VVV Survey of Blue Horizontal Branch Stars in the Bulge–Halo Transition Region of the Milky Way

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Summary

We characterize the population of blue horizontal branch (BHB) stars in the bulge–halo transition region of the Milky Way using the VISTA Variables in the Vía Láctea (VVV) ESO Public Survey data. The selection of BHB stars is made using the globular cluster M22 as a reference standard and constructing color–magnitude and color–color diagrams with specific cuts in the ZYJHKs near-infrared (IR) passbands. A total of 12,554 BHB stars were detected, in a region within $-10\leq l \leq 10$ and $-8\leq b \leq 8$. We provide accurate coordinates and near-IR photometry for this sample of BHB stars. We searched for overdensities of stars with sizes similar to those of known globular clusters and stellar streams. By comparing real data with Monte Carlo simulations, we conclude that the few overdensities detected are of low significance. We also constructed $K_s$-band light curves for the BHB stars to study their variability. Taking an average of 52 epochs to calculate periods and amplitudes, we identify hundreds of candidate eclipsing binaries and a dozen pulsating stars. Finally, we made some comparisons with results obtained in a previous study for RR Lyrae variable stars in this same region.

Key words: binaries: eclipsing – Galaxy: bulge – stars: horizontal-branch

Supporting material: machine-readable tables

1. Introduction

The VISTA Variables in the Vía Láctea (VVV) is an ESO Public Survey that is targeting the central parts of the Galaxy, covering an area of $\sim$540 deg$^2$ (Minniti et al. 2010). Its main goal is to study our galaxy’s bulge and southern disk in order to reveal the corresponding 3D structure through variable stars. VVV combines high-resolution ($\sim$0.34 pixel$^{-1}$), deep ($K_s \geq 18$ mag), near-IR photometry in five bands (ZYJHK$_s$), thus alleviating the problem of high interstellar dust extinction and better resolving the high stellar density regions, allowing us to unveil the stellar populations in this complex area (Saito et al. 2012b). In addition, multi-epoch observations allow us to construct $K_s$-band light curves to study different variable stars, enabling the construction of a 3D map of the surveyed region (Gran et al. 2016).

Old metal-poor stars, e.g., RR Lyrae and blue horizontal branch (BHB) stars, are ideal for tracing old regions of the Milky Way (>5 Gyr) and constructing their associated number-density maps. They are also very good standard candles, which enable accurate determination of their distances (Clewley & Jarvis 2006). However, BHB stars are $\sim$10 times more numerous than RR Lyrae stars. Considering these advantages, as well as the accuracy and depth of the photometric data obtained by the VVV Survey, we can use BHB stars to study the (expected) most ancient part of the Galaxy, such as the bulge–halo transition region. We define this region loosely, at projected Galactocentric distances 1 kpc < $R_G$ < 2 kpc. This very special place contains precious information about the assembly history of the Milky Way.
the Galaxy out to 60 kpc (Xue et al. 2008) and to explore the age structure of the halo (Santucci et al. 2015). Some 130,000 photometrically selected BHB candidates from SDSS were used by Carollo et al. (2016) to obtain the first accurate estimate of the age gradient in the Galactic halo based on field stars and to confirm the existence of a so-called “ancient chronographic sphere” of old stars in the halo (first suggested by Santucci et al. 2015), extending from immediately outside the bulge, past the solar vicinity, out to $\sim 15$ kpc from the Galactic center. Due to the selection criteria employed in the above-mentioned studies, none of these samples extended into the bulge region.

Bulge BHB stars have also been studied in the past, both photometrically and spectroscopically (e.g., Peterson et al. 2001; Zoccali et al. 2003; Terndrup et al. 2004; Busso et al. 2005; Koch et al. 2016), firmly establishing that the Galactic bulge, in spite of being predominantly metal-rich, still contains old and metal-poor BHB stars. However, these previous studies were limited to a relative handful of stars. One of the goals of the present work is to assemble a massive catalog of bulge BHB stars, complementing the existing halo- and disk-system catalogs, in order to enable a suite of follow-up studies. Therefore, in this paper we make a census of these old BHB stars in the bulge–halo transition region, using the VVV near-IR data. We also use this new catalog to search for new globular clusters and for variable stars such as eclipsing binaries and RR Lyrae.

