The Oosterhoff Dichotomy in the Galactic Bulge

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We explore the possibility that the Oosterhoff dichotomy in fundamental-mode RR Lyrae stars exists also in the Galactic bulge. We utilized data from the OGLE-IV survey together with a recently published list of non-modulated RR Lyraes in this region. The aforementioned stars form two hook patterns in the Fourier parameter space. These structures can be well separated by dividing them in the period–I band amplitude plane, which resembles the division of Oosterhoff groups known from other samples of RR Lyrae stars. In addition, we compare detected Oosterhoff groups in the Galactic bulge with the two Oosterhoff populations in the Sagittarius dwarf galaxy, LMC, SMC, and globular clusters.

1 Introduction

The occurrence of RR Lyrae stars has always been closely connected with globular clusters. One of the long-standing puzzles in RR Lyrae variables is a dichotomy in their mean periods in globular clusters. This effect, today known as the Oosterhoff dichotomy (named after its discoverer, Oosterhoff, 1939), separates globular clusters containing RR Lyraes into two groups: Oosterhoff type I and type II. The Oosterhoff type I (Oo I) globular clusters contain on average RR Lyraes with higher metallicity and shorter pulsation periods. In contrast, the Oosterhoff type II (Oo II) globular clusters have the opposite properties. A separation of both groups can be achieved in the period-amplitude plane where they occupy separate areas.

One of the targets in studies focused on the Oosterhoff dichotomy was the Galactic bulge. Kunder & Chaboyer (2009) used data from the MACHO survey to study fundamental mode RR Lyraes (RRab) in the Galactic bulge. They found that the main locus of the Oo I variables is shifted towards shorter pulsation periods. In addition, Kunder & Chaboyer (2009) note that there seems to be no sign of a bimodality (no locus for the Oo II group).

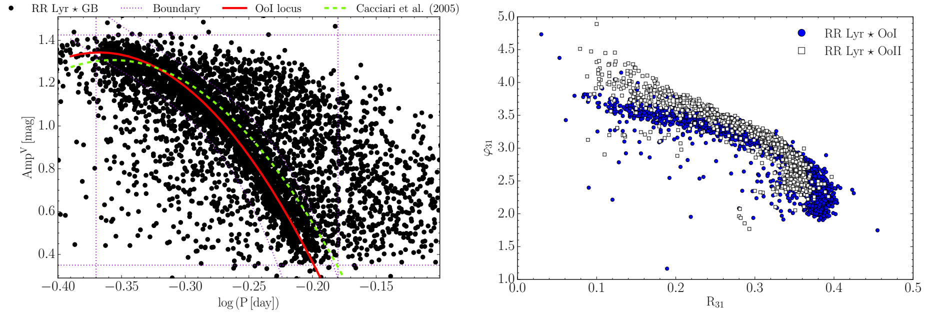

Fig. 1: Left panel: Period-amplitude diagram. Black dots represent the selected fundamental-mode RR Lyrae stars. The violet dashed lines represent the selected region for binning the main locus of the Oo I stars. The red line stands for our new relation for the locus of Oo I stars, while the green line denotes to the second-degree polynomial from Cacciari et al. (2005). Right panel: A plot of the Fourier coefficients R_{31} vs. φ_{31}. Blue and red points represent stars of Oo type I and II, respectively.

2 Separation of the Oosterhoff Groups in the Galactic Bulge

In our study, we used data from the OGLE-IV survey (Soszyński et al., 2014) for RR Lyrae stars in the Galactic bulge. We selected only fundamental mode pulsators that did not show any sign of period change or modulation (the Blazhko effect, Blažko, 1907). We utilized a sample analyzed by Prudil & Skarka (2017) consisting of 4623 RRab stars.

