Draft version September 7, 2016
Preprint typeset using LaTeX style AASTeX6 v. 1.0

VVV SURVEY RR LYRAE IN THE NUCLEAR BULGE OF THE MILKY WAY AND THE FORMATION OF THE GALACTIC NUCLEI

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ABSTRACT

Galactic nuclei, like the one of the Milky Way, are extreme places with high stellar densities and, in most cases, hosting a supermassive black hole. One of the scenarios proposed for the formation of the Galactic nucleus is by merging of primordial globular clusters (Capuzzo-Dolcetta 1993). An implication of this model is that this region should host stars characteristically found in old Milky Way globular clusters. RR Lyrae stars are primary distance indicators, well known representatives of old and metal-poor stellar populations, and therefore regularly found in globular clusters. Here we report the discovery of a dozen RR Lyrae ab-type stars in the vicinity of the Galactic center, i.e. in the so-called nuclear stellar bulge of the Milky Way. This discovery provides the first direct observational evidence that the Galactic nuclear stellar bulge contains ancient stars (>10 Gyr old). Based on this we conclude that merging globular clusters likely contributed to building-up the high stellar density in the nuclear stellar bulge of the Milky Way.

Keywords: editorials, notices — miscellaneous — catalogs — surveys

1. INTRODUCTION

There are very limited observational tests that can be applied to shed light on the origins of galactic nuclei, with their stars and black holes. The only galactic nucleus where detailed stellar population properties can be derived with sufficiently high resolution and accuracy is that of the Milky Way, making it therefore a fundamental testbed for different formation models. There we can in principle resolve individual stars, probing a wide range of stellar ages and metallicities. There are two main scenarios proposed for the formation of the nuclear bulge of the Milky Way, and of all galactic nuclei in general: merging of globular clusters (Tremaine et al. 1975; Capuzzo-Dolcetta 1993; Gnedin et al. 2014; Guillard et al. 2016), and fast gas accretion and star formation onto the central region (Milosavljević 2004; Schinnerer et al. 2008).

Here we concentrate on testing the first of these theories. In that scenario, dynamical friction causes orbital decay, dragging globular clusters deep into the potential well, where they merge and form a high density nuclear bulge with a nuclear star cluster at its center. While merging globular clusters typically bring in old-stellar populations, comparison with observations requires some additional in situ star formation (Antonini et al. 2015), or sub-sequent growth of the newly formed nuclear cluster via wet merger with other clusters that bring with them additional gas reservoirs that contribute younger stars (Guillard et al. 2016). Therefore, young or intermediate-age stellar populations often dominate the total light in galactic nuclei, even in those cases where they make a minor contribution total the total stellar mass. It is then very difficult, in an environment like the Galactic center, to establish the presence of the ancient stellar populations, and to estimate their ages and metallicities. Such old populations must be present if the nuclear bulge of the Milky Way was made by merging of primordial globular clusters (Capuzzo-Dolcetta 1993).

Theoretically, if the nuclear stellar bulge formed by merging of several globular clusters, the expected extension of the final merger product is about 100pc (Capuzzo-Dolcetta 1993; Gnedin et al. 2014; Antonini et al. 2012; Antonini 2014). This size appears to be obtained by the simulations regardless the presence or absence of a central massive black hole (Capuzzo-Dolcetta 1993; Antonini et al. 2012; Antonini 2014; Capuzzo-Dolcetta & Miocchi 2008; Capuzzo-Dolcetta & Mastrobuono-Battisti 2009).

Observationally, the nuclear stellar bulge of the Milky Way is well fit by two components: the nuclear star cluster, a compact component with half-light radius of 4 pc (2 arcmin) that dominates the inner 30 pc, and the nuclear stellar bulge, a shallower component extending out to about 120 pc (Launhardt et al. 2002). This size is comparable to the sizes of well studied nuclear stellar bulges of other external galaxies (Hartmann et al. 2011; Carollo et al. 2002; Lotz et al. 2001).

As globular clusters are tidally disrupted, they yield their stars, including RR Lyrae, to the field. So far, there has been no search for variable stars deep enough to find RR Lyrae in the complex Galactic center region. However, this can now be tested observationally with the VISTA Variables in the Via Lactea (VVV) ESO public survey (Minniti et al. 2010; Saito et al. 2012), that contains deep multi-epoch photometry in the near-IR, allowing to find faint variable sources.

