Inspection of 19 globular cluster candidates in the Galactic bulge with the VVV survey

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ABSTRACT

Context. The census of the globular clusters (GCs) in the Milky Way is still a work in progress. The advent of new deep surveys has made it possible to discover many new star clusters both in the Galactic disk and bulge, but many of these new candidates have not yet been studied in detail, leaving a veil on their true physical nature.

Aims. We explore the nature of 19 new GC candidates in the Galactic bulge by analysing their colour–magnitude diagrams (CMDs) in the near-infrared (NIR) using the VISTA Variables in the Via Láctea Survey (VVV) database. We estimate their main astrophysical parameters: reddening and extinction, distance, total luminosity, mean cluster proper motions (PMs), metallicity, and age.

Methods. We obtain the cluster catalogues including the likely cluster members by applying a decontamination procedure on the observed CMDs based on the vector PM diagrams from VIRAC2. We adopt NIR reddening maps in order to calculate the reddening and extinction for each cluster, and then estimate the distance moduli and heliocentric distances. Metallicities and ages are evaluated by fitting theoretical stellar isochrones. We also calculate their luminosities in comparison with known Galactic GCs.

Results. We estimate a wide reddening range of $0.25 \leq E(J - K_s) \leq 2.0$ mag and extinction $0.11 \leq A_{K_s} \leq 0.86$ mag for the sample clusters, as expected in the bulge regions. The range of heliocentric distances is $6.8 \leq D \leq 11.4$ kpc. This allows us to place these clusters between 0.56 and 3.25 kpc from the Galactic centre, assuming $R_\odot = 8.2$ kpc. Also, their PMs are kinematically similar to the typical motion of the Galactic bulge, apart from VVV-CL160, which shows different PMs. We also derive their metallicities and ages, finding $-1.40 \leq [\text{Fe}/\text{H}] \leq 0.0$ dex and $t \approx 8\text{--}13$ Gyr respectively. The luminosities are calculated both in K_s - and V -bands, recovering $-3.4 \leq M_V \leq -7.5$. We also examine the possible RR Lyrae members found in the cluster fields.

Conclusions. Based on their positions, kinematics, metallicities, and ages, and comparing our results with the literature, we conclude that nine candidates are real GCs, seven need more observations to be fully confirmed as GCs, and three candidates are discarded as GCs and appear to be younger open clusters.

Key words. Galaxy: bulge – Galaxy: center – Galaxy: stellar content – globular clusters: general – infrared: stars – surveys

1. Introduction

As suggested by the Λ CDM model, globular clusters (GCs) are the first stellar associations formed in the early Universe (Phipps et al. 2019), and therefore their physical properties are strongly linked with those of their host galaxies (Brodie & Strader 2006). These ancient star clusters have survived destruction over long galactic histories to become the fossil relics of the earliest epoch of galaxy formation (Kerber et al. 2019; Ferraro et al. 2021). Consequently, they represent powerful tools with which to investigate the formation and evolution of galaxies. However, the information coming from the analysis of a handful of Milky Way (MW) GCs may still be incomplete, either because some of them are very faint, too small, or widespread, or because they are embedded by dust and thus difficult to find. Indeed, most of the ‘missing’ GCs are likely located in obscured regions close to the Galactic centre or near the Galactic plane on the far side of the Galaxy (Minniti et al. 2017a; Garro et al. 2020, 2021b).

Our main long-term goal is to search for hidden GCs in order to reconstruct the formation history of our Galaxy, focussing on the Galactic bulge. For this purpose, in this paper we deal with the characterisation of 19 GC candidates located towards the MW bulge. This represents a challenge because these regions are affected by differential reddening and high stellar density. The best way to overcome these problems is to use near-infrared (NIR) observations, given that red giant stars have their emission peak in the NIR and the interstellar dust becomes almost transparent at these wavelengths. The identification of new candidates and their subsequent confirmation as real GCs can be facilitated at these spectral regions (for instance UKS 1 and VVV-CL001; Fernández-Trincado et al. 2020 and Fernández-Trincado et al. 2021, just to mention a few). A step forwards has been possible thanks to the VISTA Variables in the Via Láctea (VVV) survey and its eXtension (VVVX). More than 300 candidate star clusters have been discovered in the Galactic bulge and disk but only a fraction of them have been analysed (Froeblich et al. 2007; Borissova et al. 2014; Minniti et al. 2017b, 2021a; Camargo 2018;

Palma et al. 2019; Camargo & Minniti 2019; Garro et al. 2020, 2021b; Obasi et al. 2021, just to mention a few).

A variety of techniques have been used in the literature to identify potential star clusters against the background fields and to confirm their true nature. For example, Minniti et al. (2017a) built density maps using only the red giants, and identified the apparent over-densities to mark the location of GC candidates. Identification of the over-densities was done by visual inspection based on the size of each over-density and considering the typical size of known Galactic GCs ($\sim 2\text{--}5'$). Furthermore, these latter authors compared the CMD of potential candidates with those of well-characterised Galactic GCs as well as their respective background fields in order to verify that the cluster red giant branch (RGB) appears tighter than that observed in the background. Another method used to discriminate field stars from cluster candidates is statistical decontamination, as done by Palma et al. (2016), Minniti et al. (2011), and Garro et al. (2021b). In this latter method, the stars of the cluster CMD that fall in the same intervals of colour and magnitude as those of the background CMD are removed.

