VVV SURVEY NEAR-INFRARED PHOTOMETRY OF KNOWN BULGE RR LYRAE STARS: THE DISTANCE TO THE GALACTIC CENTER AND ABSENCE OF A BARRLED DISTRIBUTION OF THE METAL-POOR POPULATION

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ABSTRACT

We have combined optical and near-infrared data of known RR Lyrae (RRL) stars in the bulge in order to study the spatial distribution of its metal-poor component by measuring precise reddening values and distances of 7663 fundamental-mode RRL stars with high-quality photometry. We obtain a distance to the Galactic center of $R_G = 8.33 \pm 0.05 \pm 0.14$ kpc. We find that the spatial distribution of the RRL stars differs from the structures traced by the predominantly metal-rich red clump (RC) stars. Unlike the RC stars, the RRL stars do not trace a strong bar, but have a more spheroidal, centrally concentrated distribution, showing only a slight elongation in its very center. We find a hint of bimodality in the density distribution at high southern latitudes ($b < -5^\circ$), which needs to be confirmed by extending the areal coverage of the current census. The different spatial distributions of the metal-rich and metal-poor stellar populations suggest that the Milky Way has a composite bulge.

Key words: Galaxy: bulge – Galaxy: stellar content – Galaxy: structure – stars: variables: RR Lyrae

Online-only material: color figures

1. INTRODUCTION

RR Lyrae stars are easily identifiable primary distance indicators, which can be used to trace the structure of the Milky Way. They sample an old and metal-poor population, and are particularly useful in the reddened regions of the Galactic bulge because of several reasons: (1) they have a relatively high number density in the bulge (e.g., Soszyński et al. 2011); (2) they follow precise period–luminosity (PL) relations in the near-infrared (NIR; e.g., Catelan et al. 2004); (3) their PL relations allow the determination of the interstellar extinction on a star-by-star basis; (4) their metallicities can be estimated using photometric data alone (e.g., Jurcsik & Kovács 1996; Smolec 2005); and (5) their brightness and amplitude ($0.1 \lesssim a_K \lesssim 0.5$ mag) make them detectable out to large distances.

The VISTA Variables in the Vía Láctea (VVV) ESO Public Survey (Minniti et al. 2010; Catelan et al. 2011; Saito et al. 2012) aims to probe the three-dimensional (3D) structure of the Galactic bulge using various distance indicators. In a series of papers, the VVV $ZJHK_s$ color atlas was used to trace the spatial distribution of red clump (RC) giants (Saito et al. 2011; Minniti et al. 2011; Gonzalez et al. 2011a), and to provide photometric reddening and metallicity maps of the bulge (Gonzalez et al. 2011b, 2012, 2013; Chen et al. 2013). The RC stars clearly trace a complex, X-shaped distribution, as was first suggested by McWilliam & Zoccali (2010) and Nataf et al. (2010). They are predominantly metal-rich, with the mode of their [Fe/H] distribution falling between $-0.5$ and $0$ dex, following a radial gradient (Zoccali et al. 2008; Johnson et al. 2011, 2013; Gonzalez et al. 2012). However, there is a more metal-poor population of stars present in the bulge. More than 16,000 RR Lyrae stars have been found in the bulge so far by the OGLE-III survey (Soszyński et al. 2011), and the census is still limited to a fraction of the complete bulge area. Their metallicity distribution is centered around [Fe/H] $= -1$ (Pietrukowicz et al. 2012) and has a very narrow spread, suggesting that they trace a more ancient stellar population with respect to the RC stars.

