are difficult to distinguish from short-period RR Lyr variables, when their absolute magnitudes are not *a priori* known.

It was relatively easy to discriminate RRab stars from overtone pulsators and other types of variable stars, since fundamental-mode RR Lyr stars have character-

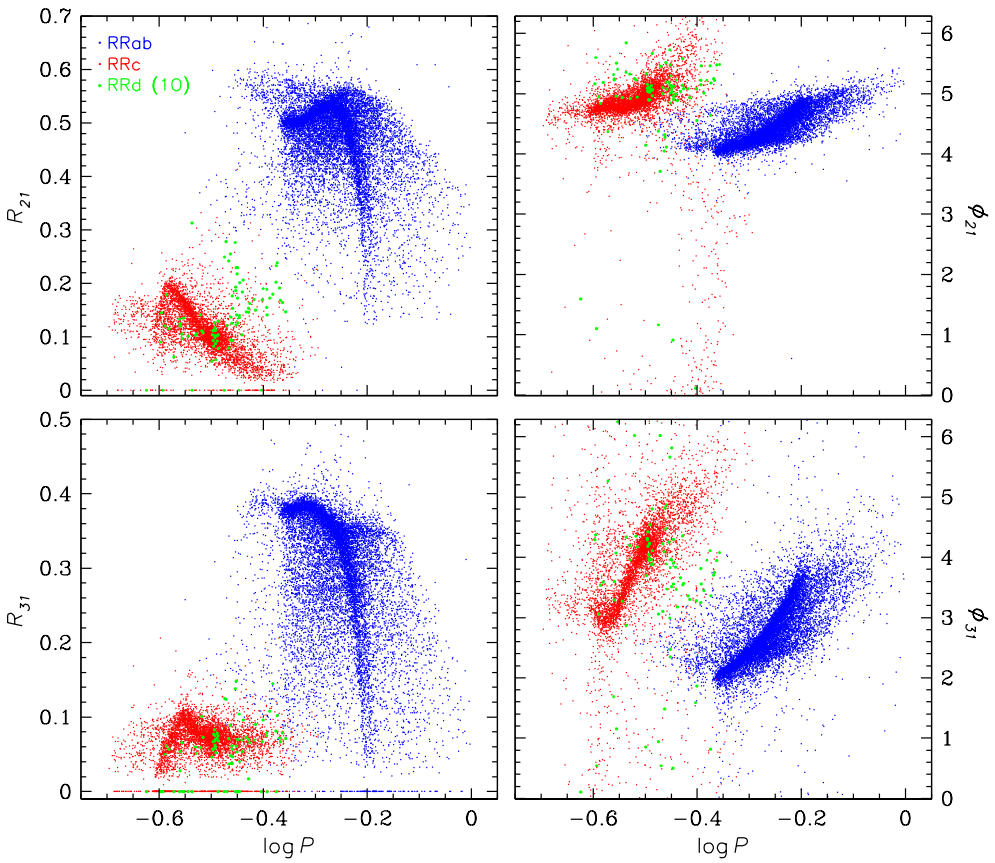

Fig. 1. Parameters R_{21}, ϕ_{21}, R_{31} and ϕ_{31} of the Fourier light curve decomposition (Simon and Lee 1981) plotted against the logarithm of periods for RR Lyr stars from our catalog. Blue dots represent RRab variables, red are RRc stars while green dots show the first overtone mode of RRd stars.

istic, asymmetric light curves. The correct classification was more problematic in the case of the overtone pulsators (RRc stars), as their light curves are much more sinusoidal and may be confused with W UMa, ellipsoidal, rotating, etc. variable stars. In this catalog we classified as RRc stars only those objects, which reveal detectable asymmetry of their light curves. This affects the completeness of the RRc list among the fainter stars. In difficult cases we took into account the position of a star in the period–Fourier coefficients (Fig. 1), period–amplitude (Fig. 2), color–magnitude diagrams (Fig. 3), and a ratio of amplitudes in the *V*- and *I*-bands (when the number of observing points in the *V* band was high enough to determine the amplitude in this band). However, the classification of about one hundred objects in our catalog remains uncertain. Information about these stars can be found in the remarks of the catalog.

In contrast to the OGLE-III catalogs of RR Lyr stars in the Magellanic Clouds (Papers I and II), we have not distinguished between RRc and RRe stars, *i.e.*, the

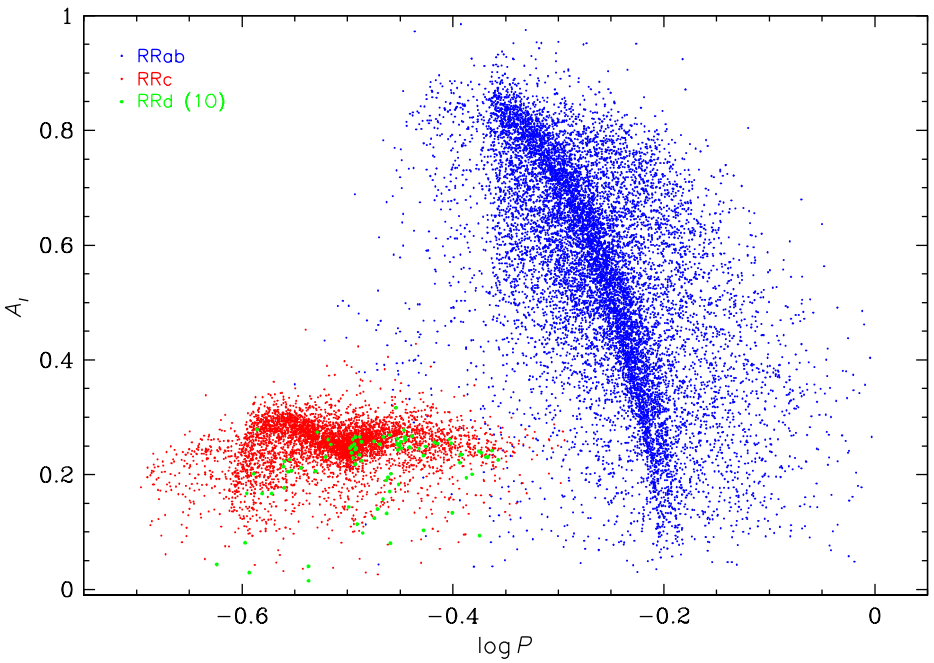

Fig. 2. Period–amplitude diagram for RR Lyr stars toward the Galactic bulge. Different colors represent the same type of stars as in Fig. 1.