However, not all over-densities are true clusters; they may simply be groups of stars or statistical fluctuations of the projected stellar density in the plane of the sky (Gran et al. 2019; Palma et al. 2019; Minniti et al. 2021b). Therefore, one of the most reliable methods capable of confirming or discarding the existence of a cluster is the kinematic analysis. Coherent stellar motions ensure the cluster membership, and allow us to separate the stars belonging to an association from those randomly distributed in the field. Several studies (Zoccali et al. 2002; Sariya & Yadav 2015; Baumgardt et al. 2018; Garro et al. 2020, 2021b; Obasi et al. 2021; Minniti et al. 2021a, just to mention a few) have incorporated this technique, especially exploiting the high precision of *Gaia* proper motions (PMs), confirming, in many cases, the GC nature of some objects. Complementary evidence in support of the cluster identification is the presence of RR Lyrae stars, which are good tracers of old stellar populations (e.g., Minniti et al. 2017b).

In Sect. 2, we briefly describe the datasets used in this work. In Sect. 3, we describe the decontamination procedure, and the two tests performed in order to confirm the existence of the cluster. The methods to estimate the main physical parameters are explained in Sect. 4. In Sect. 5, we present the results of our search for RR Lyrae stars belonging to the clusters in order to confirm the GC nature. A comparison with the literature and final notes are reported in Sect. 6 and a summary and conclusions are presented in Sect. 7.

2. Observational dataset

We use the NIR dataset from the VVV survey (Minniti et al. 2010; Saito et al. 2012), which was acquired with the VISTA InfraRed CAMera (VIRCAM) at the 4.1m wide-field Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson & Sutherland 2010) at ESO Paranal Observatory. The VVV data were reduced at the Cambridge Astronomical Survey Unit (Irwin et al. 2004) and further processing and archiving was performed with the VISTA Data Flow System (Cross et al. 2012) by the Wide-Field Astronomy Unit and made available at the VISTA Science Archive. We use preliminary data from VIRAC version 2 (VIRAC-2; Smith et al. 2017), which is described in detail in Smith et al. (in prep.). In summary, VIRAC-2 identifies the sources in the VVV images and extracts their photometry through point spread function (PSF)-fitting techniques using DoPhot (Schechter et al. 1993;

Alonso-García et al. 2012, 2018). Their astrometry is calibrated to the *Gaia* DR2 (Gaia Collaboration 2018b) astrometric reference system, and their photometry is calibrated in the VISTA magnitude system (González-Fernández et al. 2018) against the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) using a globally optimised model of frame-by-frame zero points plus an illumination correction.

We use also the 2MASS catalogue in order to include brighter stars with $K_s < 11$ mag, because these stars are saturated in the VVV images. Additionally, we transformed the 2MASS photometry into the VISTA magnitude scale (González-Fernández et al. 2018), because the magnitude scale is different in the two photometric systems.

Moreover, we also explore the optical *Gaia* Early Data Release 3 (EDR3; Gaia Collaboration 2021) for eight GC candidates: FSR 0009, FSR 1775, VVV-CL131, VVV-CL143, ESO 393-12, ESO 456-09, DB044, and Kronberger 49, for which we obtain suitable CMDs and reliable physical parameters. Nevertheless, we cannot use the *Gaia* EDR3 data for the other targets because the CMDs are largely affected by the differential reddening, which distorts all optical evolutionary sequences. For this purpose, we use the contaminated VVV-CL150 field as representative, making a comparison between the NIR and optical wavelengths in order to show how the dust is opaque in the optical image and does not allow seeing beyond; also, it distorts the VVV-CL150 CMD, as demonstrated by Fig. 1. For that reason, we cannot use the optical *Gaia* EDR3 dataset for the other star clusters.

3. Proper motion decontamination procedure

We investigated 19 GC candidates that are located towards the Galactic bulge and are situated within a projected angular distance of 10° from the Galactic centre, as shown in Fig. 2. For the VVV, 2MASS, and *Gaia* EDR3 data, we performed a decontamination procedure in order to build a clean, decontaminated catalogue of probable cluster members following the same procedure applied by Garro et al. (2020, 2021b).

Briefly, we underline the main steps taken to obtain the final cluster catalogues. First of all, we include all stars with parallax values smaller than 0.5 mas, discarding all nearby stars. It is very difficult to derive the sizes of the clusters, especially in such crowded regions and for very weak clusters. For that reason, we derive the cluster size using two methods: (i) we inspect the density diagrams as a function of sky position in order to visually identify the cluster dimensions, and (ii) we apply the Gaussian kernel density estimate (KDE; e.g., Rosenblatt 1956; Parzen 1962). In summary, considering the scatter plot on the left-hand side of Fig. 3, overlapping points make the figure hard to read. Even worse, it is impossible to determine how many data points are in each position. In this case, a possible solution is to cut the plotting window into several bins (100–300 bins), and colour code the number of data points in each bin. Following the shape of the bin, this makes a 2D histogram. It is then possible to obtain a smoother result using the Gaussian KDE. Its representation is called a 2D density plot, and we add a contour to denote each density step. We use both density maps and KDE contours to identify the optimal cluster size, selecting the higher density area around the cluster centre. Therefore, we select all stars within the typical GC radius $r < 3'$ from the cluster centre, although we adopt a smaller radius $r < 1.8'$ for the cluster VVV-CL153, and a larger radius for the clusters FSR 0009 and VVV-CL154, $r < 3.6'$ and $r < 4.2'$, respectively. We then construct and inspect the vector PM diagram

Fig. 1. VVV (on the *left*) and *Gaia*+VVV (in the *middle*) density maps for a $r = 10'$ field centred on VVV-CL150, which is used as a representative cluster. The redder areas are representative of over-densities, while the yellow areas are lower densities. The *Gaia* EDR3 + VVV CMD (on the *right*) is displayed for the same field.