In this Letter, we analyze the spatial distribution of RR Lyrae stars from the OGLE-III catalog (Soszyński et al. 2011) by combining their $I$-band optical data with the available VVV $K_s$-band photometry. Our optical–NIR data set has some important advantages over optical studies. First, the PL relations have increasing precision and decreasing metallicity dependence toward longer NIR wavelengths (Catelan et al. 2004). The combined optical–NIR data allow us to rely primarily on the highly precise $K_s$-band relation—with the $I$-band one appearing only in the reddening estimation—and to leave out the very rough correlation between the absolute $V$-band magnitude and the metallicity from the analysis. This yields more precise distances by increasing the precision of both the absolute magnitudes and individual reddening values through the intrinsic color indices. Secondly, since NIR wavebands are much less sensitive to interstellar reddening than optical ones, and due to the wide wavelength separation between the $I$ and $K_s$ bands, the uncertainties in the intrinsic colors of the stars will cause much smaller errors in the reddening values ($R_{K_s-I} \ll R_{I-V-I}$), and in turn, the distances. Finally, the VVV $K_s$-band average magnitudes are more accurate than the Optical Gravitational Lensing Experiment (OGLE) $V$-band ones because of the higher phase coverage and smaller amplitude of the light-curves—increasing the accuracy of the distance determination.

2. THE VVV NIR PHOTOMETRY OF THE OGLE RR LYRAE STARS

Our study is based on VVV $K_s$ photometric data provided by the VISTA Data Flow System (see Emerson et al. 2004),

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6 Also at The Milky Way Millennium Nucleus, Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile.
7 Also at Vatican Observatory, V-00120 Vatican City State, Italy.
8 http://mill.astro.puc.cl/BEAM/calculator.php
acquired between 2009 October 19 and 2012 September 28. We used magnitudes measured on single detector frame stacks (a.k.a. "pawprints") by aperture photometry, using small, flux-corrected apertures, suitable for moderately crowded stellar fields (Irwin et al. 2004). The number of observational epochs varies between ~20 and 60, depending on the brightness and the location of the object. The limiting $K_s$ magnitude ranges from ~18.0 to ~16.5 mag (depending on the Galactic latitude), which is enough to detect RR Lyrae stars all the way through the Galaxy, even with high interstellar extinction.

We performed a positional cross-matching procedure between sources extracted from VVV images and the complete catalog of 11756 fundamental-mode RR Lyrae (type RRab) stars from the OGLE-III survey (Soszyński et al. 2011) using the STILTS7 software. In order to rule out photometric contamination by seeing-dependent source merging, nearby saturated stars, spurious signals, etc., we excluded all data points with cross-matching separations larger than 0′.35 ~ 1 pixel (less than 10% of all data) or lying closer to the detector edges than the jitter offset, and only considered sources with morphological classifications of −1, −2 or 1 (see Saito et al. 2012). The procedure resulted in our initial database of 9694 $K_s$-band light-curves with OGLE-III $I$-band counterparts.

We computed precise mean $K_s$-band magnitudes for each star by employing the template Fourier fitting method of Kovács & Kupi (2007), using linear scaling of sixth-order Fourier-sums fitted to the template light-curves of Jones et al. (1996), and iteratively omitting outliers during the procedure. Figure 1 illustrates our data quality showing a typical light-curve with the fitted template. In order to reject light-curves dominated by noise or systematic variations, we rejected all light-curves with $a\sqrt{N}/\sigma < 25$, where $a$ is the total amplitude of the template fit, $\sigma$ is the standard deviation of the residual, and $N$ is the number of data points. The above limit was set by a visual inspection of ~10% of all fitted light-curves, and resulted in the rejection of ~20% of light-curves in our initial sample. For minimizing the presence of systematic errors in the computed distances, we required the light-curves to comply with the following set of further selection criteria. We rejected all light-curves having a phase coverage8 less than 0.6, and $\sigma > 0.1$ mag. Furthermore, to exclude sources suspected to be affected by blending or fitting runaways, we omitted stars outside the amplitude threshold of

![Figure 1. VVV $K_s$-band light-curve of a bulge RRab star with the fitted template. The identifier and period of the star are shown in the header.](image)