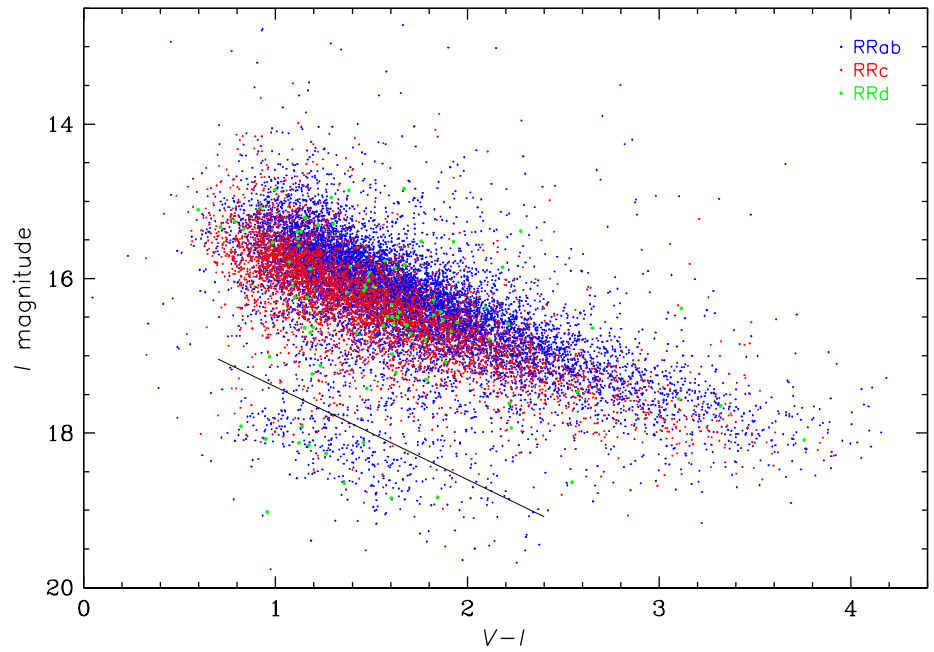

Fig. 3. Color–magnitude diagram for RR Lyr stars toward the Galactic bulge. Different colors correspond to types of stars as shown in Fig. 1. RR Lyr stars below the black line have been recognized as members of the Sgr dSph.

the first- and potential second-overtone pulsators. Despite the fact that RR Lyr stars in the bulge are closer than in the Magellanic Clouds, so the quality of the photometry is better, we have not noticed any natural boundary between RRc and RRe variables.

3.2. Multi-Periodic Variables

RR Lyr stars pulsating simultaneously in two radial modes (RRd stars) are very rare in the Galactic bulge (Moskalik and Poretti 2003, Mizerski 2003). Only five objects of this type have been known to date in this region of the Milky Way. Our search for multiperiodic RR Lyr stars has been carried out in two ways. First, we used the database of periods measured for all stars observed by OGLE in the bulge. We selected and visually inspected light curves with periods and period ratios characteristic for the previously known RRd stars, *i.e.*, with longer periods in the range 0.42–0.6 days and the shorter-to-longer period ratios between 0.74 and 0.75. Second, we performed a search for secondary periods in the previously selected set of RR Lyr stars. Each light curve was fitted with the Fourier sum with the number of elements that minimizes the χ^2 per degree of freedom. Then, the function was subtracted from the light curve and the search for additional periodicities was performed on the residual data.

The latter method revealed, somewhat surprisingly, that the well known sequence in the Petersen diagram (*i.e.*, the diagram of the period ratios *vs.* the longer periods) has its continuation toward shorter periods and smaller period ratios. Fig. 4 shows the Petersen diagram for RRd stars in the bulge. For comparison we plotted 986 RRd stars detected in the LMC (Paper I). Though the total number of the RRd in the Galactic bulge is by two orders of magnitude lower than in the LMC, yet the range of the period ratios is considerably wider. This appears strange but in part may be explained by the difference in metal abundance between these two environments. Selected results of our calculations shown as the segments in Fig. 4 demonstrate that models of high metal abundance account for the low values of the period ratios in the bulge RRd stars. In Section 6.2 we discuss application of RRd stars as a probe of metallicity.

In total, we identified 91 RRd stars (0.5% of the whole sample of RR Lyr stars), confirming very low incident rate of these stars in the bulge. In the LMC (Paper I) RRd stars constitute almost 4% of the total sample of RR Lyr stars, while in the SMC (Paper II) more than 10% of RR Lyr stars are double-mode pulsators. Ten of the 91 detected RRd stars in the bulge are brighter than typical RR Lyr stars in the Galactic center, so they are likely located in front of the bulge. Further 20 RRd stars are distinctly fainter than bulge RR Lyr variables, so they are located behind the bulge. Among them, 11 RRd stars most likely belong to the Sgr dSph.

In the Petersen diagram one should notice a compact group of 16 RRd stars around $P_{1O}/P_F \approx 0.74$ and $\log P_F \approx -0.36$. All these objects have the overtone mode much stronger than the fundamental one, with the amplitude ratio $A_{1O}/A_F > 2.5$.

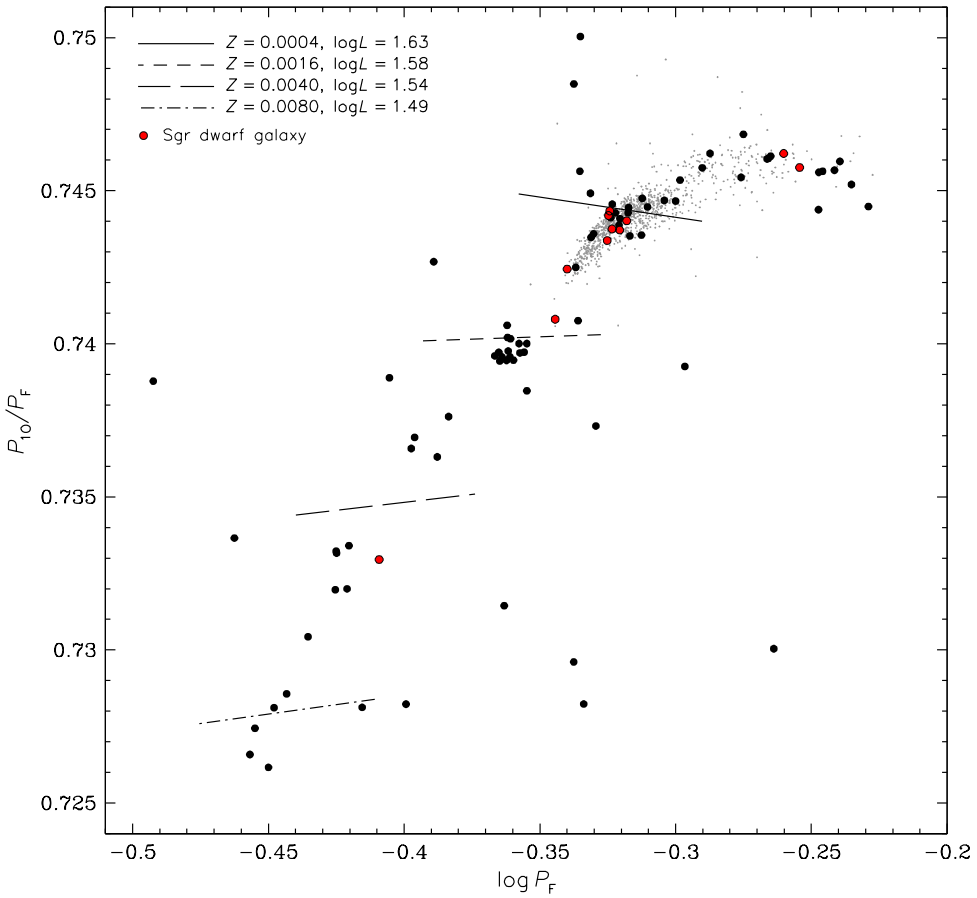

Fig. 4. Petersen diagram for RRd stars toward the Galactic bulge. Red symbols represent RRd stars in the Sgr dSph. Small grey dots show RRd stars from the LMC (Paper I). The short segments depict calculated values for selected models covering central part of the instability strip for a mass of $M \approx 0.6$ M$_\odot$. The metal abundance parameter, Z, and luminosity, L, are given in the legend.

We believe that the similarity of these stars is not by accident, and probably these objects are relicts of a disrupted dwarf galaxy or stellar cluster.