Fig. 2. Map depicting Galactic latitude versus longitude for our sample. The confirmed GCs are highlighted as red points, whereas transparent red points are used to point out the unconfirmed GCs. We also mark with open red circles the open clusters excluded from our analysis. We show known GCs from Vasiliev & Baumgardt (2021) with open green squares for comparison. We use shorter cluster identifications only for our convenience.

(VPM) as a 2D histogram of the relative cluster PMs, as shown in Fig. A.1. Given that our decontamination procedure is based on the PM selection, we also construct histograms of PM in RA (μ_{α_*} , blue histograms) and in Dec (μ_{δ} , red histograms) to clearly recognise the peak (against the noise) of the two distributions. We then visually identify the cluster peak in the VPM diagram, estimating the mean cluster PMs using the σ -clipping technique. All mean cluster PMs are kinematically in agreement with that of the Galactic bulge, except VVV-CL160 which deviates from the typical bulge values (Minniti et al. 2021a). The mean PMs for our GC sample are shown in Fig. 4 (highlighted with red circles), along with the mean PMs of all other known

MW bulge GCs measured by Vasiliev & Baumgardt (2021). Indeed, this figure illustrates that the new GCs show kinematics that are akin to the rest of the MW GCs. Finally, we select all stars within 1.0, 1.5, or 2.0 mas yr^{-1} from the mean cluster PMs. The choices to adopt different radii and PM selections (σ_{PM}) for all star clusters are motivated by the intention to only select stars that are likely members of the clusters in order to minimise the likelihood of including outer stars and excluding member stars. A preliminary step, made exclusively for clusters analysed in the optical passband, is to join the *Gaia* EDR3 and VVV datasets (using a $0.5''$ matching radius) before the decontamination procedure mentioned above. The positions,

Fig. 3. KDE technique applied to select the likely size of a cluster during the decontamination procedure. *From left to right:* scatterplot, 2D Histogram, Gaussian KDE, and 2D density with contours are shown for FSR 1767 (*top panels*) and VVV-CL160 (*bottom panels*) fields, which are used as representative. Green and yellow areas are illustrative of over-densities, while the blue areas show lower densities.

radii, and PM selections are summarised in Table 1 for every candidate.

Finally, we perform two tests in order to confirm that our targets are real clusters, even if they have previously been catalogued as such in the literature (see Sect. 6). First, we compare the spatial distribution (Fig. 5) of our clusters (using the decontaminated catalogues) with those of a sample of field stars (cleaned by nearby stars) selected at $5' \lesssim r \lesssim 8'$ from the relative centre of the cluster. We apply the KDE technique again in order to highlight over-densities. Clearly, the spatial distributions between the clusters and the fields are very different, because a clear central over-density is visible for each cluster, which decreases towards the cluster outskirts; on the other hand, a lumpy and inhomogeneous distribution is seen for the fields, as expected. However, as we can appreciate from Fig. 5, the central over-density is unequivocal for ESO 456-09 (Fig. 5a), VVV-CL160 (Fig. 5c), and VVV-CL150 (Fig. 5d), but is less clear for VVVCL-131 (Fig. 5b). This is related to the fact that some of these clusters have a sparse distribution, as they probably survived dynamical processes, typical of regions of high density such as the Galactic bulge.

As a second test, we compare our sample with field stars constructing both PM histograms and CMDs (Fig. 6). We expect that field samples include bulge+disk stars, but it is very difficult to split them and to treat them separately, because bulge and disk stars may have similar motions. As done for the clusters, we perform the σ -clipping technique in order to derive the mean field PMs listed in Table 2. We find that the means of the PMs do not differ significantly from those of the clusters, but they show much larger dispersions than the cluster sample, as expected. In this case, the CMDs represent powerful tools to indicate if a star cluster is present or not. Indeed, comparing the clusters and field CMDs, many features, such as red clump (RC), the narrow RGB,

Fig. 4. Vector PMs shown to demonstrate that the kinematics of the star clusters analysed here are consistent with those of the known GCs located in the direction of the MW bulge. Our targets are highlighted with red points, whereas the known GCs located in the bulge within $-10 < l(\text{deg}) < 10$ and $-10 < b(\text{deg}) < 10$ are represented by open green squares.

and the RGB-bump (RGBB) are clear in many cluster CMDs, while they are not visible in any field CMD. Therefore, all these features strongly support the real cluster nature of our objects.

Table 1. Position selection cuts for the PM-decontamination procedure, and mean cluster PMs for the GC candidates.

Cluster ID	RA [hh:mm:ss]	Dec [dd:mm:ss]	r [arcmin]	μ_{α_*} [mas yr ⁻¹]	μ_{δ} [mas yr ⁻¹]	σ_{PM} [mas yr ⁻¹]
FSR0009	18:28:30.6	-31:54:24	3.6	-1.39 ± 1.10	-5.22 ± 0.99	2.0
FSR1775	17:56:05.3	-36:33:57	3.0	-3.00 ± 0.80	-5.53 ± 0.73	1.0
FSR1767	17:35:43.0	-36:21:28	3.0	-3.02 ± 0.50	-4.85 ± 0.50	1.0
VVVCL110	17:22:47.0	-34:41:17	3.0	-4.25 ± 0.48	-6.23 ± 0.48	1.0
VVVCL119	17:30:46.0	-32:39:05	2.4	-3.93 ± 0.92	-6.07 ± 0.93	2.0
VVVCL128	17:39:59.0	-32:26:27	3.0	-4.22 ± 0.50	-6.22 ± 0.50	1.0
VVVCL131	17:41:17.0	-34:34:02	3.0	-3.24 ± 0.81	-5.65 ± 0.07	1.0
VVVCL143	17:44:36.0	-33:44:18	3.0	-3.18 ± 0.91	-6.17 ± 0.85	1.0
VVVCL150	17:50:41.0	-25:13:06	3.0	-3.33 ± 0.48	-5.87 ± 0.50	1.0
VVVCL153	17:53:32.0	-25:22:56	1.8	-3.96 ± 0.67	-6.44 ± 0.69	1.5
VVVCL154	17:55:08.0	-28:06:01	3.0	-1.04 ± 0.49	-3.84 ± 0.48	1.0
VVVCL160	18:06:57.0	-20:00:40	3.0	-2.90 ± 1.28	-16.47 ± 1.31	1.0
ESO393-12	17:38:37.6	-35:39:02	3.0	-2.86 ± 0.47	-5.39 ± 0.44	1.0
ESO456-09	17:53:54.3	-32:27:58	3.0	-3.41 ± 0.71	-4.36 ± 0.75	1.5
DB044	17:46:35.0	-24:53:28	3.0	-3.68 ± 1.61	-6.43 ± 1.14	2.0
Kronberger49	18:10:23.9	-23:20:25	3.0	-2.84 ± 0.69	-5.52 ± 0.71	1.0