The left-hand and right-hand panels of Fig. 1 show the period-amplitude diagram (the Bailey diagram) and a plot of the Fourier coefficients R_{31} vs. φ_{31} for the selected RRab variables, respectively. In the Bailey diagram, we clearly see the main locus for the Oo I stars, but there seems to be no locus for the Oo II stars. To separate between Oo I and II stars, one can use the polynomial relation from Cacciari et al. (2005), which was calibrated on the globular cluster M3. The locus of Oo I seems to be shifted to shorter pulsation periods (as suggested by Kunder & Chaboyer, 2009), therefore we decided to define our own relation to better describe this offset. First, we transformed I-band amplitudes to V-band using equation 1 from Dorfi & Feuchtinger (1999). Then we separated the Oo I locus in the following way. We divided our sample stars into 28 bins based on their amplitude and then averaged their pulsation periods in each bin. These mean values were then fitted with a second-degree polynomial, and we obtained the following relation:

$$A_V = -3.373 - 25.668 \log P - 34.928 (\log P)^2. \tag{1}$$

To separate both groups we used the condition for pulsation periods from Miceli et al. (2008), where every star with $\Delta \log P > 0.045$ was classified as an Oo II star. In addition, to describe the locus for the Oo II stars we need to shift our fit by a constant $\Delta \log P = +0.06$ for longer pulsation periods (Cacciari et al., 2005). Based on Eq. 1, and on the condition from Miceli et al. (2008), we separated the stars into two Oosterhoff groups and displayed the corresponding Fourier parameters in the right-hand panel of Fig. 1. Two hook structures, implying two Oosterhoff populations,

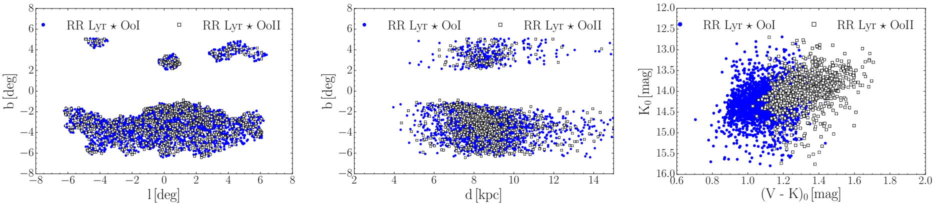

Fig. 2: Left panel: the spatial distribution of the RR Lyrae stars in Galactic coordinates. Middle panel: the Galactic latitude vs. distance. Right panel: the color-magnitude diagram, constructed using data from the VVV survey (Minniti et al., 2010) and calculated using relations from Catelan et al. (2004). In all three panels, white squares represent Oo II stars and blue points stand for Oo I stars.

	l [deg]	b [deg]	d [kpc]
D	0.034	0.040	0.035
p-value	0.243	0.110	0.212

Table 1: The Kolmogorov-Smirnov test for spatial correlation.

can be observed in the Galactic bulge. After applying our relation, both hooks are separated. Overall, approximately 26 % of the RRab stars from our bulge sample belong to the Oosterhoff II group.

3 Distribution of Oosterhoff Groups in the Galactic Bulge

We looked for possible overdensities in the spatial distribution of both Oosterhoff groups in the Galactic bulge. First, we calculated metallicities using relation 3 from Smolec (2005) and then, using the procedure from Pietrukowicz et al. (2015), calculated the distances to individual RR Lyrae stars. In the first two panels (from the left) of Fig. 2 we show the spatial distribution of the RR Lyrae stars. At first glance, there seems to be no area with a higher concentration compared to the other group. To quantify that, we used the Kolmogorov-Smirnov test for the spatial distribution of RR Lyraes. The results are listed in Tab. 3. The derived p-values are lower than the test's significance level (0.05) of the null hypothesis, i.e., that the two samples are drawn from the same distribution. As a consequence, we conclude that both samples are drawn from the same population/distribution. Therefore, we do not observe any difference in their spatial distribution.

We also used data from the infrared VVV survey (Minniti et al., 2010) in order to construct a color-magnitude diagram sensitive to temperature. The results can be found in the right-hand panel of Fig. 2. Stars that belong to the Oo II group are on average brighter and redder than their Oo I counterparts. This seems to be in agreement with the hysteresis mechanism (one of the explanations of the Oosterhoff phenomenon, van Albada & Baker, 1973).