In the present search we also find numerous bright LPVs/Miras, eclipsing binaries, Cepheids, and microlensing events, which would be reported elsewhere. We concentrate here only on the RR Lyrae because in this context they play a crucial role. Their properties make them prime representatives of the primordial stellar populations of the Milky Way: (a) they have a well known Period-Luminosity relation, and are therefore excellent distance indicators; (b) they have a very narrow range of intrinsic colors that make them excellent reddening indicators; and (c) they are old (age >10 Gyr), and metal-poor (i.e. $[Fe/H] < -0.5$).

2. VVV SURVEY PHOTOMETRY

The limiting magnitudes ($K_s \sim 18$ mag, $J \sim 20$ mag) and spatial resolution (∼0.8 arcsec) of the near-IR data provided by the VVV survey enable for the first time a successfully search of RR Lyrae throughout the Galactic center region. The PSF-fitting photometry of the individual VVV images for ∼100 epochs of the tiles b333 and b334 was carried out following the procedure described by Alonso-García et al. (2015); Minniti et al. (2015). The search for periodic variable stars, phasing of the light curves, and classification of the RR Lyrae type ab were made following the strategies outlined by Gran et al. (2016); Dékány et al. (2013). We searched for RR Lyrae with magnitudes $12 < Ks < 17$, amplitudes $0.2 < A < 1.0$, periods $0.3 < P < 1.0$ days.

Extreme crowding and extinction variations are clearly evident in near-IR images taken by the VVV survey (Figure 1). Searching for RR Lyrae in the most crowded and reddened region of the Milky Way is therefore a daunting task, in which several problems need to be faced and sorted out. Specifically, the completeness depends on the position in the field, as these are near-IR mosaics. The stellar density is very high, and the presence of numerous saturated stars in the field that obliterate their surroundings is a limiting factor in the photometry. In addition, the large and differential reddening, highly variable even on small spatial scale, affects the photometric completeness, although the effect is less severe than the crowding. Indeed, the VVV photometry is generally deep enough to reach well below the RR Lyrae region of the color-magnitude diagram even in the most reddened region at the distance of the Galactic center (Figure 2). The photometric completeness in this region measured from red clump giants at $14.3 < K_s < 15.9$, the magnitude range of the spanned by the observed RR Lyrae, has an average value of 80% (Valenti et al. 2016). However, the variable seeing and uneven sampling of the observed epochs contribute to further reduce the completeness of our sample. The faint magnitudes of the targets also prevent us from finding/classifying RR Lyrae that have very small amplitudes (< 0.2 mag).

For all these reasons, we do not claim full completeness for the detection of RR Lyrae, but conversely we expect many more to be found in dedicated high resolution deep searches that might enable to establish the total RR Lyrae density number in the Galactic center region.

The shape of the light curves is also an important limiting factor, with contamination from eclipsing binaries being a serious problem for the sinusoidal light curves, and therefore limiting us to select mostly RRab with asymmetric light curves. The total number of epochs (i.e. points in the light curves) is ∼100 epochs, generally sufficient to select RR Lyrae with confidence. However, sampling is a problem, with many good candidates that need to be discarded as aliases. We therefore have many more RR Lyrae candidates for which additional observations are needed in order to measure their periods accurately. These observations would be acquired in the next 3 years as part of the VVV extended survey (VVVX).

3. THE INNERMOST RR LYRAE

We report here the discovery of a dozen RR Lyrae type ab (fundamental mode pulsators) stars within 36 arcmin (84 pc) from the Galactic center (Figure 1), plus a couple of c-type RRLyrae (pulsating in their first overtone). We measure accurate positions, projected distances from the Galactic center, mean IR magnitudes and colors, periods, and amplitudes for all of our targets (Table 1). The clear variability signature of RR Lyrae, including their characteristic saw-tooth light curve shape, and their measured amplitudes and periods, are the unambiguous signatures that we are detecting individual ancient and faint RR Lyrae, and not stellar blends or other artefacts.