During the search for double-mode RR Lyr stars we found a significant number of objects with the secondary periods very close to the primary periods. Such a behavior may be related to the Blazhko effect (Blažko 1907) or changes of the primary period. Long-term OGLE photometry offers an opportunity to study both phenomena. Using the methods described by Poleski (2008), we initially selected RR Lyr stars with detectable rates of period change. We performed this search only among objects with high quality photometry (brighter than 16.5 mag in I) covering a time baseline longer than 2000 days. As a result we obtained incident rates of RR Lyr stars with variable periods. RRab stars that change their periods are relatively rare and constitute less than 4% of the total population. Variable

stars with unstable periods are much more common among overtone pulsators, and reach 38% of all RRc stars. In this group changes of periods are more frequent among longer-period variables. About 75% of RRc stars with periods in the range of 0.35–0.45 days show detectable rates of period changes.

Our preliminary analysis confirm a high incident rate of Blazhko-type RRab stars in the Galactic bulge (Mizerski 2003). At least 30% of RRab stars with high-quality photometry exhibit closely-spaced secondary frequencies. Among RRc stars Blazhko variables constitute about 8% of the whole population (excluding stars with variable periods). Fig. 5 presents example light curves with exceptionally long Blazhko periods (up to about 3000 days) or with large amplitude variations.

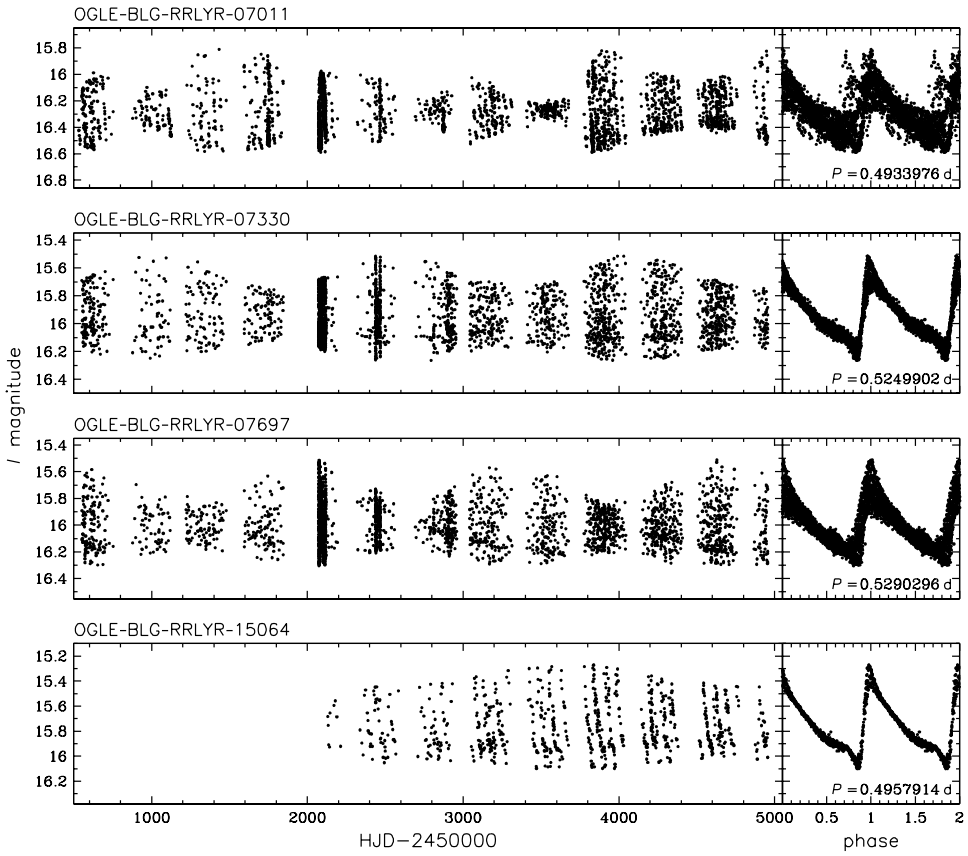

Fig. 5. Light curves of four RR Lyr stars with the Blazhko effect. *Left panels*: unfolded OGLE-II (if available) and OGLE-III *I*-band light curves. *Right panels*: the same light curves folded with the pulsation periods.

Despite many years of efforts, there is not even one case of RR Lyr star in a binary system known today. During the search for the secondary periods we paid particular attention to the eclipsing variations superimposed on the pulsation light curves. In the bulge we detected one promising candidate for an RR Lyr star

in an eclipsing binary system. The light curve of OGLE-BLG-RRLYR-02792 is plotted in Fig. 6. The original *I*-band photometry folded with the pulsation period is shown in the left panel, while the right panel shows the eclipsing light curve after subtracting the RR Lyr component. Further spectroscopic observations would confirm or exclude the possibility that we detected an RR Lyr star being a member of the binary system. It is interesting to note that we found very similar (in the sense of the pulsation and orbital periods and the light curve shapes) case of an RR Lyr star with eclipsing modulation in the LMC (Paper I). Besides, we identified in the Galactic bulge three additional RR Lyr stars (OGLE-BLG-RRLYR-03539, -09197, -11361) that exhibited one eclipsing-like fading during the whole time span covered by the OGLE-III observations. These objects will be monitored during the OGLE-IV phase.

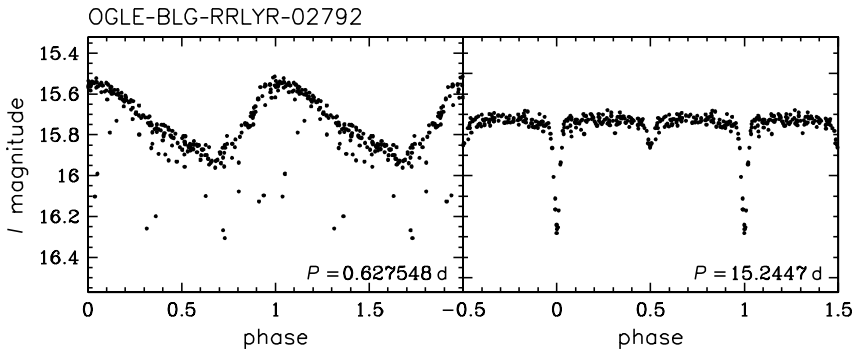

Fig. 6. Light curve of the RR Lyr star with additional eclipsing variability. *Left panel*: the original photometric data folded with the pulsation period. *Right panel*: eclipsing light curve after subtracting the RR Lyr component.