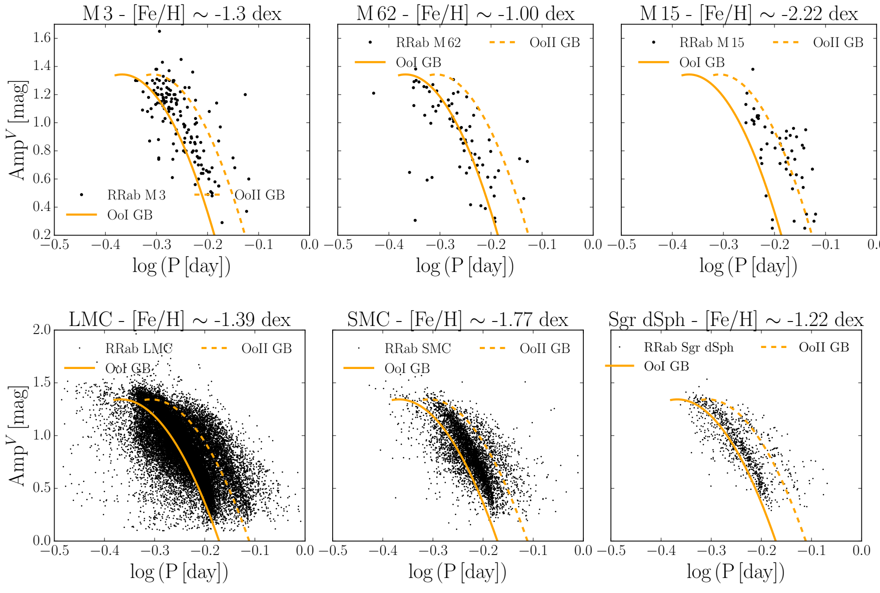

Fig. 3: The period-amplitude diagrams for Galactic and extragalactic objects. The black dots represent individual fundamental mode RR Lyrae stars, orange lines stand for the polynomial relation defined for Galactic bulge RR Lyraes, for Oo I (solid lines) and Oo II (dashed lines). Data from Clement et al. (2001) and OGLE-IV survey (Soszyński et al., 2014).

4 Comparison with Globular Clusters and Extragalactic Systems

In this section, we compared our fit of the Oo I locus for the bulge RR Lyraes with Galactic and extragalactic systems. In the top panel of Fig. 3, we see period-amplitude diagrams for three globular clusters (M3, M62, and M15). M3 and M62 were previously classified as Oo I systems. For M3, we see an offset between our fit (orange line) and RRab stars associated with this cluster. The shift in the Bailey diagram for M3 might be caused by the higher metallicity for RRab stars in the Galactic bulge ($\langle[\mathrm{Fe/H}]\rangle_{\mathrm{M3}} \sim -1.3$ dex and $\langle[\mathrm{Fe/H}]\rangle_{\mathrm{bulge}} \sim -1.0$ dex on the Jurcsik (1995) scale). In the case of M62, our relation describes reasonably well the Oo I locus ($\langle[\mathrm{Fe/H}]\rangle_{\mathrm{M62}} = -1.00$ dex on the Jurcsik (1995) scale). The main locus of the globular cluster M15 (Oo II cluster, $\langle[\mathrm{Fe/H}]\rangle_{\mathrm{M62}} = -2.22$ dex) can be also reasonably well described with the locus for the same group in the Galactic bulge.

The bottom panels of Fig. 3 displays period-amplitude diagrams for three extragalactic systems (the LMC, SMC, and the Sagittarius dwarf galaxy). We see that our polynomial relation does not describe the Oo I locus in any of the three objects. The largest offset seems to be for the Small Magellanic Cloud, which is also the most metal-poor object among these three systems. The Large Magellanic Cloud and the Sagittarius dwarf galaxy also seem to have a small fraction of Oo II stars. For both objects, our relation is shifted towards shorter pulsation periods, which is probably caused by the difference in metallicity. The metallicities on the Jurcsik (1995) scale are listed in the title of each period-amplitude diagram.

5 Summary

We studied the two Oosterhoff populations in the Galactic bulge using unmodulated RRab variables from the OGLE-IV survey. These two groups create two hook-like structures in the R_{31} vs. φ_{31} plane. The Oo I locus is slightly shifted to shorter pulsation periods when compared with more metal-poor globular clusters of the same Oosterhoff type. Therefore, we defined a new polynomial relation to better describe the Oo I locus in the period-amplitude diagram. This relation helped us to separate both groups. The Oosterhoff populations seem to be evenly distributed in the Galactic bulge. We compared our polynomial fit with the fundamental mode RR Lyraes in three Galactic globular clusters, the LMC, SMC, and Sgr dSph galaxy using a period-amplitude diagram. We found that our equation is slightly shifted to lower pulsation periods. This offset is most likely caused by the differences in metallicity in aforementioned systems.

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