We also found a candidate type II Cepheid at a projected distance of 45pc (20 arcmin) from the Galactic center. This type II Cepheid with P= 1.809 days, mean $K_s = 14.66$, and $(J - K_s) = 4.02$, is also representative of an old and metal-poor population present in the vicinity of the nuclear star cluster. A fundamental implication about the old age of the variable stars found here is that the nuclear stellar bulge must have been in place since the origins of the Milky Way. In addition, we discovered several more bonafide RR Lyrae over a wider area, within 36 - 50 arcmin (84 - 109 pc) of the Galactic center, just outside of the nuclear bulge.

The near-IR color-magnitude diagram obtained from PSF fitting photometry shows the high extinction of the field where these RR Lyrae have been discovered (Figure 2). The target RR Lyrae are fainter and bluer than the bulge red clump giants. When taking into account the large extinction difference across the bulge, the comparison of the color-magnitude diagram of these RR Lyrae and in other regions of the bulge (Minniti et al. 2010; Saito et al. 2012) is consistent with them being RR Lyrae located in the region of the Galactic center.

3.1. *Extinction corrections*

Extinction corrections to the measured near-IR magnitudes is a mandatory step in order to assess the location of the sample RR Lyrae within the Galactic nucleus. The RR Lyrae lie in the instability strip, which is a narrow band in the color-magnitude diagram, and their intrinsic colors can be assumed to be $(J - K)_0 = 0.15 \pm 0.05$ mag. Although we only have K_s-band light curves and a single (or a few) J-band epoch, the color corrections for de-reddened RR Lyrae due to the single J-band observation is negligible (Gran et al. 2016; Dékány et al. 2013). In fact, the color variation along the light curves is typically small in the near-IR ($\Delta(J - K_s) < 0.05$ mag). When computing the reddening for a specific target, the most important systematic error is the uncertain slope of the reddening law (Gonzalez et al. 2012; Nataf et al. 2016; Majaess et al. 2016). For example, comparing $A_k = 0.528E(J - K)$ given by Nishiyama et al. (2009) with $A_k = 0.72E(J - K)$ from Cardelli et al. (1989), and $A_k = 0.435E(J - K)$ from Alonso-García et al. (2015), the corresponding differences for the typical extinction values of the Galactic center region ($E(J - K) \sim 3.0$ to 4.0) are significant. Adopting the most recent value given by Alonso-García et al. (2015) that applies to the VVV data, and that also agrees with the slope of the reddened red giant clump seen in the color-magnitude diagram (Figure 2), we find for each candidate the reddening $E(J - K_s)$ and extinction A_k listed in Table 2.

3.2. *Metallicities*

In order to explore the properties of globular clusters that could have initially formed the Galactic nuclear bulge, we examine the properties of the Oosterhoff types I and II globular cluster populations (Oosterhoff 1939; Catelan 2009). A way to distinguish between these two populations is by measuring the average periods of their RR Lyrae, which are shorter in the mean for type I ($< P >= 0.55$ days) than for type II Oosterhoff cluster populations ($< P >= 0.65$ days) (Catelan 2009). We find that the distribution of periods of the nuclear bulge RR Lyrae has a mean of $P = 0.55$ days, resembling an Oosterhoff type I population (more metal-rich than $[Fe/H] = -1.6$ dex).

Alternatively, the mean metallicities for RR Lyrae type ab can be estimated using their period-amplitude-metallicity relation. After discarding the RR Lyrae type c, we obtain mean metallicities $< [Fe/H] >$=-1.0, -1.4, and -1.3 dex for the sample RR Lyrae using the calibrations from Alcock et al. (2000); Yang et al. (2010); Feast et al. (2010), respectively.

The Bailey diagram is shown in Figure 3, in comparison with the bulge RR Lyrae. The resulting individual metallicities using the Galactic RR Lyrae calibration from Feast et al. (2010) (that should only be taken as indicative until spectroscopic measurements become available), are listed in Table 2. Therefore, we suggest that most of the merged clusters were Oosterhoff type I globulars (with $-1.6 < [Fe/H] < -0.9$ dex). Even though we cannot discard that a few of the primordial globular clusters that merged into the nuclear stellar bulge might have been very metal-poor (with $[Fe/H] < -2$ dex like VVV-RRL-40405), they do not appear to be the dominant population. Interestingly, the star VVV-RRL-40405 that is located only 16 arcmin away from the Galactic center is the most metal-poor star of this sample, with $[Fe/H] \sim -2.2$ dex. This very metal-poor object is the first RR Lyrae that is a likely member of the nuclear star cluster. Knowing its intrinsic color, distance, and extinction (Table 2), we can estimate its visual magnitude, V = 29.5 mag, much too faint and out of reach for current optical instruments.