4. Catalog of RR Lyr Stars Toward the Galactic Bulge

The OGLE-III Catalog of RR Lyr Stars in the Galactic Bulge consists of 16 836 objects, of which 11 756 have been classified as RRab, 4989 as RRc and 91 as RRd stars. 394 objects in our catalog (343 RRab, 40 RRc and 11 RRd stars) likely belong to the Sgr dSph. The list of all stars, their identifications with the previously published catalogs, basic parameters, time-series *I*- and *V*-band photometry and finding charts are available only in electronic form *via* FTP site or WWW interface:

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

The file ident.dat at the FTP site lists all RR Lyr stars with their coordinates and identifications in various databases. Designations of objects in this catalog follow the scheme presented in the previous parts of the OIII-CVS – stars are named with

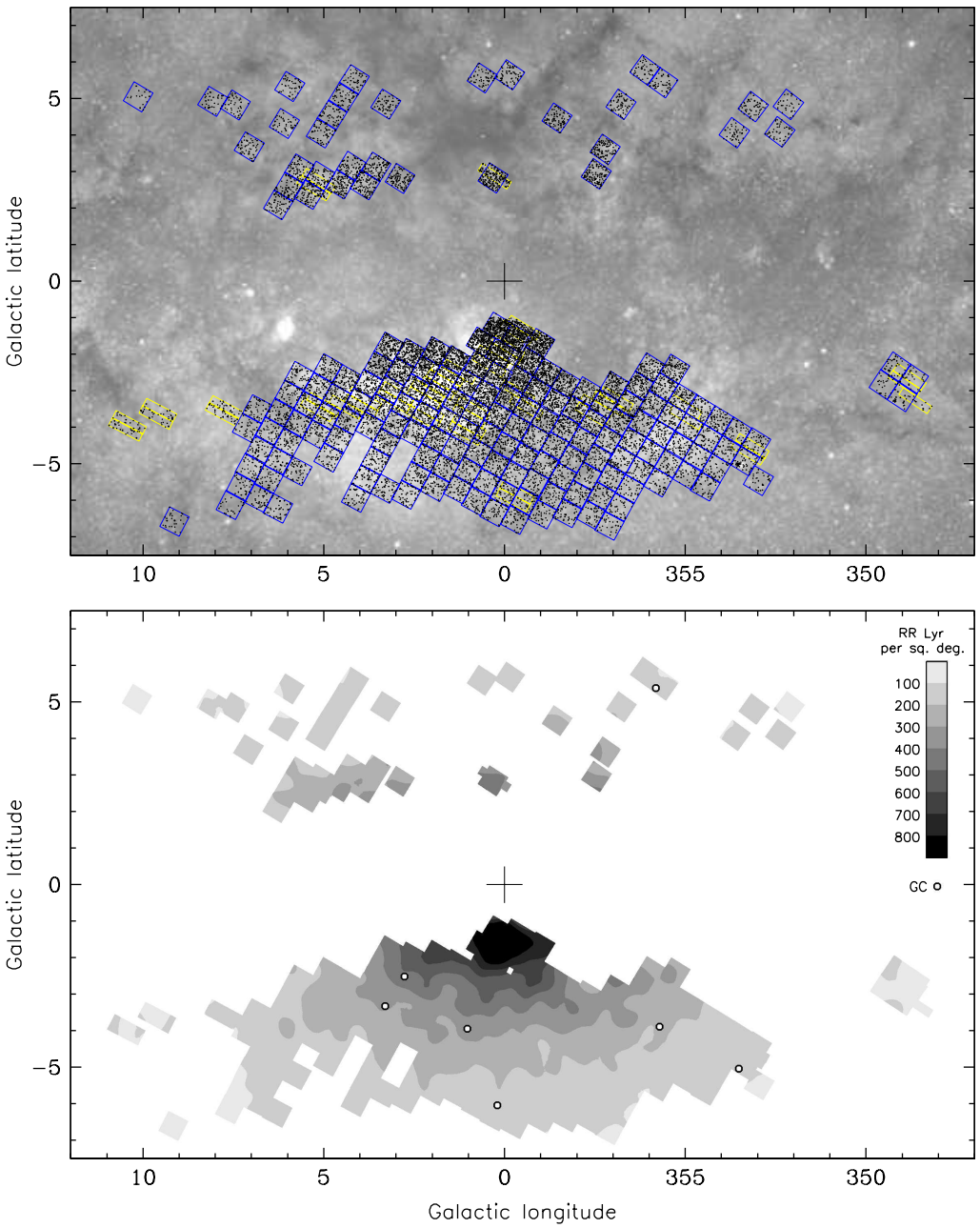

Fig. 7. *Upper panel*: spatial distribution of RR Lyr stars toward the Galactic bulge. The background image of the bulge originates from the Axel Mellinger's Milky Way Panorama (Mellinger 2009). Yellow and blue contours show OGLE-II and OGLE-III fields with the number of observations exceeding 30. *Lower panel*: surface density map of RR Lyr stars toward the Galactic bulge obtained by blurring the upper map with the Gaussian function. White circles show positions of globular clusters which contain RR Lyr stars.

the symbols OGLE-BLG-RRLYR-NNNNN, where NNNNN is a five-digit consecutive number. Objects are arranged according to increasing right ascension. The subsequent columns in the file ident.dat give: star designation, OGLE-III field and internal database number (consistent with the photometric maps of the bulge by Szymański *et al.* in preparation), mode of pulsation (RRab, RRc, RRd), J2000.0 right ascension and declination, cross-identifications with the OGLE-II photometric database (Szymański 2005), cross-identifications with the MACHO catalog of RR Lyr stars in the bulge (Kunder *et al.* 2008) and cross-identifications with the General Catalogue of Variable Stars (GCVS, Kholopov *et al.* 1985).

Observational parameters of the RR Lyr stars – intensity-averaged I and V magnitudes, periods with uncertainties (derived with the TATRY code of Schwarzenberg-Czerny 1996), peak-to-peak I-band amplitudes, epoch of maximum light and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} (Simon and Lee 1981) derived for I-band light curves – are provided in the files RRab.dat, RRc.dat, and RRd.dat. The latter file gives relevant information about both periodicities of the double-mode stars. When the number of observing points in the V-band was less than 20, we derived mean V magnitude by fitting a template light curve, which was obtained from scaled and shifted I-band light curve. Additional information on some objects (*e.g.*, additional periods, uncertain classification, proper motion, etc.) 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, oriented with N up and E to the left.

A spatial distribution of RR Lyr stars from our catalog is presented in Fig. 7. The upper panel shows individual stars plotted on the background image originated from the Axel Mellinger's Milky Way Panorama (Mellinger 2009). Contours of the OGLE-II and OGLE-III fields (only those with the number of observing points larger than 30) are also plotted in Fig. 7. The bottom panel in Fig. 7 presents a surface density map obtained by the convolution of the upper distribution with the Gaussian function. The strong concentration of RR Lyr stars toward the Galaxy center is well visible.

5. Completeness of the Catalog

The RR Lyr stars in our catalog cover practically the entire range of magnitudes ($13 < I < 20.5$ mag) that may be detected with the OGLE data. We expect that the completeness of the catalog strongly depends on the brightness of stars, amplitudes, shape of the light curves, stars surrounding individual objects and number of observing points. In order to test and improve the completeness of our catalog we compared our sample with the MACHO and OGLE-II catalogs of RR Lyr stars in the Milky Way center and with the previous identifications collected by the GCVS.

The largest list of RR Lyr stars in the Galactic bulge hitherto published is the

catalog of RRab stars by Kunder *et al.* (2008) compiled from the MACHO photometry. Among 2114 MACHO RR Lyr stars that are covered by the OGLE fields, we found counterparts for 2087 (98.7%) objects in the preliminary version of our catalog. This result may be regarded as the upper limit for our catalog completeness, and it is valid only for brighter fundamental-mode RR Lyr stars. We carefully checked the missing 27 objects and noticed that 13 of them were located close to bright, saturated stars and were masked during the reduction process. We included these RR Lyr stars in the final version of the catalog providing their DoPHOT photometry. Most of the remaining missing RR Lyr stars were affected by a small number (< 30) of observing points, usually due to their location at the edge of the OGLE fields. When it was possible, we supplemented our catalog with these objects.