2. The VVV Data

2.1. Observations

The VVV is a public near-IR survey of the inner Milky Way using the ZYJHK$_s$ passbands (Minniti et al. 2010; Catelan et al. 2011; Saito et al. 2012a), whose coordinates have subarcsecond accuracy (Smith et al. 2018), a necessary requirement in this high stellar density region. The VVV observations were taken with the near-IR camera VIRCAM at the Visible and Infrared Survey Telescope for Astronomy (VISTA) located at ESO Cerro Paranal Observatory (Emerson & Sutherland 2010). VISTA is a 4 m telescope that has been optimized for the near-IR. The VISTA Infrared Camera (VIRCAM) has 16 near-IR detectors with a scale of $0^\prime.34$/pixel, arranged in a $4 \times 4$ pattern with significant gaps between them. The observing sequence consists of six individual exposures, spatially shifted in a mosaic pattern, and later combined into a single image, which we refer to as a “tile.” Each tile covers approximately $1.1 \times 1.5$ deg$^2$ on the sky. The VVV bulge observations comprise 196 tiles in total, covering a 307 deg$^2$ field of view, within $-10^\circ.0 \leq \ell \leq 10^\circ.2$ and $-15^\circ.2 \leq b \leq 5^\circ.0$. Figure 1 shows a schematic of the bulge region observed by the VVV survey.

The observations are made using the ZYJHK$_s$ filters and consist of two epochs in ZYJH, taken at the beginning and the end of the survey, in years 2010 and 2015, respectively, plus multiple epochs in the $K_s$ band. The $K_s$-band variability campaign was carried out between 2010 and 2016, obtaining a total of about 75 observations per field in the VVV bulge area.

The data reduction, calibration, and aperture photometry were carried out by the Cambridge Astronomical Survey Unit (CASU; Irwin et al. 2004). The CASU photometry is tied to the 2MASS system (Cutri et al. 2003; Hodgkin et al. 2009) and is made publicly available at the VISTA Science Archive (VSA; Montenegro et al. 2019 February 20)

![Figure 1. Artistic representation of the Milky Way, seen face-on, based on the Spitzer satellite data. (Credits: R. Hurt/Spitzer Space Observatory/NASA.) Each concentric circle indicates the distance to the Sun. The shaded region corresponds to the area covered by the VVV survey used in this study.](image)

![Figure 2. VVV Bulge area in Galactic coordinates (measured in degrees). Tiles used in this work (b201–b228) are colored in blue and are located in the bulge–halo transition region of the Milky Way.](image)

Hambly et al. 2004; Cross et al. 2009). In addition, we have performed single-epoch PSF photometry in the ZYJHK$_s$ bands for the entire VVV bulge data set using DoPhot (Alonso-García et al. 2015) in order to obtain deeper and more accurate photometry, adequate for the selection of BHB stars. In this work, we analyze the outermost southern VVV bulge tiles, from b201 to b228 (Figure 2), covering an area within $10^\circ.0 \leq \ell \leq 10^\circ.2$ and $-10^\circ.2 \leq b \leq -8^\circ.0$, for a total of about 44 deg$^2$, comprising VVV tiles b201 to b228. This area is sufficiently far from the Galactic plane that extinction and crowding do not present severe limitations.

2.2. Selection of BHB Stars

In order to select BHB stars in the bulge, one can fit theoretical isochrones to their CMDs (e.g., Brown et al. 2004). However, we preferred an empirical selection approach, as we needed to consider the presence of complex stellar populations as well. For that reason we use the globular cluster M22 (NGC 6656) as a standard sample, as it comprises an old stellar population with a prominent horizontal branch. This cluster was observed in the near-IR by the VVV in the same way, with...
the same instrumental setup, sharing the biases and constraints of our BHB star sample.

Given the known distance difference, the bulge BHB stars would be located in the CMD about two magnitudes fainter than the M22 BHB stars. The bulge BHB stars can be clearly seen in the deep VVV near-IR CMDs (Figure 3).

We used the $Y - J$ versus $J - K_s$ color–color diagram to select bulge BHB stars, demanding $Y - J < 0.15$ and $J - K_s < 0.35$ (Figure 4). These cuts are applied in most fields and only relaxed to $Y - J < 0.20$ and $J - K_s < 0.45$ in the most reddened fields, e.g., b212, which are contaminated by RGB stars from the Sgr dwarf galaxy.