3.3. *Distances*

In order to compute distances we also have to take into account the different sources of errors. An important systematic error is the absolute magnitude scale for the period-luminosity (P-L) relation. We make two different assumptions to compute distances, in order to illustrate the uncertainties involved. First (case 1), we use the P-L relation given by eq. 14 from Muraveva et al. (2015) that is based on the cleanest sample of Hipparcos and HST RR Lyrae parallaxes, and the extinctions listed in Table 2, obtaining distances that are consistent with membership to the Galactic nuclear bulge. Second (case 2), as the P-L relation also depends on the chemical composition (the so-called P-L-Z relation), assuming that these RR Lyrae are the debris of Oosterhoff type I globular clusters, we adopt a mean $[Fe/H] = -1.0$ dex in the P-L-Z relation of Alonso-García et al. (2015), as well as a steeper extinction law from Nishiyama et al. (2009). In this way we also obtain distances that are consistent with membership to the Galactic nuclear bulge, but larger in the mean by about 500 pc that in the first case considered above. For both cases, Table 2 summarizes the RR Lyrae reddenings, extinctions, distance moduli and distances in kpc from the Sun, and metallicities. In all this we have also assumed that the photometric VVV zero point error is negligible (< 0.01 mag).

The distance distributions of the RR Lyrae in our sample compared with 1019 RR Lyrae type ab recently discovered in the outer bulge from the VVV survey (Gran et al. 2016) have consistent peak values. The distribution of the present sample is very concentrated, much more so than the observed distribution of RR Lyrae in the inner and outer bulge. Considering all these uncertainties, we can conclude that most of our RR Lyrae are located at the distance of the Galactic center. Only two of the brightest ones (VVV-RRL-65743, and VVV-RRL-55144) could be foreground objects, although we cannot completely discard the possibility that they are blended sources. The two main types of sources that brighten an object in this region would be bulge clump stars (which are redder), or foreground disk stars (which are bluer). However, the colors alone cannot help to distinguish these possibilities given the large and non-uniform reddening.

4. CONCLUSIONS

For the first time, we find that there are RR Lyrae in the region well within the nuclear stellar bulge of our Galaxy, suggesting that they could be the remains of the primordial globular clusters that built up the nuclear bulge. The dozen RR Lyrae stars presented here give a limit to the age and metallicity of the nuclear bulge, and thus provide valuable clues about its origin. While there is ample evidence that the stellar population of the nuclear star cluster is composite, containing a mixture of young, intermediate and old stellar populations (Genzel et al. 2010; Schödel et al. 2014; Chatzopoulos et al. 2015), the RR Lyrae stars we found suggest that the nuclear bulge is very old (> 10 Gyr), perhaps as old as the Milky Way itself.

Are these RR Lyrae special in any way? How do they compare with the RR Lyrae previously found in the Milky Way bulge? RR Lyrae are numerous in globular clusters and in the Milky Way halo, and are taken as prime tracers of old (>10 Gyr), and metal-poor stellar populations. However, not all globular cluster RR Lyrae are similar. For example, there are two populations of globular clusters (Oosterhoff 1939; Catelan 2009): the Oosterhoff type I clusters, that are more metal-rich ($-0.9 < [Fe/H] < -1.6$ dex), and the Oosterhoff type II clusters, that are more metal-poor ($[Fe/H] < -1.6$ dex). With a mean period of $< P >= 0.55$ days, most of the RR Lyrae discovered here are representative of an Oosterhoff type I population (Figure 3).

Overall, the properties of the present sample are consistent with the bulge RR Lyrae population (Gran et al. 2016), being more concentrated to the Galactic centre. The evidence supports the scenario where the nuclear stellar bulge was originally made out of a few globular clusters that merged through dynamical friction (Capuzzo-Dolcetta 1993; Guillard et al. 2016), and as such it could well be the most massive and oldest surviving star cluster of our Galaxy.