We also cross-identified our catalog with the list of 1888 RRab stars detected by Collinge *et al.* (2006) in the OGLE-II fields. We missed only one object – a blended star, and thus with reduced amplitude. An independent test of the completeness of our catalog was the search for RR Lyr stars carried out by us in the OGLE-II fields using generally the same methods as in the OGLE-III fields. In this way we extended our catalog by more than 400 RR Lyr stars, mostly in the regions monitored by the OGLE-II survey, and not covered by the OGLE-III fields, or with number of points collected during the OGLE-III phase smaller than 30. Five of these newly detected RR Lyr stars could potentially be identified on the basis of the OGLE-III data only, but were overlooked at the first stage of the search. Most of them were faint RRc variables with nearly sinusoidal light curves and initially were categorized as close binaries.

Among stars classified as RR Lyr variables in the GCVS (Kholopov *et al.* 1985), 403 objects can potentially be found in the OGLE bulge fields. We successfully identified 371 of them in our catalog. Half of the missing stars have no information about periods in the GCVS, and we could not properly identify them in the dense bulge fields. From the remaining stars, seven turned out to be eclipsing binaries, for further seven stars we were not able to identify objects with similar periods close to their coordinates and only two objects were identified as saturated RR Lyr stars.

In summary, our catalog of RR Lyr stars in the Galactic bulge is close to be complete, especially for RRab stars. For RRc stars the completeness depends on the light curve shape (sinusoidal variable stars may be missed) and brightness (among the faintest RR Lyr stars in our catalog the incident rate of RRc stars is artificially reduced due to the problems with classification). One should remember that the optical OGLE photometry is not able to penetrate regions highly obscured by the interstellar medium. The faintest stars observed by OGLE have *I*-band magnitudes of about 20.5 mag. For this reason the spatial density of the RR Lyr is underestimated in the narrow area close to the Galaxy center (see Fig. 7). These regions will be observed in the near-infrared domain by the VISTA Variables in the Via

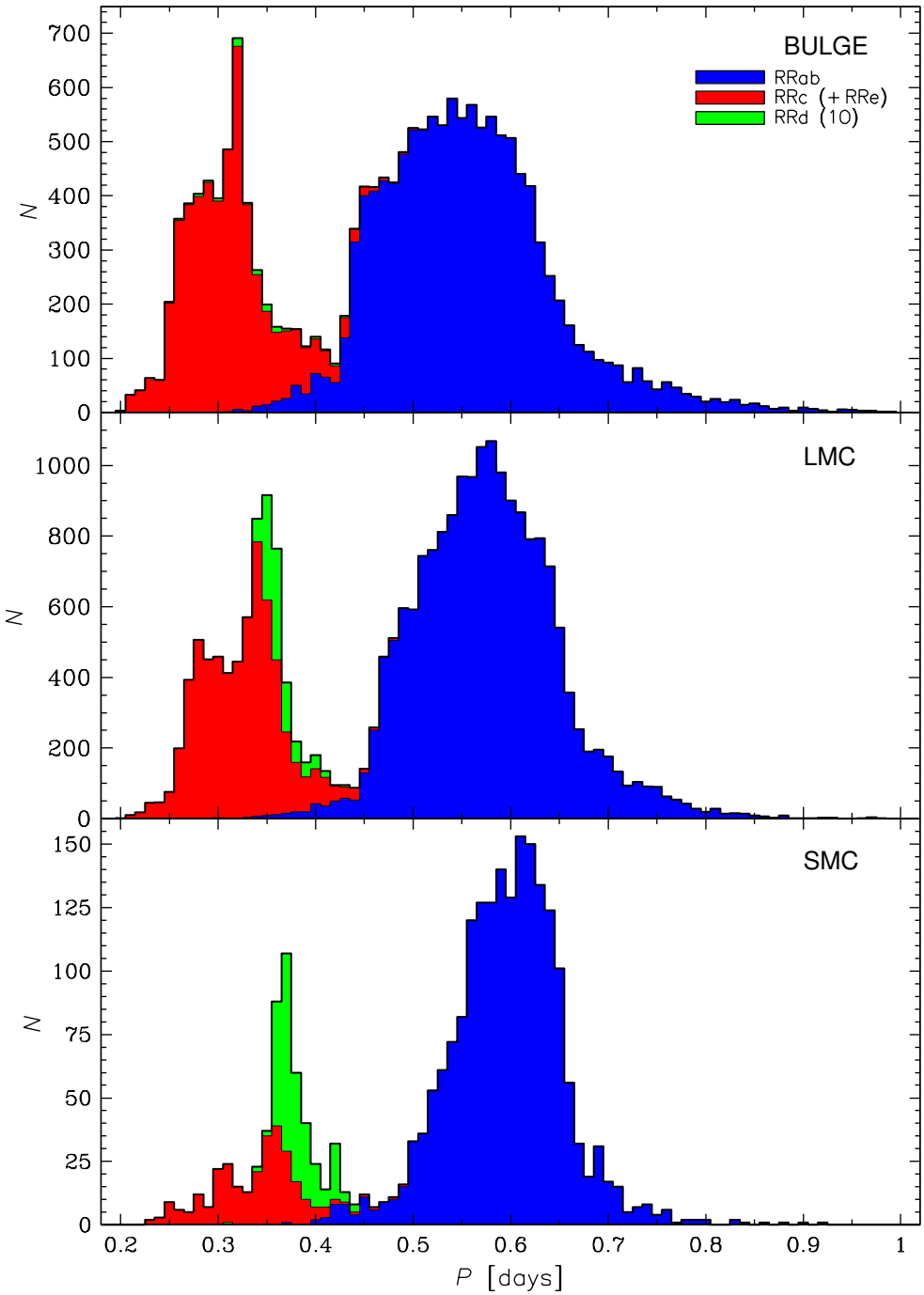

Fig. 8. Period distribution of RR Lyr stars in the Galactic bulge, LMC and SMC. Each color represents different type of pulsators. Blue regions show RRab stars, red – RRc (+RRe) stars and green – the first-overtone period of RRd stars. The width of bins is 0.01 day.

Lactea (VVV) survey (Minniti *et al.* 2010). Our catalog is also incomplete in the very cores of globular clusters, due to the extreme spatial density of stars in these regions.

6. Discussion

6.1. Period Distribution

The distribution of periods of RR Lyr stars is a powerful tool for studying properties of the oldest stellar population. It is well known that average periods are correlated with the metallicity of RR Lyr stars, or more specifically, longer-period variables are generally more metal-poor. Fig. 8 displays the histograms of periods of RR Lyr stars from the bulge, LMC (Paper I) and SMC (Paper II). Each bin was proportionally divided among different modes of pulsation and presented in different colors. RRc and RRe stars from the Magellanic Clouds were combined and marked with the same (red) color in Fig. 8.

It is clear that RR Lyr stars in the Galactic bulge have on average shorter periods than in the Magellanic Clouds. The mean period of RRab stars in the bulge is 0.556 days, which is exactly 0.02 days shorter than in the LMC (0.576 days) and 0.04 days shorter than in the SMC (0.596 days). The difference between these RRab populations is larger, when comparing the most frequent (modal) periods: 0.54, 0.58 and 0.62 days for the bulge, LMC and SMC, respectively. Also the overtone RR Lyr variables have shorter mean periods in the more metal-rich environments: 0.310 days (mode: 0.32 days) in the bulge, 0.323 days (mode: 0.34 days) in the LMC (merging together RRc and RRe stars), and 0.338 days (mode: 0.37 days) in the SMC.