At the faintest magnitudes there is contamination from other A-type stars (e.g., Brown et al. 2004; Clewley & Jarvis 2006). For example, some bulge blue-straggler stars in particular share a similar location in the CMDs. Also, in these fields, there is some contamination from the main sequence of the Sgr dSph galaxy. In order to take the contamination from A-type stars into account, we added another near-IR color cut: $J - H < 0.10$. This is because, according to Brown et al. (2004), the BHB stars have $-0.20 < (J - H)_0 < 0.10$ and $-0.10 < (H - K)_0 < 0.10$ (Figure 5), with $J - H$ being a good indicator to discard A-type stars, as they tend to have redder $(J - H)_0$ colors. Our final sample contains 12,554 bulge BHB star candidates.

3. A Search for New Globular Clusters

Minniti et al. (2017a, 2017b, 2017c) recently reported the discovery of dozens of new globular cluster candidates in the Galactic bulge. BHB stars are well-known representatives of old and metal-poor populations, often found in old globular clusters. Single stellar population (SSP) models tell us that, in a globular cluster, for every BHB star there are hundreds of red giant branch and thousands of main-sequence stars (even though recently it has been found that not all GCs are SSPs; see, e.g., Piotto et al. 2005).

In this work, we aim to detect overdensities of BHB stars in the selected 28 fields, as they may lead to the discovery of heretofore unknown globular clusters and complement other stellar population studies. To accomplish this, we generated density maps of BHB candidates (Figure 6) with different bin sizes. We also generated random homogeneous samples of 12,554 points (equivalent to the total number of BHB stars in our catalog), distributed across the 28 tiles. The results of these Monte Carlo simulations were plotted together with the BHB...
stars of the sample. The objective was to analyze if there were overdensities that could correspond to previously undiscovered globular clusters or streams. We experimented with a number of different bin searches. Ultimately, from a density plot with hexagonal bins and a color gradient, we obtained a number of different bin searches. We chose to report a negative result; even though there may be some overdensities, these are probably not due to previously unknown globular clusters. These overdensities could correspond to streams, which will be addressed in future work.

4. Light Curves

4.1. Variability

We search for variability by constructing light curves of all the BHB stars in our sample. In order to do this, additional data were needed, which were downloaded from the VISTA Science Archive\(^8\) (VSA) hosted on the Royal Observatory of Edinburgh website. Then, a cross-match was performed using the VSA and the original data available for each star. For each object there are on average 52 epochs; each magnitude has its respective error. Typical errors range from 0.01 to 0.06 mag at the brightest and faintest magnitudes of our sample, respectively.

The tiling pattern produces overlap regions between the tiles, corresponding to about 7% of the total VVV Survey area (Saito et al. 2012b). In these regions, the data for each source are combined, thus producing light curves with double, or even four times more, data points. In our sample, 80 objects are in the overlap regions, with light curves reaching +100 epochs in total. In order to account for spuriously large photometric errors, we apply sigma clipping by eliminating the points that are more than 3\(\sigma\) away from the mean of the light curve.

With this information, plots of amplitude versus magnitude were made (Figure 9, top panel) in order to find a suitable cut for the minimum amplitude that could yield a cleaner and easier to study light curve. A cut of minimum amplitude is set at Amp \(K_s = 0.15\) mag for the light curves of interest, after a visual inspection of Figure 9 (top panel).

Finally, Figure 9 (bottom panel) shows the magnitudes of the selected BHB stars and their amplitudes, after cleaning the light curves and applying the cut in amplitude. A total of 7665 light curves were obtained using this criterion, which corresponds to 61\% of the original sample and whose magnitudes are within the range 12.68 \(\leq K_s \leq 16.80\). The remaining 39\% of the sample are BHB stars that do not exhibit variability, which are beyond the scope of this work, but these candidate stars are still being studied and will be presented in a future paper.

4.2. Period Searches

The Lomb–Scargle periodogram (Lomb 1976; Scargle 1982) is a statistical tool used to detect periodic signals in unevenly spaced observations; it works by making a search for the maximum peak in frequency of the light-curve data. This estimating function was used to determine the period of our BHB stars’ phased light curves.

An alias is a false period that contaminates the periodograms. In particular, daily aliases occur when the interval between observations matches the day/night cycle, half or some other multiple of this (Scargle 1982; Balucic 2012). Observing the values obtained for the periods and the light curves of our sample of BHB stars, we find that 1721 of them.

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\(^8\) http://horus.roe.ac.uk/vsa/
correspond to daily aliased periods between 0.1 and 3.3 days, being the most common alias of one day. These light curves, like the one shown in Figure 10, are left out of our analysis.