Table 1. Photometric Observations

ID	RA (J2000)	DEC (J2000)	R arcmin	K_s	J	$(J-K_s)$	P days	A
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
40405	266.17164326	-28.86342987	15.5	15.78	20.05	4.27	0.780597	0.323
65743	266.40425763	-29.31187570	18.3	14.27	18.17	3.90	0.594484	0.223
55278	266.79651367	-29.08202592	20.4	15.60	19.07	3.47	0.624883	0.353
37068	266.28880383	-28.68220478	20.7	15.26	18.34	2.98	0.618563	0.299
80042	266.62151461	-28.71032145	20.8	15.44	18.63	3.19	0.408153	0.286
84844	266.06131561	-28.83296846	21.4	15.87	19.69	3.82	0.549641	0.364
58214	266.11652879	-28.65279182	26.5	15.79	18.87	3.08	0.403153	0.264
55144	266.10448919	-28.65918014	26.6	14.64	18.00	3.36	0.508399	0.389
89691	266.24177968	-28.58633606	26.9	15.74	19.33	3.59	0.376027	0.249
33007	266.92238653	-28.83231159	28.6	15.27	18.74	3.47	0.621276	0.241
42332	266.10220084	-28.61729278	28.7	15.34	17.93	2.59	0.520099	0.298
65271	266.26347962	-28.47343076	33.1	14.81	17.75	2.94	0.369534	0.298
8444	266.09247811	-28.51255523	34.3	15.52	18.60	3.08	0.487035	0.437
33289	266.20795127	-28.43858475	35.9	15.58	18.61	3.03	0.480476	0.325

Table 2. Measured stellar parameters

ID	$E(J-K_s)$	A_K	$(m-M)_0$ [a]	$D_\odot$ [a] kpc	$(m-M)_0$ [b]	$D_\odot$ [b] kpc	$[Fe/H]$ dex	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
40405	4.12	1.79	14.67	8.6	14.92	9.6	-2.2	RRab
65743	3.75	1.63	13.02	4.0	13.27	4.5	-1.5	RRab foreground?
55278	3.32	1.44	14.59	8.3	14.85	9.3	-1.6	RRab
37068	2.83	1.23	14.45	7.8	14.67	8.6	-1.6	RRab
80042	3.04	1.32	14.09	6.6	14.32	7.3	-0.6	RRab-c
84844	3.67	1.60	14.56	8.2	14.82	9.2	-1.3	RRab
58214	2.93	1.27	14.47	7.8	14.71	8.8	-0.6	RRab-c
55144	3.21	1.40	13.45	4.9	13.70	5.5	-1.2	RRab foreground?
89691	3.44	1.50	14.12	6.7	14.36	7.4	-0.5	RRc
33007	3.32	1.44	14.26	7.1	14.50	7.9	-1.6	RRab
42332	2.44	1.06	14.51	8.0	14.75	8.9	-1.2	RRab
65271	2.79	1.21	13.54	5.1	13.69	5.8	-0.4	RRc
8444	2.93	1.27	14.41	7.6	14.66	8.6	-1.1	RRab

Table 2 continued on next page

Table 2 *(continued)*

ID	$E(J-K_s)$	A_K	$(m-M)_0$ [a]	$D_\odot$ [a] kpc	$(m-M)_0$ [b]	$D_\odot$ [b] kpc	$[Fe/H]$ dex	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
33289	2.88	1.25	14.47	7.8	14.72	8.8	-1.0	RRab

[a] *Case 1*: By using the P-L relation given by eq. 14 from Muraveva et al. (2015) and the extinctions listed in Table 1

[b] *Case 2*: By using the P-L-Z relation of Alonso-García et al. (2015) and assuming a mean $[Fe/H] = -1$ dex

We gratefully acknowledge the use of data from the VVV ESO Public Survey program ID 179.B-2002 taken with the VISTA telescope, and data products from the Cambridge Astronomical Survey Unit (CASU). The VVV Survey data are made public at the ESO Archive. Support for the authors is provided by the BASAL Center for Astrophysics and Associated Technologies (CATA) through grant PFB-06, and the Ministry for the Economy, Development, and Tourism, Programa Iniciativa Cientifica Milenio through grant IC120009, awarded to the Millennium Institute of Astrophysics (MAS). D.M. acknowledges support from FONDECYT Regular grants No. 1130196. M.Z. and F.G. acknowledge support from FONDECYT Regular grants No. 1150345.