Fig. 5. Spatial distribution for four clusters (on the *top*) and their relative fields (on the *bottom*) selected at $5' \leq r \leq 8'$ from the cluster centre, taken as representative. We use the KDE technique, as in Fig. 3, in order to better distinguish the over-densities (yellow/green colours) from lower-densities (blue colours). (a) ESO 456-09, (b) VVV-CL131, (c) VVV-CL160, (d) VVV-CL150.

4. Estimation of physical parameters

As shown in Fig. 2, the closest cluster is VVV-CL154 situated within 2.5° of the Galactic centre, while the most distant clusters are FSR 0009, BICA 523, and 524. These regions are strongly affected by stellar crowding and interstellar extinction, which impact the CMDs. Therefore, in order to overcome some of

these difficulties, we estimate the reddening and the extinction towards the clusters following Ruiz-Dern et al. (2018). Indeed, we first construct the cluster luminosity functions (Fig. 7) in order to clearly distinguish the RC position, as the peak of the distribution, and then we assign the RC magnitude error as the average of the K_s magnitude errors at the RC level. After that, we use the mean magnitude of RC stars in the NIR from

Fig. 6. Normalised PM histograms and CMDs for field (in red) and cluster (in blue) stars. We fit the Gaussian distributions (dashed lines) using means and standard deviations listed in Table 2. (a) FSR 0009, (b) FSR 1775, (c) FSR 1767, (d) VVV-CL110, (e) VVV-CL119, (f) VVV-CL128, (g) VVV-CL131, (h) VVV-CL143, (i) VVV-CL150 (j) VVV-CL153, (k) VVV-CL154, (l) VVV-CL160, (m) ESO 393-12, (n) ESO 456-09, (o) DB 044, (p) Kronberger 49.

Ruiz-Dern et al. (2018). Their absolute magnitude in the K_s -band is $M_{K_s} = -1.605 \pm 0.009$ mag and the intrinsic colour is $(J - K_s)_0 = 0.66 \pm 0.02$ mag, whereas for the optical wavebands their intrinsic RC magnitude is $M_G = 0.459 \pm 0.009$ mag. Additionally, we adopt the following relations for the extinctions and reddenings: $A_{K_s} = 0.428 \times E(J - K_s)$ (because our targets are located in the inner Galactic regions, Alonso-García et al. 2017), $A_{K_s} = 0.11 \times A_V$, $A_G = 0.86 \times A_V$ and $A_G = 2.0 \times E(BP - RP)$ (Wang & Chen 2019). Also, we derive the colour excess for the optical passband comparing the cluster colours with the absolute colour by Gaia Collaboration (2018a). As expected, the cluster fields exhibit a large range of extinction $0.11 \leq A_{K_s} \leq 0.86$ mag as well as a large range of reddening $0.25 \leq E(J - K_s) \leq 2$ mag in the NIR, demonstrating again that the reddening is not uniform, which translates into uncertainties in the calculation of the main physical parameters. For example, VVV-CL128, CL150, and CL154 have wide RGBs due to differential reddening

and/or residual contamination, as we can see from our CMDs (Fig. A.2). The final reddenings obtained from the CMDs are listed in Table 3. We also compare our reddenings with the high-resolution reddening map by Surot et al. (2020), finding excellent agreement ($0.2 \lesssim E(J - K_s) \lesssim 2.0$ mag). Figure 8 shows the de-reddened CMDs for the field stars and FSR 1767, which we take as a representative sample cluster. We selected: (i) field stars in an adjacent area ($5' \leq r \leq 8'$ from the cluster centre), cleaned by nearby stars; and (ii) PM members of FSR 1767. Comparing these two samples, we do not see a very large spread in colour. However, we can see a well-defined RGB sequence, and also the RC and the RGB-bump are visible in the FSR 1767 CMD, which disappear in the field CMD, a feature that is commonly observed among GCs. Clearly, the position of the RC and RGBB could depend on the bin size in the M_{K_s} magnitude; however, in the FSR 1767 CMD (see Fig. A.2), a double over-density is clear at the same magnitudes.

Fig. 6. continued.