With a total of 5944 good-quality light curves, we carried out a visual inspection at least three times to determine what kind of variable stars they were. Following the models exhibited by Prša et al. (2011), we detected a total of 336 eclipsing binaries (Figure 11). We classified 232 of them as first category (Figure 11, top panel), due to their error bars being on average 0.02 mag, and the other 104 sources were classified as second category, because they exhibited error bars with an average of 0.04 mag (Figure 11, bottom panel). Regardless, all of them exhibit light curves that are sufficiently clear to distinguish them from other variable stars. The remaining 5608 variable stars remain unclassified until more epochs become available in their light curves.

We also found 12 RR Lyrae stars, such as that shown in Figure 12; all are listed in Table 1. Seven of these RR Lyrae were independently discovered by Gran et al. (2016), using a different selection method that does not consider the color of the stars as in this work. The remaining five RR Lyrae have bluer colors ($J - K_s \sim 0.27$). Considering the Hess diagram presented by Gran et al. (2016), our five RR Lyrae have colors within the color range of their stars.

4.3. Classification of Eclipsing Binaries

An eclipsing variable is a binary system with its orbital plane oriented edge-on toward the Earth in such a way that eclipses and transits can occur. According to the General Catalogue of Variable Stars9 (Samus et al. 2017), eclipsing binaries can be classified into three groups, depending on the shape of their light curves: EA (Algols), EB ($\beta$ Lyrae), and EW (W Ursae Majoris).

From visual inspection, we classified a total of 42 EA eclipsing binaries (Figure 13), as these are different from the other two types, mainly due to the flat portion of their light curves. Then, to distinguish between the other two types, EB and EW, a deeper analysis is made, considering their periods and amplitudes in addition to visual inspection of the light curve shape, thus obtaining 119 EB-type (Figure 14) and 175 EW-type (Figure 15) eclipsing binaries in our sample of BHB candidates in the outer bulge.

The region of the CMD occupied by the BHB stars is rich in variable stars, including eclipsing binaries, as recently shown

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9 http://www.sai.msu.su/gcvs/gcvs/
Figure 8. Some interesting overdensities corresponding to the second binning exercise (bin size of 12°).

Figure 9. Top panel: amplitude vs. \(K_s\) magnitude for the total sample of BHB stars. This plot allows us to determine a cut of minimum amplitude. Bottom panel: amplitude of the light curve versus mean \(K_s\) magnitude after cleaning the light curve with our sigma clipping constraint and applying the cut at Amp \(K_s = 0.15\) mag.

Figure 10. Example of a BHB star light curve with a daily aliased period.
by the *Gaia* satellite (Eyer et al. 2018). In particular, shorter period eclipsing binaries predominate in our sample because they are easier to detect than longer-period ones. As expected, the EWs are more concentrated toward shorter periods than the EAs and EBs.

### 4.4. Period–Amplitude Diagram

Bailey (1902) classified RR Lyrae stars by their periods and amplitudes of variation. Even now, the period–amplitude diagram (a.k.a. the Bailey diagram) is quite useful for the classification and study of the intrinsic properties of variable stars.

From inspection of the top panel of Figure 16, one can see that the periods of our eclipsing binaries span between 0.2 < $P$ < 19.2 days, and their amplitudes are in the range 0.15 < Amp $K_\alpha$ < 0.91 mag. Eclipsing binaries, corresponding to

![Figure 11](source.png)  
**Figure 11.** Top panel: light curve of a BHB star classified as a first category eclipsing binary. Bottom panel: light curve of a BHB star classified as a second category eclipsing binary.

![Figure 12](source.png)  
**Figure 12.** RR Lyra star found in our sample.

![Figure 13](source.png)  
**Figure 13.** EA eclipsing binaries. A synthetic light curve (obtained from Kallrath & Milone 2009) in the top panel can be compared with one of our EA light curves shown in the bottom panel.

![Figure 14](source.png)  
**Figure 14.** EB eclipsing binaries. A synthetic light curve (obtained from Kallrath & Milone 2009) in the top panel can be compared with one of our EB light curves in the bottom panel.

2.7% of the BHB stars’ original sample, are more homogeneously distributed than the remaining variable stars in the sample, which are strongly concentrated at low amplitudes and
We have studied an area of 40 deg$^2$ on the sky in order to characterize the population of BHB stars in the direction of the Galactic bulge using VVV data. This area corresponds to 28 tiles of 1.1 $\times$ 1.5 deg$^2$ each in the bulge–halo transition region of the Milky Way. We discovered a total of 12,554 BHB candidate stars using a strict color selection, taking the BHB members of the old and metal-poor globular cluster M22 as a reference. The present bulge BHB catalog is used here to search for new globular clusters and variable stars.