The existence of the second-overtone pulsators among RR Lyr stars (RRe) is a matter of debate. There is no doubt that the overtone RR Lyr variables in the Galaxy center show two maxima in the period distribution, although the short-period peak is not as prominent as in the LMC and SMC. Moreover, the "RRe peak" does not follow the rule defined by the "RRab" and "RRc peaks", *i.e.*, the bulge RRe stars do not have shorter periods than the LMC ones. The local maximum in the period distribution for the short-period overtone RR Lyr stars is at 0.29 days for the bulge, 0.28 days for the LMC and 0.31 days for the SMC. The origin of this additional peak in the period distribution of RR Lyr stars remains a mystery.

6.2. The RRd Stars

The segments shown in the Petersen diagram (Fig. 4), were selected from our survey of the linear pulsation of stellar envelope models in the relevant range of parameters. More results from this survey is shown in Fig. 9. We considered models with masses and luminosities appropriate for horizontal branch stars. In the adopted effective temperature range, which is about 300 K wide, first two radial modes are unstable. Comparing these two figures, we note that with the adopted

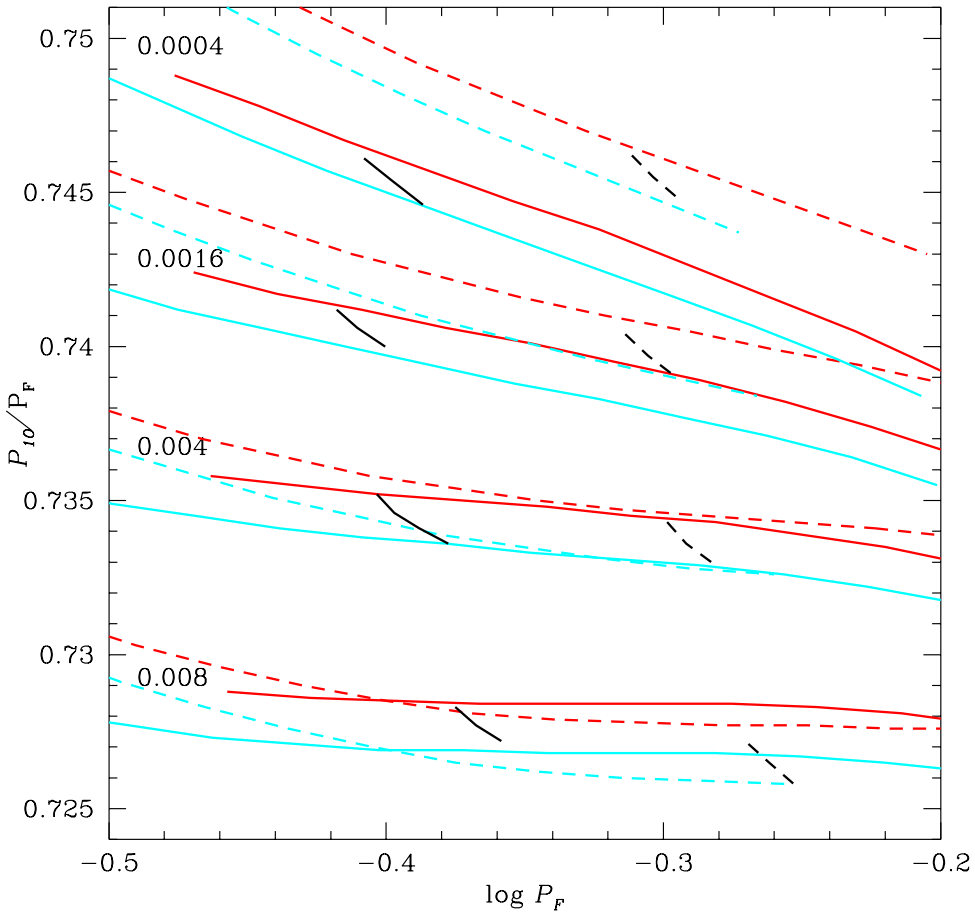

Fig. 9. RR Lyr star models in the Petersen diagram. At each four indicated values of the metallicity parameter, $Z = 0.0004$, 0.0016, 0.004, and 0.008 (the respective [Fe/H] values are -1.67, -1.07, -0.67, and -0.36) there are four lines. The solid lines correspond to $M = 0.7$ M$_\odot$ and dashed to $M = 0.55$ M$_\odot$. The cyan and red colors correspond to the hot and cool boundaries, respectively, of the adopted effective temperature range. Luminosity varies along these lines from $\log(L/\mathrm{L}_\odot) = 1.42$ to $\log(L/\mathrm{L}_\odot) = 1.75$. The short black segments show the loci of the frequencies $\nu_{1O} = 0.5(\nu_F + \nu_{2O})$ within the temperature range.

range of Z, almost the whole observed range is covered. Only some stars lying in the upper right corner may need $Z < 0.0004$ and those in the lower left corner $Z > 0.008$.

At the specified P_F, the period ratio mainly depends on Z. A slight decrease with increasing $T_{\rm eff}$ is seen in the difference between red and cyan lines. The solid and dashed lines represent different masses. Calculated numbers depend somewhat on the adopted heavy element mixture and source of opacity data, which is more significant (Buchler 2008). In models calculated for Fig. 9 we used the OPAL opacity data.

In any case, to explain the existence of the short period RRd stars in the Galactic bulge we need to postulate that these objects have metal abundance much closer

to the young population of the LMC, than to RRd stars in this galaxy. This is acceptable in light of what has been known about metallicity in the bulge. Let us note that to explain the exceptionally short-period tail in the distribution of bulge RRab stars seen in Fig. 8, we also need models with high Z values.

Kunder and Chaboyer (2008), who based their assessment of the RR star metallicity in the Galactic bulge on light curve data, found a broad range of the [Fe/H] values extending up to -0.15 dex. Our result provides an independent evidence for existence of high metallicity RR Lyr stars in the Galactic bulge.

The high metallicity RR Lyr stars in the Galactic field have been known for long time, but still their existence presents a challenge for stellar evolution theory. There are no satisfactory evolutionary models starting from ZAMS for metal rich horizontal branch stars. In particular, even with enhanced mass loss BaSTI tracks (Pietrinferni *et al.* 2006) calculated with $Z \gtrsim 0.004$ enter the instability strip during the helium phase only, if the initial mass is less than 0.9 $M_{\odot}$. However, it takes time longer than the Universe age for such objects to reach this phase of evolution. Still larger mass loss in the red giant phase than adopted in the BaSTI tracks is needed. These issues has been contemplated by various authors (see *e.g.*, Catelan 2009). The question why it is more likely to happen in the bulge than in other environments remains to be answered.

We also do not have explanation for the large disparity in the incident rate of double mode pulsation between the LMC and the Galactic bulge RR Lyr stars, due to insufficient understanding of how such a form of pulsation arises. This problem in the context of Cepheid pulsation was discussed recently by Smolec and Moskalik (2010). One effect that they identify as a possible source of such a pulsational behavior is the $\omega_{1O} = \frac{1}{2}(\omega_F + \omega_{2O})$ resonance. It may also play a role in our sample of RRd stars. The segments in Fig. 9 mark positions where the resonance condition is satisfied exactly. For other acceptable models the condition is nearly satisfied. However, only nonlinear modeling may provide an answer whether this is the actual cause of the double mode pulsation.