Facilities: ESO, VIRCAM@VISTA

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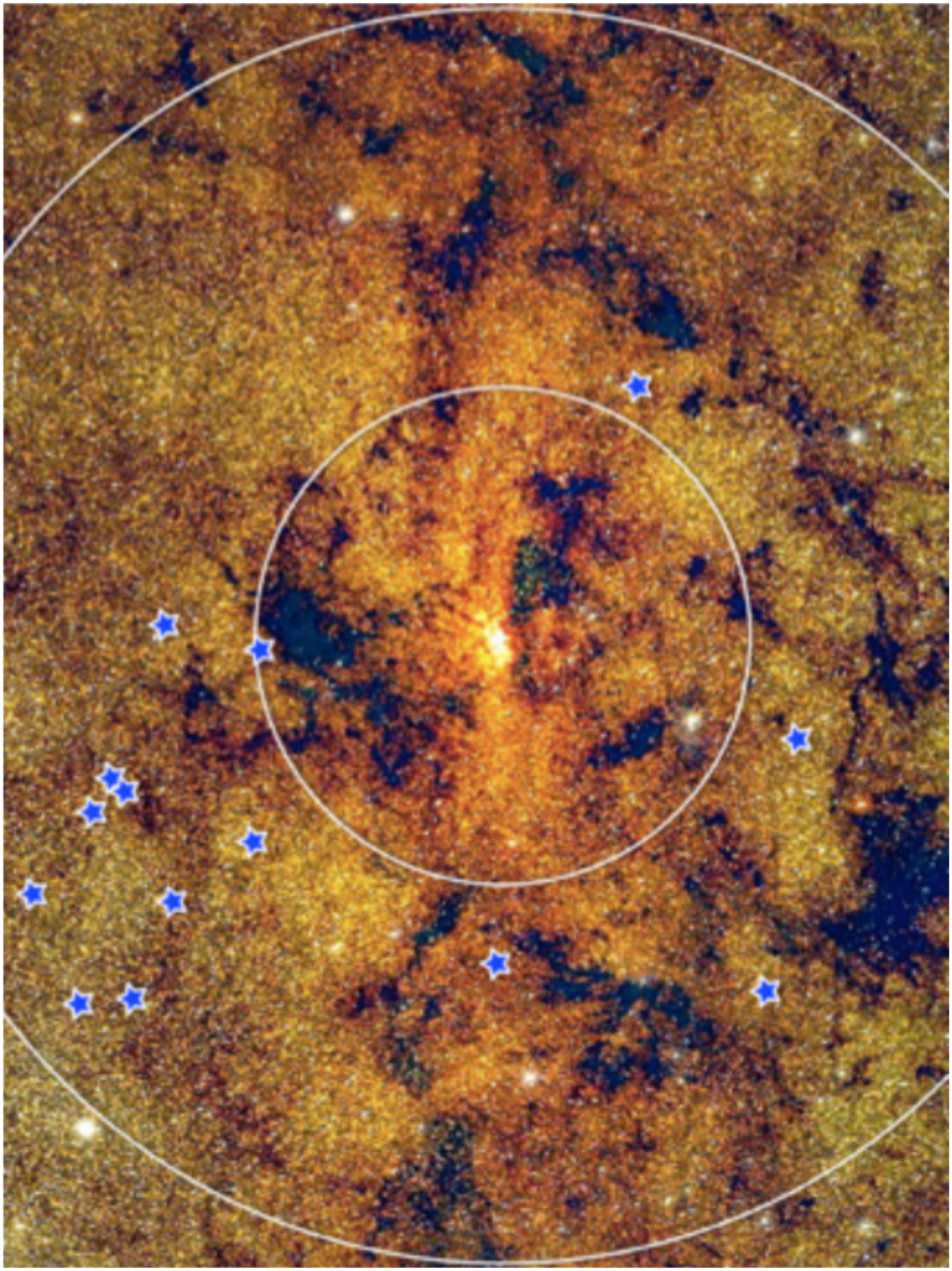

Figure 1. Location of the RR Lyrae type ab stars. Near infrared JHKs color image of the Galactic center region from the VVV survey (Minniti et al. 2010). The extensions of the nuclear star cluster (R∼35 pc), and the nuclear bulge (R∼100 pc) are indicated with the small and large circles, respectively. One of the leading theories for the formation of the nuclear bulge of the Milky Way is by merging of primordial globular clusters (Launhardt et al. 2002). The RR Lyrae from these disrupted clusters are now found throughout this central region (blue stars). One of them (VVV-RRL-40405) has measured distance and reddening consistent with membership to the innermost nuclear star cluster, with a projected distance of 16 arcmin (35 pc) from the Galactic center.