Monte Carlo simulations were performed with the goal of detecting overdensities that could be undiscovered globular

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### Table 1

| VVV ID     | VVV ID Gran et al. (2016) | R.A. (J2000) | Decl. (J2000) | Period | Amp $K_s$ | Z | Y | J | H | $K_s$ |
|------------|---------------------------|-------------|---------------|--------|-----------|---|----|---|----|-------|
| VVV 515706039923 | J180039.53-400902.4        | 18:00:39.6  | −40:09:03.6   | 0.6497 | 0.40      | 14.14 | 14.32 | 14.00 | 13.79 | 13.73 |
| VVV 515673239493 | J180949.72-364838.9        | 18:09:49.6  | −36:48:39.6   | 0.5354 | 0.41      | 14.01 | 14.18 | 13.90 | 13.76 | 13.68 |
| VVV 515672602244 | J180958.42-380307.7        | 18:09:58.3  | −38:03:07.2   | 0.5230 | 0.32      | 14.76 | 14.86 | 14.61 | 14.48 | 14.41 |
| VVV 515698297724 | J181011.78-384805.0        | 18:10:11.7  | −38:48:03.6   | 0.6101 | 0.25      | 14.63 | 14.74 | 14.49 | 14.32 | 14.22 |
| VVV 515656519651 | J181418.96-352242.8        | 18:14:18.9  | −35:22:44.4   | 0.3964 | 0.30      | 14.49 | 14.64 | 14.35 | 14.17 | 14.08 |
| VVV 515598433507 | J182748.94-332826.0        | 18:27:48.9  | −33:28:26.4   | 0.5406 | 0.49      | 14.83 | 15.02 | 14.69 | 14.47 | 14.39 |
| VVV 515553139402 | J183758.88-290835.4        | 18:37:58.8  | −29:08:34.8   | 0.5395 | 0.45      | 15.04 | 15.13 | 14.85 | 14.58 | 14.50 |
| VVV 515705907121 | ...                       | 17:59:59.2  | −40:21:00.0   | 0.6145 | 0.29      | 14.85 | 14.97 | 14.70 | 14.51 | 14.40 |
| VVV 515655923198 | ...                       | 18:14:50.4  | −36:23:27.6   | 0.4511 | 0.29      | 15.93 | 16.08 | 15.77 | 15.57 | 15.53 |
| VVV 515598807255 | ...                       | 18:26:03.6  | −32:22:55.2   | 0.4550 | 0.42      | 14.86 | 15.01 | 14.71 | 14.57 | 14.47 |
| VVV 515533825718 | ...                       | 18:38:25.2  | −28:11:27.6   | 0.3488 | 0.19      | 15.19 | 15.33 | 15.00 | 14.84 | 14.76 |
| VVV 515456403764 | ...                       | 18:41:49.9  | −23:56:45.6   | 0.6272 | 0.24      | 14.72 | 14.90 | 14.48 | 14.18 | 14.11 |

Note. The complete parameters: VVV ID, R.A. (J2000), decl. (J2000), period (days), amplitude of $K_s$, magnitude, and $Z Y J H K_s$ magnitudes.

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**Figure 15.** EW eclipsing binaries. A synthetic light curve (obtained from Kalrath & Milone 2009) in the top panel can be compared with one of our EW light curves in the lower panel.

short periods. The average period is 1.12 days for eclipsing binaries, which is a similar value to that obtained by Rozyczka et al. (2017) for 29 BHB stars that correspond to eclipsing binaries in the field of the globular cluster M22, which have an average period of 1.86 days.

According to the Gaia DR2 variable star CMD given by Eyer et al. (2018, their Figure 4), there are eclipsing binaries present in the horizontal branch. For this reason, we decided to perform a cross-match between our sample of BHB eclipsing binaries and the objects detected by Gaia DR2 in this area of the Milky Way, considering only sources that were classified as variables. We found 100 matches in total, corresponding to about one-third of our eclipsing binaries sample, which we consider a good confirmation of our results. We expect an increase in the number of matches when Gaia completes the classification of variable and nonvariable objects in the area studied here.