Once reddening and extinction are obtained and the RC absolute magnitude by Ruiz-Dern et al. (2018) is taken into account, we are able to derive the distance moduli of the GCs and therefore their heliocentric distances. We find that the distance varies from 6.8 to 11.4 kpc from the Sun. In order to confirm our VVV results, we also report in Table 4 the optical results using the *Gaia* EDR3 photometry for those clusters for which we obtain suitable *Gaia* EDR3 data. Furthermore, we use the VVV distances to place our candidates at their respective distances R_G from the Galactic centre, assuming that the Sun is located at $R_\odot = 8.2$ kpc (GRAVITY Collaboration 2019). We find that they are located at Galactocentric distances ranging between 0.56 kpc (for the VVV-CL150) and 3.26 kpc (for the VVV-CL28), as listed in Table 3. Their 3D distribution adopting the Galactocentric coordinates (X, Y, Z) in the Galactic bulge is shown in Fig. 9.

Once distances and PMs are known, we can derive their tangential velocities (V_T), as shown in Fig. 10. It is clear that their tangential velocities are consistent with those measured

by Vasiliev & Baumgardt (2021) for the known GCs located towards the MW bulge. This is further confirmation that they are part of the bulge component.

Using the reddening and distance estimates, we fit the alpha-enriched PARSEC isochrones (Bressan et al. 2012; Marigo et al. 2017) –which reproduce the evolutionary sequences in the observed CMDs slightly better than the solar-scaled model– in order to derive both metallicity and age for our targets. We perform isochrone-fitting, reproducing in particular the position of the RC, blue horizontal branch stars (BHB), and the RGB (Fig. A.2). We compare our evolutionary sequences in the CMDs with the isochrones generated for different ages and metallicities and visually select the best fit. Deriving the metallicity is more straightforward than the age, because metallicity has a particularly significant effect on the evolved sequences (i.e. RC, HB, and RGB). Therefore, first of all we fix the metallicity for each candidate, and then we derive the ages. We find 11 metal-rich GCs with $[\text{Fe}/\text{H}] = 0.0$ to -0.6 , while 3 are metal-poor GCs

Table 2. PMs comparison between field and cluster stars.

Cluster+Field	μ_α^* [mas yr ⁻¹]	$\sigma_{\mu_\alpha^*}$ [mas yr ⁻¹]	μ_δ [mas yr ⁻¹]	σ_{μ_δ} [mas yr ⁻¹]
FSR 0009	-1.39	0.93	-5.1	1.09
Field	-1.25	5.08	-3.90	4.95
FSR 1775	-3.00	0.80	-5.53	0.73
Field	-1.61	4.86	-3.99	5.08
FSR 1767	-3.01	0.49	-4.85	0.49
Field	-2.24	4.05	-3.88	4.14
VVV-CL110	-4.25	0.48	-6.23	0.48
Field	-3.38	3.64	-4.08	3.66
VVV-CL119	-3.93	0.91	-6.07	0.93
Field	-3.20	3.48	-3.96	3.58
VVV-CL128	-4.22	0.50	6.22	0.50
Field	-3.14	4.43	-4.69	4.68
VVV-CL131	-3.55	0.78	-5.84	0.82
Field	-2.74	3.31	-4.41	3.81
VVV-CL143	-3.18	0.91	-6.18	0.85
Field	-2.54	3.24	-4.64	4.1
VVV-CL150	-3.33	0.5	-5.87	0.5
Field	-2.33	4.40	-3.61	4.50
VVV-CL153	-3.96	0.67	-6.44	0.68
Field	-2.35	4.49	-4.13	4.60
VVV-CL154	-1.04	0.49	-3.85	0.48
Field	-2.67	6.53	-4.09	6.38
VVV-CL160	-2.90	1.21	-16.48	1.26
Field	-3.22	5.1	-4.14	5.02
ESO 393-12	-2.83	0.49	-5.37	0.46
Field	-2.06	2.62	-4.57	2.90
ESO 456-09	-3.41	0.71	-4.36	0.75
Field	-2.43	3.32	-5.09	3.42
DB 044	-3.37	1.3	-6.1	1.3
Field	-2.61	3.17	-4.92	3.33
Kronberger 49	-2.84	0.69	-5.51	0.71
Field	-1.93	2.78	-4.35	3.02

with $[\text{Fe}/\text{H}] = -1.2$ and -1.4 , and 2 show intermediate values of $[\text{Fe}/\text{H}] = -0.7$ and -1.1 , with a mean error of ± 0.2 dex. On the other hand, estimating ages is a challenging task, as one usually needs to reach ~ 2 mag below the main sequence turn-off (MSTO) to determine their absolute values. Nevertheless, we are unable to go beyond $K_s > 17.5$ mag (and $G > 17.0$ mag), meaning that the MSTO lies below the detection limit. Despite this, we can obtain a robust lower limit for ages, considering three observables from the CMDs. Firstly, we use the vertical method, estimating the difference in magnitude between the HB and the MSTO. In our cases, the $\Delta K_s(\text{HB-MSTO}) \gtrsim 2$ mag, therefore ensuring that our candidates are older than ~ 8 Gyr. Secondly, a large extension of the giant branch suggests an intermediate age system, indicating that bright and red stars are present especially along the asymptotic giant branch (Freedman et al. 2020). Also, the presence of RR Lyrae variable stars guarantees that the ages are older than 10 Gyr (Sect. 5).

Most of the analysed clusters show ages that are consistent with the old ages expected for GCs, except for BICA 523 located at RA = 17:14:58.0, Dec = -36:48:28, BICA 524 situated at RA = 17:15:08.0, Dec = -36:47:12, and FSR 0022 placed at RA = 17:56:23.7, Dec = -23:11:35, which are likely open clusters with Age < 6 Gyr (i.e. Salaris et al. 2004). We there-

fore exclude these latter from further analysis because our main long-term goal is to complete a census of the GCs in the MW.