![Figure 2. Galactic coordinates of our final sample of 7663 OGLE-III RRab stars (dots) in the bulge area of the VVV Survey. The VVV bulge subfields are shown by an overlaying grid. The grayscale background shows the interstellar extinction map of Schlegel et al. (1998).](image)

0.08 < $a_{K_s}$ < 0.6. By applying these cuts, we obtained our final sample of 7663 RRab light-curves. Figure 2 shows the location of the these sources in comparison with the bulge area covered by the VVV Survey. The various cuts in the sample does not result in any bias in the $(l, b)$ distribution of the objects, and yields an increased relative precision in the traced spatial distribution out to high distances. The cost of this gain is a slightly increased incompleteness toward the far side of the bulge, due to the preference for rejecting faint stars, since their light-curves are more noisy and have less data.

3. DISTANCES TO THE RR LYRAE STARS

We derived the absolute $K_s$ and $I$ magnitudes of the stars using the theoretical period–luminosity–metallicity (PLZ) relations from Catelan et al. (2004), estimating the apparent equilibrium brightnesses of the stars with their intensity-averaged mean magnitudes obtained from the template-fitting procedure (see Section 2). Since the original $K$-band relation in the above study is given in the Glass system, first we transformed the $K$ magnitudes for each and every individual synthetic star in the Catelan et al. (2004) synthetic horizontal-branch populations into the VISTA filter system. For this purpose, we used Equations (A1)–(A3) from Carpenter (2001) to transform first into the Two Micron All Sky Survey system, and then the

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7 http://www.star.bristol.ac.uk/~mbt/stilts/
8 1 minus the maximum phase lag.
equations provided by CASU\(^9\) for transforming these into the VISTA system. We then recomputed all the linear regressions, leading to the following relation for the VISTA \(K_s\) band:

\[
M_{K_s} = -0.6365 - 2.347 \log P + 0.1747 \log Z.
\]  

(1)

In estimating the log \(Z\) values of the RRab stars, we used the exact same approach as Pietrukowicz et al. (2012), applying the empirical \(P, \phi_{31} \rightarrow [\text{Fe/H}]\) relation of Smolec (2005) with the periods and phase differences derived from the OGLE-III \(I\)-band light-curves (as provided by Soszyński et al. 2011).

We determined the color excess of each star by comparing its observed color index to the intrinsic one predicted by the theoretical PLZ relations:

\[
E(I - K_s) = (I - K_s) - (M_I - M_{K_s}).
\]  

(2)

For converting the color excess values into absolute extinction in the \(K_s\) band, we adopted the reddening law of Cardelli et al. (1989) with \(R_V = 3.1\). Using their Equations (2a-b) and (3a-b) with an effective wavelength of \(\lambda_{\text{eff}} = 0.798 \mu m\) for the Cousins \(I\)-band and \(\lambda_{\text{eff}} = 2.149 \mu m\) for the VISTA \(K_s\)-band, we obtained the following relation:

\[
A_{K_s} = 0.164 E(I - K_s).
\]  

(3)

We note that due to the large wavelength difference between the bands, the coefficient in this relation changes only marginally (to the value of 0.160) if we adopt \(R_V = 2.5\), as recently suggested by Nataf et al. (2013).

Finally, we calculated the individual distances to our bulge RRab sample using the relation

\[
\log R = 1 + 0.2(K_{s,0} - M_{K_s}).
\]  

(4)

where \(K_{s,0}\) is the extinction-corrected \(K_s\)-band magnitude.