From inspection of the bottom panel of Figure 16, one can see that the periods of the remaining variables are in the range $0.1 < P < 8.5$ days, and their amplitudes span between $0.15 < \text{Amp } K_s < 1.32$ mag. These variables stars, corresponding to 44.7% of the BHB candidates in the original sample, reach the highest amplitudes and periods, almost as long as the eclipsing binaries; an average period of 0.53 days. As expected, the 12 RR Lyrae (Figure 17) found in our sample are included within the ranges of this part of the sample. Tables 2 and 3 present the characteristics (coordinates, periods, amplitudes, and magnitudes) of each of these candidate BHB eclipsing binary stars. Likewise, Figures 18–27 and 28–32 show the light curves of first and second category examples of these 336 stars, respectively. In addition, in our sample, most of the long-period variables have smaller amplitudes, while short-period variables have larger amplitudes, on average.

In spite of their small numbers, our RR Lyrae are located in the Oosterhoff type I region of the Bailey diagram, different from the M22 RR Lyrae that are Oosterhoff type II. This is in agreement with the previous results of Gran et al. (2016), who analyzed the Bailey diagram for a thousand bulge RR Lyrae discovered by the VVV survey.
clusters, covering the total area first and then each tile individually. The first simulations used a bin size of 2′—some overdensities were discovered, but all of them were of low significance. The second simulation used an extreme bin size of 12′—some of the corresponding overdensities reveal two possible streams, whose analysis will be a part of future work.

We also examined the variability of the BHB sample, plotting light curves having an average of 52 epochs. By choosing as a minimum amplitude $K_{\text{Amp}} = 0.15$ mag, we found 7665 variable BHB candidates with mean magnitudes between $12.68^{\text{K}_{\text{s}}} - 16.80$. Their mean magnitudes are consistent with the majority of them being located at the distance of the Galactic bulge, $d \approx 8$ kpc. Their periods were determined using the Lomb–Scargle periodogram, yielding an average of 1.12 days for eclipsing binaries and 0.53 days for the remaining variables. A total of 1721 variable stars with aliased periods was detected, which were discarded. We performed a visual inspection of the remaining sample of 5944 BHB stars, finding 336 good-quality eclipsing binary candidates, with periods up to $P = 19.2$ days. These were further subclassified as detached, semicontact, and contact

| VVV ID | R.A. (J2000) | Decl. (J2000) | Period | $A_{Ks}$ | Z   | Y   | J   | H   | $K_s$ | Class |
|--------|--------------|--------------|--------|----------|-----|-----|-----|-----|-------|-------|
| VVV 515455705872 | 18:41:02.6 | −25:08:27.6 | 3.2937 | 0.18 | 14.75 | 14.93 | 14.51 | 14.24 | 14.12 | EB    |
| VVV 515455735619 | 18:37:32.4 | −24:42:03.6 | 14.4274 | 0.16 | 15.20 | 15.38 | 15.04 | 14.93 | 14.82 | EB    |
| VVV 515455749525 | 18:40:50.8 | −25:02:27.6 | 1.0277 | 0.19 | 15.67 | 15.80 | 15.53 | 15.35 | 15.27 | EB    |
| VVV 515455859192 | 18:38:27.6 | −24:35:16.8 | 0.7135 | 0.29 | 14.74 | 14.92 | 14.52 | 14.29 | 14.17 | EB    |
| VVV 515455988959 | 18:39:40.5 | −24:29:13.2 | 0.9647 | 0.25 | 13.47 | 13.66 | 13.23 | 12.98 | 12.85 | EW    |
| VVV 515456105530 | 18:41:39.6 | −24:29:24.0 | 1.0014 | 0.39 | 15.13 | 15.31 | 14.94 | 14.75 | 14.63 | EA    |
| VVV 515456121023 | 18:41:49.6 | −24:28:48.0 | 0.7075 | 0.39 | 15.45 | 15.61 | 15.25 | 15.01 | 14.92 | EB    |
| VVV 515456130444 | 18:40:15.1 | −24:17:02.4 | 0.5331 | 0.19 | 15.37 | 15.59 | 15.13 | 14.81 | 14.77 | EW    |
| VVV 515456170484 | 18:39:16.0 | −24:06:28.8 | 0.3856 | 0.64 | 13.84 | 14.02 | 13.61 | 13.39 | 13.27 | EB    |

Note. The complete parameters: VVV ID, R.A. (J2000), decl. (J2000), period (days), amplitude of $K_s$ magnitude, $ZYJHK_s$ magnitudes, and type of eclipsing binary. (This table is available in its entirety in machine-readable form.)