Furthermore, we derive the global metal content for the sample from the slope of the RGB in order to minimise the effect of age-metallicity degeneracy (e.g., Ferraro et al. 2000; Valenti et al. 2004). We use the $[\text{Fe}/\text{H}]$ -slope_{RGB}^{JK} relation by Cohen et al. (2015), finding excellent agreement with our original estimates, within the errors (see Table 3).

After finding the best-fitting age and metallicity simultaneously, we also give an estimation of the age and metallicity errors by varying the parameters until the isochrones are not adequate to reproduce the evolutionary sequences as shown by Fig. A.2. However, it is clear that the correct determination of the age is still one of the most arduous tasks, especially in environments with high stellar density and with differential reddening, and our ages are only rough estimates.

Additionally, we show the *Gaia* optical CMDs in Fig. 11 and list the physical parameters in Table 4 for the eight GCs for which we also carried out the photometric analysis in the optical passbands. Although it is difficult to simultaneously reproduce all the evolutionary sequences, we notice that both optical and NIR analyses are in good agreement within the errors, confirming the VVV results.

Finally, the total luminosities in the K_s -band (M_{K_s}) for all the GCs in our sample were derived by first measuring the flux for each star and then the total flux for the cluster. We then converted the latter into the M_{K_s} , listed in Table 3. As mentioned above, faint stars below the MSTO are missing in our catalogues, and so the integrated luminosities of our clusters should be considered as lower limits. For this purpose, we compared our GC M_{K_s} with other known and well-characterised Galactic GCs listed in Table 5, where we recovered their reddening and distance modulus. We follow the same approach as Garro et al. (2021a). The main goal is to quantify the fraction of luminosity that comes from the faintest stars in order to better estimate the total luminosity of each cluster. We obtain an empirical correction to our cluster's luminosities under the assumption of similarity among Galactic GCs. We find that most of them are low-luminosity GCs, with M_V fainter than the MW globular cluster luminosity function (GCLF) peak ($M_V = -7.4 \pm 0.2$ mag; Harris 1991; Ashman & Zepf 1998). On the other hand, there are two GCs with total luminosities comparable with the MW GCLF peak: VVV-CL119 ($M_V = -7.5$) and VVV-CL154 ($M_V = -7.2$).

All their main physical parameters are listed in Table 3, where we summarise the cluster identification (ID), the RC position, the reddening and extinction, the distance, the luminosity, the mean cluster PMs, the metallicity, the age, and the classification type for each candidate.

5. Searching for RR Lyrae stars

We also searched for RR Lyrae stars within a radius of 12' centred on the clusters (Table B.1), as these variables are good tracers of old populations and are also excellent distance indicators. Our selection includes samples from the Optical Gravitational Lensing Experiment (OGLE; Soszyński et al. 2014), and the VVV (Majaess et al. 2018) and *Gaia* (Clementini et al. 2019) catalogues. We detect RR Lyrae stars in the fields of FSR 1775 ($N_{\text{RRLS}}^{12'} = 8$), FSR 1767 ($N_{\text{RRLS}}^{12'} = 7$), Kronberger 49 ($N_{\text{RRLS}}^{12'} = 9$), ESO 393-12 ($N_{\text{RRLS}}^{12'} = 15$), ESO 456-09 ($N_{\text{RRLS}}^{12'} = 30$), DB044 ($N_{\text{RRLS}}^{12'} = 32$), VVV-CL131 ($N_{\text{RRLS}}^{12'} = 16$), VVV-CL143 ($N_{\text{RRLS}}^{12'} = 22$), and VVV-CL154 ($N_{\text{RRLS}}^{12'} = 58$). The

Fig. 7. Luminosity functions in K_s -band for each star cluster. *Top*: densogram used in order to more easily recognise the RC and avoid the binning dependence. The yellow colour depicts the highest density, with density decreasing towards magenta and then dark blue. We use a bin size of 0.1.

Table 3. Main physical parameters for each star cluster candidate using the VVV photometry.