The precision of the resulting distances to individual stars is significantly higher than in earlier studies due to the advantages of NIR photometry mentioned in Section 1. The typical accuracy of the average \(K_s\) magnitudes obtained from the template fitting procedure is between 0.01–0.02 mag, depending on the amplitude and the brightness of the star—which is similar to the 0.02 mag nominal accuracy of the \(I\)-band average magnitudes. The internal dispersion of the photometric metallicity estimator is 0.18 dex (Smolec 2005), and its observational error is dominated by the error in \(\phi_{31}\), which is determined by the quality of the \(I\)-band light-curves, and which is negligible for most of the stars in our sample, according to Pietrukowicz et al. (2012). The error in log \(Z\) propagates into the distance through both \(M_{K_s}\) and \(A(K_s)\), but the latter gives only a marginal contribution due to the very low ratio of absolute to selective extinction. Assuming a median statistical error of 0.18 dex in \(\log Z\), and 0.02 mag for the error in the average magnitudes in both bands, we get a statistical error of only 0.01 mag in \(A(K_s)\). The errors propagate into a statistical uncertainty of only 0.053 mag in the extinction-corrected distance moduli, which converts into a distance error of 0.2 kpc for a star at a distance of 8.5 kpc. This is less than half the median statistical error in the distances obtained from optical photometry, as quoted by Pietrukowicz et al. (2012).

In addition to the statistical errors discussed above, there might be a significant net systematic error in the distances, originating from various different sources. A detailed exploration of the possible sources of systematic errors is out of the scope of this Letter; here we merely use a relevant globular cluster study as reference. Coppola et al. (2011) provide a detailed comparison of various recent PL/PLZ relations through the distance determination of the globular cluster M5, based on a sizable sample of RR Lyrae stars; and the resulting distance moduli from different empirical and theoretical relations are within \(1\sigma\) agreement, showing a high reliability of the method. Since this cluster is located at a similar distance as the Galactic center (GC), the spread of 0.07 mag in the distance moduli obtained from four different relations for RRab stars in their study is highly indicative of the possible mean systematic error in our analysis. Therefore, we adopted a mean systematic distance error of 0.14 kpc, corresponding to the same error in the distance modulus at the distance of the GC (see Section 4).

4. THE DISTANCE TO THE GALACTIC CENTER

We determined the center of the RR Lyrae distribution by first projecting the individual distances to the Galactic plane, and then correcting the distance distribution for the distorting effect of our sample being distributed in a solid angle, thus observing more objects at larger distances (i.e., we scaled the distribution by \(R^{-2}\)). Figure 3 shows the histogram of the projected distances of all RRab stars in our \textit{final sample} based on the combined \(IK_s\) photometry, before and after correcting for the aforementioned “cone-effect.” We measured the center of the RR Lyrae spatial distribution (assumed to coincide with the GC, \(R_0\)) by determining the center of the density function of the best-fitting analytical distribution. We found that the distance distribution shows a very significant non-normality due to its heavy tails, and can be best represented by the Student’s \(t\)-distribution. This is consistent with the result of Pietrukowicz et al. (2012), who found that the Cauchy–Lorentz\(^{10}\) distribution fits best the distances obtained from the optical data.

The distribution of RR Lyrae distances shows a natural asymmetry toward higher distances due to the “cone-effect.” In our case, the distribution is further perturbed by our rejection procedure (see Section 2), resulting in a slight incompleteness at higher distances (since the light-curves of fainter stars have

\(^9\) http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/photometric-properties/sky-brightness-variation/view

\(^{10}\) Student’s \(t\)-distribution with 1 degree of freedom.
5. THE SPATIAL DISTRIBUTION OF RR LYRAE STARS

The distribution of RC giants in the bulge is known to be barred (Stanek et al. 1997; Cao et al. 2013). Figure 4 shows the spatial distribution of the RRab stars obtained in the present study at various latitudinal stripes at negative latitudes, where our sample has sufficiently high number density. The stars show a centrally concentrated distribution at all latitudes. Figure 4(a) shows all stars in our final sample—note that the elongation along the line of sight (LOS) is an observational bias due to our incomplete longitudinal coverage. It already implies, however, that the RR Lyrae stars do not trace an inclined prominent bar like the RC stars do. Figures 4(b)–(e) show latitudinal subsets of the distribution. The longitudinal coverage between \( l = \pm 5^\circ \) is very close to contiguous at \(-4.5 < b < -2.5\) and fully contiguous at \(-4^\circ < b < -3^\circ \) (see Figure 2), therefore the distribution is free of any significant bias between these longitudes. The longitudinal ranges of contiguous coverage are more confined at higher southern latitudes, but should still be free from a significant bias between \( l = +2.5^\circ \) and \(-5^\circ \) approximately (Figures 4(d) and (e)).