6.3. Interstellar Extinction

Since RR Lyr stars have approximately the same absolute magnitudes and colors they are excellent indicators of the interstellar extinction, in the sense of measuring both – the amount of extinction and the extinction law. The study of the extinction toward the Milky Way center were undertaken by Kunder *et al.* (2008) using RRab stars identified in the MACHO fields. The map of the interstellar extinction on the basis of our catalog will be prepared elsewhere. In this paper we present only the map of the mean apparent $(V-I)$ colors of RR Lyr stars in the bulge (Fig. 10). Very large reddening toward the Milky Way center changes the apparent colors of RR Lyr stars up to $(V-I) > 4$ mag. In the most obscured regions the RR Lyr stars are too faint to be observed by the OGLE project in the *V*-band, and only the *I*-band light curves are available. In Fig. 10 the lines of constant mean

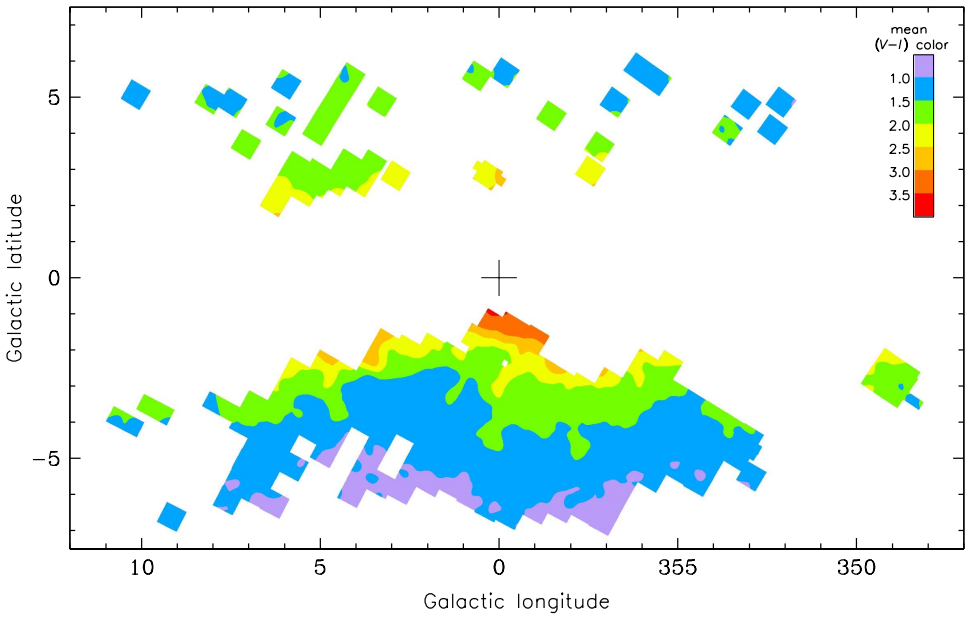

Fig. 10. Spatial distribution of the mean apparent $(V-I)$ colors of RR Lyr stars toward the Galactic bulge.

colors are roughly parallel to equatorial plane of the Galaxy, which is expected when the absorbing medium is located in the thin disk in front of the bulge. The deviation from this symmetry visible in Fig. 10 (Baade's Window) may be related to the inclined barred structure of the Galaxy center.

6.4. RR Lyr Stars in the Sagittarius Dwarf Spheroidal Galaxy

Sagittarius Dwarf Spheroidal Galaxy is a substantially tidally disrupted satellite of the Milky Way. The galaxy is distributed across much of the celestial sphere. First RR Lyr stars in Sgr dSph were discovered by Mateo *et al.* (1995) as a part of the first phase of the OGLE project. During the next years, the population of known RR Lyr stars in Sgr dSph grew significantly thanks to the studies by Alard (1996), Alcock *et al.* (1997), Cseresnjes (2001), Kunder and Chaboyer (2009).

The OGLE-III fields are located at angular distances from 7.6 to 23 degrees from the globular cluster M 54, which is believed to be the center of Sgr dSph. So, our catalog is suitable to study only the outer parts of this galaxy. The color–magnitude diagram (Fig. 3) clearly shows the sequence of faint RR Lyr stars that belong to Sgr dSph. We separated the Sgr dSph members from other RR Lyr stars by adopting a somewhat arbitrary condition: $I > 1.2(V-I)+16.2$ mag (the line in Fig. 3).

Fig. 11 presents the spatial map of 394 RR Lyr stars selected in this way. Our sample is incomplete in the regions close to the Galactic plane, where the interstellar extinction is very large. It is not surprising since the color–magnitude di-

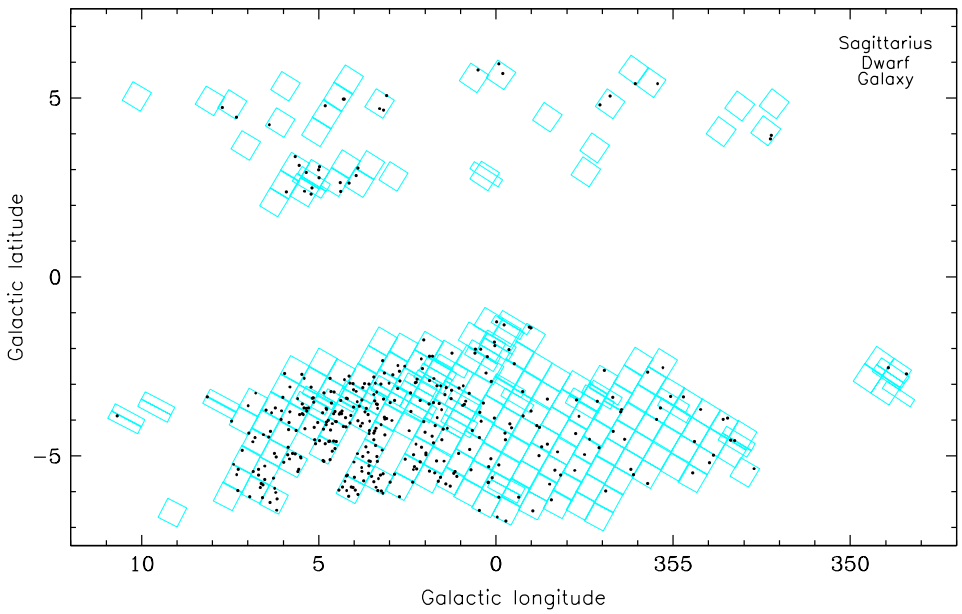

Fig. 11. Spatial distribution of RR Lyr stars from the Sagittarius Dwarf Galaxy.

agram (Fig. 3) clearly shows that Sgr dSph RR Lyr stars with apparent colors $V-I>2.4$ mag are too faint to be detected with the OGLE photometry. In the less obscured area observed by the OGLE project, the spatial gradient of RR Lyr stars in the Sgr dSph is visible.

Since RR Lyr stars in the Sgr dSph are close to the detection limit of the OGLE survey, our sample is incomplete, especially for RRc variables. Most of the overtone pulsators with symmetric light curves were probably classified as close binaries due to noisy photometry of such faint stars.

6.5. RR Lyr Stars in Globular Clusters

The OGLE fields in the Galactic bulge cover ten globular clusters[‡]. We selected RR Lyr stars which lay inside the area outlined by the angular radii of these clusters. To estimate the number of field RR Lyr stars, which may be present by chance within the cluster radii, we counted RR Lyr stars in the rings around the clusters (from 1.5 to 2.5 of the cluster radii, but we checked also other values) and rescaled the number of detected stars to the area covered in the sky by a cluster. We emphasize that our survey is not able to detect variable stars in the very cores of the globular clusters.