Cluster ID	K_s (RC) [mag]	$E(J - K_s)$ [mag]	A_{K_s} [mag]	$(m - M)_0$ [mag]	D_{VVV} [kpc]	R_G [kpc]	M_{K_s} [mag]	M_V [mag]	[Fe/H] dex	[Fe/H] _s ^(a) dex	Age Gyr	Type
FSR0009	–	0.25 ± 0.04	0.11 ± 0.03	14.20 ± 0.04	6.9 ± 0.2	1.81	-5.8 ± 0.7	–3.4	-1.2 ± 0.3	–1.10	11 ± 2	GC
FSR1775	–	0.37 ± 0.03	0.16 ± 0.01	14.75 ± 0.02	8.9 ± 0.2	1.37	-8.0 ± 1.7	–5.6	-1.1 ± 0.2	–1.10	10 ± 2	GC
FSR1767	13.8 ± 0.03	0.28 ± 0.03	0.28 ± 0.03	15.12 ± 0.04	10.6 ± 0.2	2.70	-8.4 ± 1.5	–6.3	-0.7 ± 0.2	–0.73	11 ± 2	GC
VVVCL110	14.5 ± 0.03	2.0 ± 0.04	0.86 ± 0.02	15.25 ± 0.04	11.2 ± 0.5	3.25	-8.6 ± 1.6	–6.8	-0.1 ± 0.2	–0.48	11 ± 2	GC?
VVVCL119	14.5 ± 0.05	1.98 ± 0.07	0.85 ± 0.04	15.26 ± 0.06	11.3 ± 0.6	2.24	-9.3 ± 1.8	–7.5	-0.1 ± 0.2	–0.48	10 ± 3	GC?
VVVCL128	14.2 ± 0.05	1.20 ± 0.05	0.51 ± 0.04	15.29 ± 0.06	11.4 ± 0.5	3.26	-7.5 ± 1.6	–5.7	0.0 ± 0.3	–0.11	10 ± 3	GC?
VVVCL131	13.4 ± 0.03	0.54 ± 0.04	0.23 ± 0.03	14.77 ± 0.04	9.0 ± 0.5	1.17	-8.2 ± 1.5	–5.9	-0.6 ± 0.2	–0.73	10 ± 3	GC
VVVCL143	13.4 ± 0.03	0.50 ± 0.05	0.21 ± 0.04	14.74 ± 0.05	8.9 ± 0.5	1.0	-8.2 ± 1.3	–5.9	-0.6 ± 0.2	–0.61	10 ± 3	GC
VVVCL150	–	1.32 ± 0.04	0.56 ± 0.03	14.54 ± 0.04	8.1 ± 0.5	0.56	-8.7 ± 1.7	–6.5	-1.3 ± 0.1	–1.35	12 ± 2	GC?
VVVCL153	14.1 ± 0.02	1.67 ± 0.04	0.71 ± 0.03	14.99 ± 0.04	10 ± 0.4	1.90	-8.6 ± 1.9	–6.8	-0.1 ± 0.1	–0.23	10 ± 3	GC?
VVVCL154	13.5 ± 0.03	0.85 ± 0.05	0.36 ± 0.04	14.47 ± 0.05	8.9 ± 0.5	0.78	-9.6 ± 1.8	–7.2	-0.6 ± 0.2	–0.67	11 ± 2	GC?
VVVCL160	–	1.71 ± 0.04	0.73 ± 0.03	14.17 ± 0.04	6.8 ± 0.5	1.92	-7.9 ± 1.5	–5.5	-1.4 ± 0.3	–1.47	13 ± 2	GC
ESO393-12	13.2 ± 0.02	0.54 ± 0.03	0.23 ± 0.02	14.57 ± 0.03	8.2 ± 0.4	0.98	-7.7 ± 1.5	–5.3	-0.6 ± 0.2	–0.61	10 ± 2	GC
ESO456-09	13.0 ± 0.02	0.44 ± 0.04	0.18 ± 0.03	14.42 ± 0.04	7.6 ± 0.4	0.81	-8.3 ± 1.5	–6.0	-0.6 ± 0.2	–0.61	10 ± 2	GC
DB044	13.2 ± 0.02	0.69 ± 0.03	0.30 ± 0.02	14.51 ± 0.1	8.0 ± 0.5	0.61	-8.0 ± 1.6	–6.0	-0.1 ± 0.2	–0.11	11 ± 2	GC?
Kronberger49	13.3 ± 0.03	0.69 ± 0.04	0.30 ± 0.03	14.61 ± 0.04	8.3 ± 0.5	1.14	-8.5 ± 1.5	–6.7	-0.2 ± 0.2	–0.36	11 ± 2	GC

Notes. The absolute magnitude in V-band is calculated from the comparison with the well-known GCs (see Table 5). We mark with a question mark those clusters for which we need further data in order to unveil their nature. ^(a)The [Fe/H] estimates are derived from the RGB-slope using the relation by Cohen et al. (2015).

number density of field bulge RRab stars has been estimated by Navarro et al. (2021).

In order to identify RR Lyrae stars belonging to the GCs we mainly rely on two parameters: heliocentric distances and PMs. We use the period–luminosity–metallicity (PLZ) relation in the NIR following Muraveva et al. (2015) (with RRC stars

‘fundamentalized’ by adding 0.127 to the logarithm of the period) to derive their heliocentric distances (D_{RRLS}). After that, we measure their projected distances from the GC centres (D_c), and we construct a $D_{RRLS} - D_c$ diagram as shown in Fig. 12. We then compare the RR Lyrae PMs with the cluster PMs as displayed in Fig. A.2 (left panels), keeping only those

Fig. 8. De-reddened CMDs for field stars (on the *left*) located at $5' \lesssim r \lesssim 8'$ from the FSR 1767 centre and for the FSR 1767 GC (on the *right*). We also construct the M_{K_s} luminosity function as blue histograms.

Table 4. Optical parameters derived for those GCs for which it was possible to obtain adequate *Gaia* EDR3 data, which were used to confirm the VVV results.

Cluster ID	$G(\text{RC})$ [mag]	A_G [mag]	$(m - M)_0$ [mag]	D_{GEDR3} [kpc]
FSR0009	15.7 ± 0.003	1.08 ± 0.3	14.12 ± 0.3	6.7 ± 0.8
FSR1775	16.9 ± 0.004	1.70 ± 0.6	14.70 ± 0.6	8.7 ± 1.6
VVVCL131	18.1 ± 0.003	2.80 ± 0.1	14.80 ± 0.1	9.1 ± 0.5
VVVCL143	18.0 ± 0.003	2.80 ± 0.1	14.70 ± 0.1	8.7 ± 0.5
ESO393-12	18.0 ± 0.005	3.20 ± 0.7	14.30 ± 0.7	7.3 ± 1.9
ESO456-09	17.2 ± 0.003	2.40 ± 0.7	14.31 ± 0.7	7.3 ± 1.9
DB044	18.8 ± 0.02	4.0 ± 0.5	14.30 ± 0.5	7.3 ± 1.2
Kronberger49	18.8 ± 0.01	3.80 ± 0.2	14.50 ± 0.2	8.0 ± 0.6