In Figures 4(b)–(e), we compare the spatial distributions with the observed orientation of the Galactic bar traced by RC stars at different southern latitudes (data are taken from Gonzalez et al. 2011a, 2012, see their Figures 3 and 10, respectively). It is immediately visible that the spatial distribution of RR Lyrae stars is not significantly barred at any of these latitudes. At latitudes \(-4.5 < b < -2.5\), the distribution shows a slight elongation within the inner 1 kpc. This small substructure is inclined by only \(-12.5 \pm 0.5\) with respect to the LOS toward the GC, obtained by fitting elliptical centroids to the distribution with 0.2 kpc binning over a grid of small \((X, Y)\) offsets of the bin positions. Our findings are in contrast with the results of Pietrukowicz et al. (2012), that showed a more inclined and longer bar-like substructure at certain negative latitudes based on the study of \(V, I\) optical data from the OGLE-III survey. We note again however, that our combined optical–NIR data has superior statistical quality due to the various arguments discussed in Section 3, providing extinction and distance values with significantly higher relative precision.

The spatial distribution at higher southern latitudes \((b < -5^\circ)\) has a significantly wider peak between distances of 7.7 and 9.7 kpc, approximately. It also shows a hint of bimodality, having a secondary maximum in the number density distribution at a distance of 9.6 kpc. It is somewhat reminiscent of the split distribution we see in the case of RC stars due to the split arms of the X-shaped structure toward more negative latitudes. However, the dip test of Hartigan & Hartigan (1985), indicates only marginally significant bimodality (2\(\sigma\)). Unfortunately, the current census does not extend to sufficiently high southern latitudes, preventing us from getting a true picture on this.
possible substructure; a larger sample of RR Lyrae from a more extended bulge area is required.

6. CONCLUSIONS

We combined NIR (VVV) and optical (OGLE-III) photometric data in order to measure precise redenings and distances for bulge RR Lyrae stars with high-quality light-curves. Our data are only little affected by the large and non-uniform interstellar extinction in these regions, allowing us to reach higher precision. We derive a distance to the GC of $R_0 = 8.33 \pm 0.05 \pm 0.14$ kpc. We find that the distribution of fundamental-mode RR Lyrae stars is different from the known distribution of RC giants. The most striking fact is that the RR Lyrae stars do not show a strong bar in the direction of the Galactic bulge as do the clump giants, but their distribution is more spherical, with only the central $\sim 1$ kpc showing a bar-like substructure.

In recent years, the structure of the bulge has been discovered to be more complex than just a simple bar. It is now well-established that the predominantly metal-rich bulge RC stars trace an X-shaped structure (McWilliam & Zoccali 2010; Nataf et al. 2010; Saito et al. 2011; Gonzalez et al. 2012). Recently, Ness et al. (2012, 2013) found that this structure disappears from the RC distribution at low metallicities. The observed prominent difference between the 3D structures traced by the RC and metal-poor RR Lyrae stars is in line with their findings, and suggests that the Milky Way has a composite bulge, retaining an older, more spheroidal bulge component (see, e.g., Samland & Gerhard 2003; Obreja et al. 2013). The existence of a small, central bar-like structure in such a component like the one traced by the RR Lyrae stars is consistent with current numerical simulations of composite bulges, and is a result of the angular momentum transfer between the bar and the initial classical bulge during their co-evolution (Saha & Gerhard 2013).

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