| VVV ID | R.A. (J2000) | Decl. (J2000) | Period | $A_{Ks}$ | Z   | Y   | J   | H   | $K_s$ | Class |
|--------|--------------|--------------|--------|----------|-----|-----|-----|-----|-------|-------|
| VVV 515455564844 | 18:39:58.3 | −25:03:36.0 | 0.1542 | 0.22 | 15.91 | 16.06 | 15.69 | 15.55 | 15.42 | EB    |
| VVV 515455868670 | 18:40:48.9 | −24:49:37.2 | 0.1043 | 0.20 | 15.95 | 16.10 | 15.75 | 15.55 | 15.52 | EW    |
| VVV 515455933928 | 18:39:48.9 | −24:35:56.4 | 0.1157 | 0.21 | 16.20 | 16.37 | 15.98 | 15.72 | 15.76 | EW    |
| VVV 515456085853 | 18:38:39.1 | −24:11:38.4 | 0.2052 | 0.31 | 15.41 | 15.59 | 15.16 | 14.90 | 14.79 | EA    |
| VVV 515456440625 | 18:39:44.6 | −23:38:24.0 | 0.1997 | 0.25 | 15.34 | 15.52 | 15.09 | 14.85 | 14.74 | EW    |
| VVV 515463134581 | 18:43:55.4 | −25:19:58.8 | 0.1374 | 0.19 | 15.61 | 15.78 | 15.43 | 15.32 | 15.20 | EW    |
| VVV 515463225981 | 18:42:07.9 | −24:57:36.0 | 0.1826 | 0.26 | 15.32 | 15.46 | 15.19 | 15.09 | 15.05 | EA    |
| VVV 515478514260 | 18:36:37.4 | −26:13:01.2 | 0.1662 | 0.15 | 15.51 | 15.69 | 15.36 | 15.21 | 15.16 | EB    |
| VVV 515479052288 | 18:36:22.3 | −25:14:31.2 | 0.1112 | 0.19 | 15.88 | 16.05 | 15.64 | 15.45 | 15.36 | EB    |
| VVV 515479171894 | 18:39:00.9 | −25:19:22.8 | 0.1453 | 0.17 | 15.53 | 15.70 | 15.41 | 15.25 | 15.22 | EB    |

Note. The complete parameters: VVV ID, R.A. (J2000), decl. (J2000), period (days), amplitude of $K_s$ magnitude, $ZYJHK_s$ magnitudes, and type of eclipsing binary. (This table is available in its entirety in machine-readable form.)

Figure 16. Top panel: period–amplitude diagram of eclipsing binaries from our sample. Bottom panel: period–amplitude diagram of the remaining variables. Turquoise points correspond to BHB stars, and red squares are our 12 RR Lyrae.
binaries (12.5% EA, 35.4% EB, 52.1% EW). A total of 12 RR Lyrae were detected, including 7 of them that were independently discovered by Gran et al. (2016). From a period–amplitude diagram we found that the amplitude range for the remaining variables is $0.15 \leq \text{Amp } K_s \leq 1.32$ mag and $0.15 \leq \text{Amp } K_s \leq 0.91$ for eclipsing binaries, with a period range of $0.1 < P < 8.5$ days for the remaining variables and $0.2 < P < 19.2$ for eclipsing binaries.

Finally, comparing our sample of BHB stars with the study of RR Lyrae stars in the same region by Gran et al. (2016), we see that the Galactic bulge BHB population is more than an order of magnitude larger than that of the RR Lyrae ($\sim 14 \times$).

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Figure 18. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 19. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 20. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 21. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 22. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 23. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 24. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 25. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 26. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 27. BHB stars light curves corresponding to first category eclipsing binaries.
Figure 28. BHB stars light curves corresponding to second category eclipsing binaries.
Figure 29. BHB stars light curves corresponding to second category eclipsing binaries.
Figure 30. BHB stars light curves corresponding to second category eclipsing binaries.
Figure 31. BHB stars light curves corresponding to second category eclipsing binaries.
Figure 3.2. BHB stars light curves corresponding to second category eclipsing binaries.