Seven globular cluster which may host RR Lyr stars are listed in Table 1. No RR Lyr stars were found in the following globular clusters: NGC 6355, NGC 6528

[‡]According to the list of Milky Way globular clusters available at the web page http://www.seds.org/messier/xtra/supp/mw_gc.html

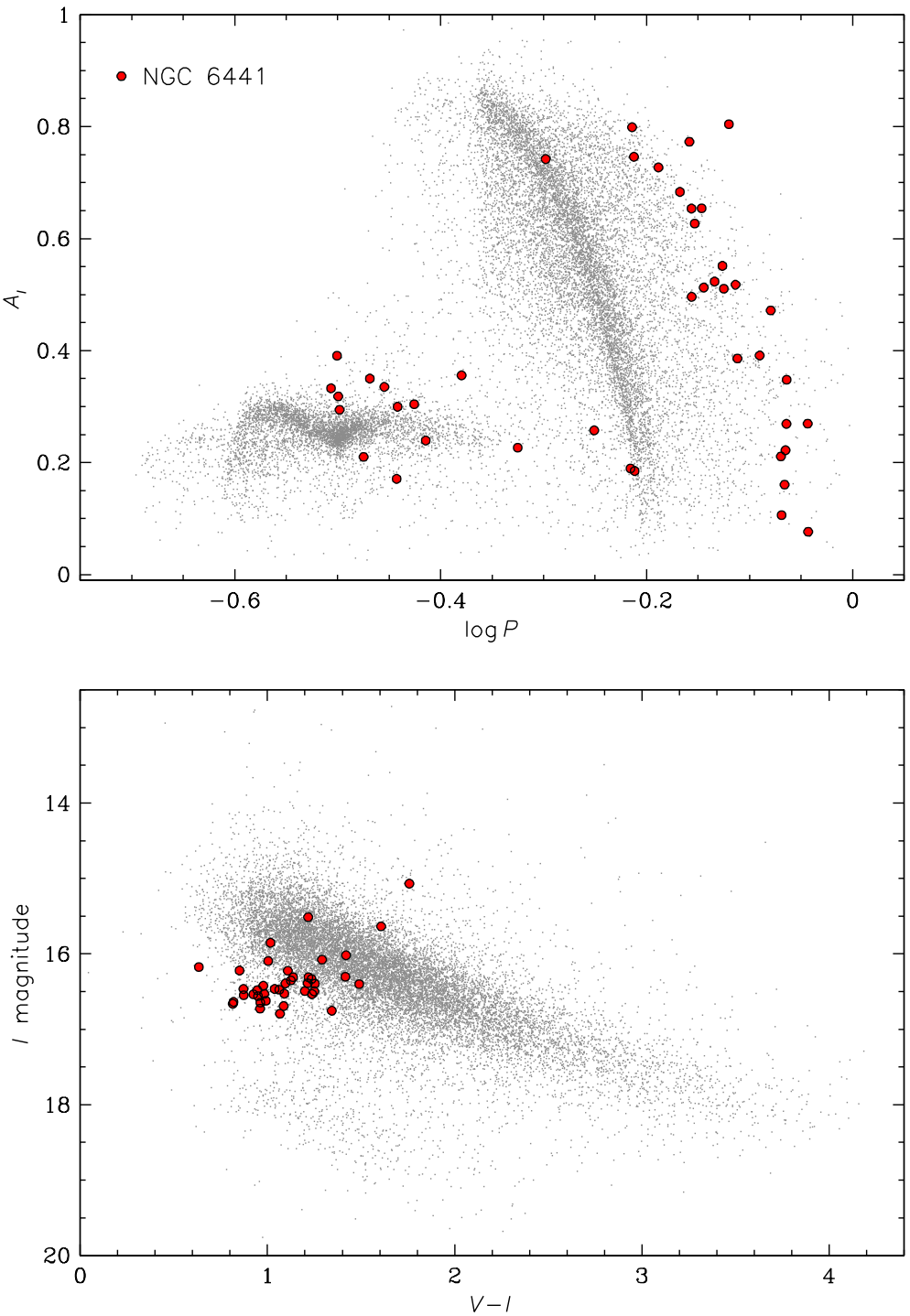

Fig. 12. Period–amplitude (*upper panel*) and color–magnitude (*lower panel*) diagrams for RR Lyr stars in the globular cluster NGC 6441 (red points). Background grey dots represent other RR Lyr stars toward the Galactic bulge.

T a b l e 1

Globular clusters in the OGLE fields containing RR Lyr stars

Cluster name	RA (J2000)	Dec (J2000)	Cluster radius [′]	$N_{\rm RR}$	$N_{\rm fieldRR}$ (estimated)
NGC 6304	$17^{\rm h}14^{\rm m}32^{\rm s}$	$-29^\circ27'44''$	4.0	5	1.5
NGC 6441	$17^{\rm h}50^{\rm m}13^{\rm s}$	$-37^\circ03'04''$	4.8	43	2.8
NGC 6453	$17^{\rm h}50^{\rm m}52^{\rm s}$	$-34^\circ35'55''$	3.8	6	2.0
Djorg 2	$18^{\rm h}01^{\rm m}49^{\rm s}$	$-27^\circ49'33''$	5.0	17	10.0
NGC 6522	$18^{\rm h}03^{\rm m}34^{\rm s}$	$-30^\circ02'02''$	4.7	15	6.5
NGC 6540	$18^{\rm h}06^{\rm m}09^{\rm s}$	$-27^\circ45'55''$	0.8	3	0.5
NGC 6558	$18^{\rm h}10^{\rm m}18^{\rm s}$	$-31^\circ45'49''$	4.2	7	0.4

and NGC 6553. Each of the further 3 clusters: NGC 6304, NGC 6453, NGC 6540, may host up to four RR Lyr stars, but it cannot be ruled out that all of the detected pulsators are field variables. Other four globular clusters observed by OGLE in the bulge – NGC 6441, Djorg 2, NGC6522 and NGC 6558 – contain RR Lyr stars, although usually only several objects.

An exceptionally rich cluster is NGC 6441, which hosts around 40 RR Lyr stars outside its core. RR Lyr variables in this cluster also have exceptionally long periods, actually the longest mean periods from all known globular clusters. Moreover, NGC 6441 together with another globular cluster, NGC 6388, violates the rule that more metal-rich clusters host shorter-period RR Lyr stars. Pritzl *et al.* (2000) suggested that NGC 6441 and NGC 6388 represent a new, third Oosterhoff group of globular clusters.

Fig. 12 shows the period–amplitude and color–magnitude diagrams for RR Lyr stars in NGC 6441 overplotted on other RR Lyr stars from our catalog. The $\log P$ of the NGC 6441 members is shifted toward longer periods by about 0.15 compared to the field bulge RRab variables. RR Lyr stars in NGC 6441 are significantly fainter than field variables surrounding the cluster in the sky, confirming the background location of the cluster with respect to the bulge. A more detailed description of RR Lyr stars in globular clusters will be presented in a separate paper.

7. Conclusions

We presented the largest catalog of RR Lyr stars toward the Galactic bulge published so far. Our sample is about five times larger than the largest set of RR Lyr stars identified in the bulge before. A huge number of objects distributed over a relatively large area in the central parts of the Galaxy, high completeness (especially for RRab stars), and excellent multi-epoch standard photometry gives an opportunity to map a 3D structure of the bulge, to test the presence of barred distribution

among the oldest population of stars, to explore the earliest history of the Galaxy formation, and to determine an accurate distance to the Milky Way center.

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