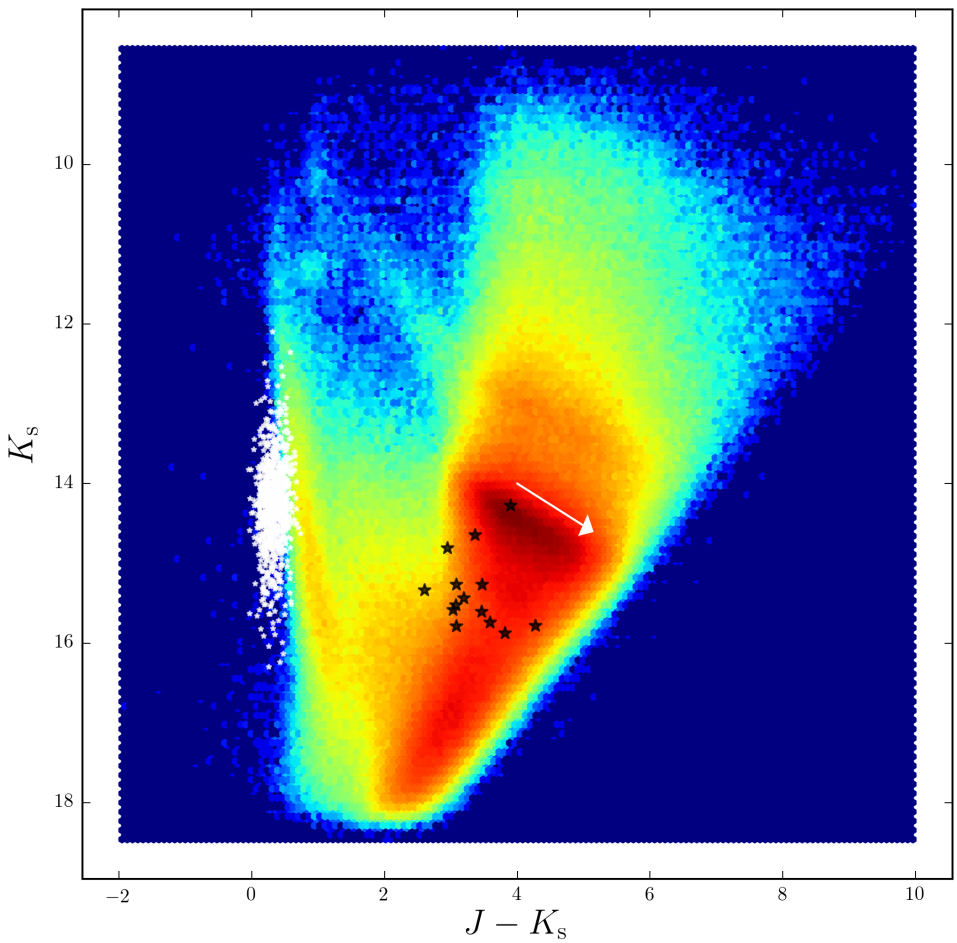

Figure 2. VVV Near-infrared color-magnitude diagram for the Galactic center region showing the position of the nuclear bulge RR Lyrae (black stars). For comparison, the unreddened outer bulge RR Lyrae Gran et al. (2016) are shown to the left of the color-magnitude diagram (white dots). The direction of the reddening vector is shown also. This vector is a fit to the shape of the reddened clump giants, and agrees with the slope measured by Alonso-García et al. (2015). We measure the extinctions and distances using the near-IR photometry, which also place these RR Lyrae at the Galactic center region.