**References**

Alonso-García, J., Dékány, I., Catelan, M., et al. 2015, AJ, 149, 99

Bailey, S. I. 1902, AnHar, 38, 1

Balouev, R. 2012, MNRAS, 422, 3

Beers, T. C., Preston, G. W., & Shectman, S. A. 1988, ApJS, 67, 461

Beers, T. C., Rossi, S., Wilhelm, R. J., et al. 2007, ApJS, 168, 277

Beers, T. C., Wilhelm, R. J., Doinidis, S. P., & Mattson, C. 1996, ApJS, 103, 433

Brown, W., Beers, T. C., Wilhelm, R., et al. 2008, AJ, 135, 564

Brown, W., Geller, M., Kenyon, S., et al. 2004, ApJ, 127, 1555

Busso, G., Moehler, S., Zoccali, M., Heber, U., & Yi, S. K. 2005, ApJL, 633, L29

Carollo, D., Beers, T. C., Placco, V. M., et al. 2016, NatPh, 12, 1170

Catelan, M., Minniti, D., Lucas, P. W., et al. 2011, in Carnegie Observatories Astrophysics Ser. 5, RR Lyrae Stars, Metal-Poor Stars, and the Galaxy, ed. A. McWilliam (Pasadena, CA: The Observatories of the Carnegie Institution of Washington), 145

Chen, C. W., & Chen, W. P. 2010, ApJ, 721, 1790

Christlieb, N., Beers, T. C., Thom, C., et al. 2005, A&A, 431, 143

Clewley, L., & Jarvis, M. J. 2006, MNRAS, 368, 310

Cross, N. J. G., Collins, R. S., Hambly, N. C., et al. 2009, MNRAS, 399, 1730

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, yCat, 2246, 0

Emerson, J., & Sutherland, W. 2010, Msngr, 139, 2

Eyer, L., Rimoldini, L., Audard, M., et al. 2018, A&A, in press (arXiv:1804.09382)

Gran, F., Minniti, D., Saito, R. K., et al. 2016, A&A, 591, A145

Hambly, N. C., Mann, R. G., Bond, I., et al. 2004, Proc. SPIE, 5493, 423

Hodgkin, S. T., Irwin, M. J., Hewett, P. C., & Warren, S. J. 2009, MNRAS, 394, 675

Irwin, M. J., Lewis, J., & Hodgkin, S. 2004, Proc. SPIE, 5493, 411

Kallrath, J., & Milone, E. F. 2009, in Eclipsing Binary Stars: Modeling and Analysis (New York: Springer), 120

Koch, A., McWilliam, A., Preston, G. W., & Thompson, I. B. 2016, A&A, 587, 124

Lomb, N. R. 1976, Ap&SS, 39, 447

Minniti, D., Alonso-García, J., Braga, V., et al. 2017a, RNAAS, 1, 16

Minniti, D., Alonso-García, J., & Pullen, J. 2017b, RNAAS, 1, 54

Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, NewA, 15, 433

Minniti, D., Palma, T., Dékány, I., et al. 2017c, ApJL, 838, L14

Peterson, R. C., Terndrup, D. M., Sadler, E. M., & Walker, A. R. 2001, ApJ, 547, 240

Pier, J. R. 1982, AJ, 87, 1515

Piotto, G., Villanova, S., Bedin, L. R., et al. 2005, ApJ, 621, 777

Preston, G. W., Shectman, S. A., & Beers, T. C. 1991, ApJ, 375, 121

Prša, A., Batalha, N., Slawson, R. W., et al. 2011, AJ, 141, 83

Rozyczka, M., Thompson, I. B., Pych, W., et al. 2017, arXiv:1709.09572

Ruhlland, C., Bell, E. F., Rix, H. W., & Xue, X. X. 2011, ApJ, 731, 119

Saito, R. K., Hempel, M., Minniti, D., et al. 2012, A&A, 537, A107

Saito, R. K., Minniti, D., Dias, B., et al. 2012, A&A, 544, A147

Samus, N. N., Kazarovets, E. V., Durlevich, O. V., et al. 2017, ARep, 61, 80

Santucci, R. M., Beers, T. C., Placco, V. M., et al. 2015, ApJL, 813, L14

Scargle, J. D. 1982, ApJ, 263, 835

Smith, K. W., Buiter-Jones, C. A., Klement, R. J., & Xue, X. X. 2010, A&A, 522, A88

Smith, L. C., Lucas, P. W., Kurtev, R., et al. 2018, MNRAS, 474, 1826

Sommer-Larsen, J., Beers, T. C., Flynn, C., et al. 1997, ApJ, 481, 775

Terndrup, D. M., An, D., Hansen, A., et al. 2004, Ap&SS, 291, 247

Thom, C., Flynn, C., Bessell, M., et al. 2005, MNRAS, 360, 354

Xue, X.-X., Rix, H.-W., Zhao, G., et al. 2008, ApJ, 684, 1143

Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377

York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579

Zoccali, M., Renzini, A., Ortolani, S., et al. 2003, A&A, 399, 931