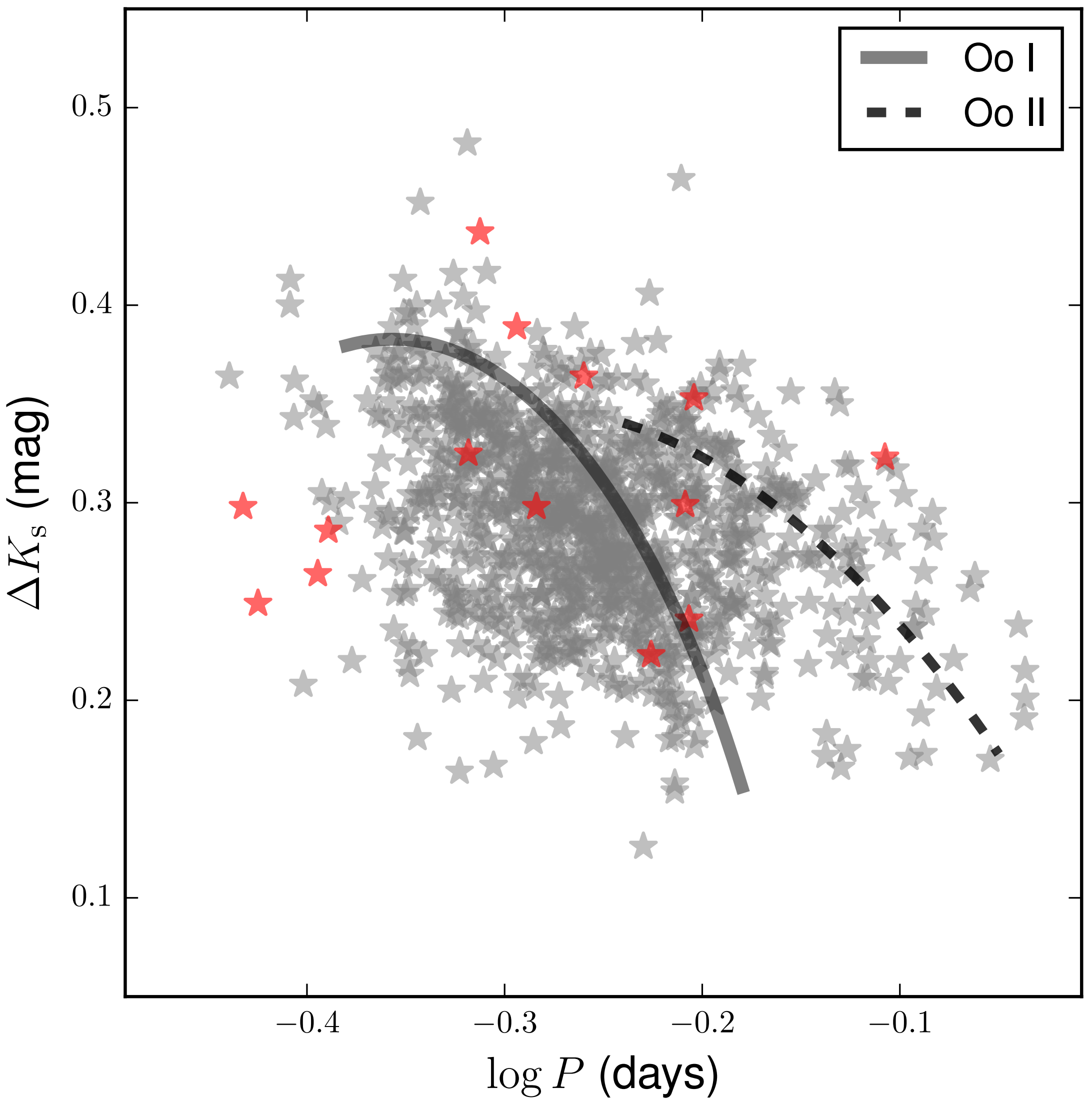

Figure 3. Bailey diagram: amplitude vs period for the nuclear bulge RR Lyrae (red stars) compared with 1019 RR Lyrae type ab found in the outer bulge Gran et al. (2016). The main ridge lines for the Oosterhoff types I and II are indicated, which are the left and right groups, respectively. Most of the nuclear bulge RR Lyrae share the location of the more metal-rich Oosterhoff type I population that has a metallicity $-0.9 < [Fe/H] < -1.6$ dex (Catelan 2009).