stars that have PMs matching the mean cluster PMs within the errors. According to PMs and heliocentric distances, we strictly identify $N_{\text{RRLS}}(\text{FSR1775}) = 2$, $N_{\text{RRLS}}(\text{FSR1767}) = 2$, $N_{\text{RRLS}}(\text{Kron49}) = 3$, $N_{\text{RRLS}}(\text{ESO393-12}) = 3$, $N_{\text{RRLS}}(\text{ESO456-09}) = 6$, $N_{\text{RRLS}}(\text{DB044}) = 6$, $N_{\text{RRLS}}(\text{VVV-CL131}) = 2$, $N_{\text{RRLS}}(\text{VVV-CL143}) = 4$, and $N_{\text{RRLS}}(\text{VVV-CL154}) = 15$, as GC members. We verified our distances using the PL relations from Navarrete et al. (2017) and Gaia Collaboration (2017), yielding slightly larger distance values, and Alonso-García et al. (2021), yielding slightly shorter distance values in the mean. For the latter, we transformed the metallicities listed in Table 3 into $\log Z$ using the relation shown in Navarrete et al. (2017), assuming $f = 10^{[\alpha/\text{Fe}]/2} = 3$ and $Z_\odot = 0.017$. However, we find that Alonso-García et al. (2021) follows the DB044 and ESO 456-09 RR Lyrae trends better than Muraveva et al. (2015), and so we use the Alonso-García et al. (2021) relation for these clusters. Nevertheless, both relations are still within the mean errors of ~ 0.5 kpc obtained by the comparison between these four PLZ relations.

Although these variables are usually found in metal-poor populations, such as Terzan 10 ($[\text{Fe}/\text{H}] = -1.59$) and NGC 6656 ($[\text{Fe}/\text{H}] = -1.70$), there is evidence (e.g., Alonso-García et al. 2021) of RR Lyrae stars located in metal-rich GCs, such as NGC 6441 ($[\text{Fe}/\text{H}] = -0.46$) and Patchick 99 ($[\text{Fe}/\text{H}] = -0.20$ – Garro et al. 2021b), as well as in intermediate-metallicity GCs, like 2MASS-GC 02 ($[\text{Fe}/\text{H}] = -1.08$) and NGC 6569 ($[\text{Fe}/\text{H}] = -0.76$). In our case, we note that the GCs containing RR Lyrae show a metallicity range between -0.6 and -1.2 .

However, Kronberger 49 with $[\text{Fe}/\text{H}] = -0.2$ and DB044 with $[\text{Fe}/\text{H}] = -0.1$ could include three and six RR Lyrae members, respectively. Nonetheless, we are careful to state that the three RR Lyrae definitely belong to Kronberger 49 because we have noticed that no PM RR Lyrae matches with cluster PMs within $\sigma < 1 \text{ mas yr}^{-1}$. Also, another caveat is that some variables are situated beyond $5'$ from the centre. This means that their position could be beyond the cluster core or tidal radius, suggesting that their membership is less likely. This is the case for VVV-CL143 for example, as the RR Lyrae that could be considered as members are located so far away from the cluster centre that their cluster membership is really unlikely. Regardless, it is very unlikely that clusters with high metallicity host RR Lyrae stars. Hence, we need spectroscopic observations in order to confirm their nature.

Finally, we use these variables to determine the cluster distance independently. We find good agreement between the distances found by the VVV photometry (see Table 3) and the RR Lyrae estimates derived from Muraveva et al. (2015) and Alonso-García et al. (2021) relations: $D_{\text{RRLS}}(\text{VVV-CL154}) = 8.1 \text{ kpc}$, $D_{\text{RRLS}}(\text{VVV-CL131}) = 9.2 \text{ kpc}$, $D_{\text{RRLS}}(\text{VVV-CL143}) = 8.8 \text{ kpc}$, $D_{\text{RRLS}}(\text{FSR1775}) = 9.4 \text{ kpc}$, $D_{\text{RRLS}}(\text{FSR1767}) = 9.4 \text{ kpc}$, $D_{\text{RRLS}}(\text{ESO393-12}) = 7.9 \text{ kpc}$ and $D_{\text{RRLS}}(\text{ESO456-09}) = 7.5 \text{ kpc}$. In any case, if we include the Kronberger 49 variables, we find $D_{\text{RRLS}}(\text{Kron49}) = 8.3 \text{ kpc}$, and if we include DB044 RR Lyrae on top of that then we obtain $D_{\text{RRLS}}(\text{DB044}) = 8.0 \text{ kpc}$, both in agreement with the VVV distances.

The magenta squares and points in the CMDs, VPM diagrams, and distance diagrams (Figs. A.2 and 12) depict the RR Lyrae members of each GC.

6. Notes on individual clusters

Below we report on the individual clusters. We display the estimated parameters for each cluster, and we compare our results with those already present in the literature, if any. This helped us to classify our targets as GCs, if possible.

6.1. FSR catalogue

FSR 0009, also referred to as Milky Way Star Cluster (MWSC) 2921, was identified as a Galactic open cluster in the list of Buckner & Froebrich (2013). These authors placed it at

Fig. 9. Three-dimensional distribution of the star clusters analysed in this work towards the Galactic bulge using the Galactocentric coordinates (X, Y, Z). The red cross depicts the Galactic centre position at (0, 0, 0). The colour of points indicates the Galactocentric distance (R_G in kpc) as specified by the legend.

Fig. 10. As Fig. 4, we show the star clusters tangential velocities to demonstrate that the kinematics of the star clusters analysed here are consistent with those of the known GCs from [Vasiliev & Baumgardt \(2021\)](#) located in the direction of the MW bulge.

equatorial coordinates (J2000) $RA = 18:28:32.9$, $Dec = -31:54:18$ and Galactic coordinates $l = 1.86$, $b = -9.52$, $\sim 30''$ away from our centre. They concluded that it is a poorly populated cluster with 73 members, its PMs are $\mu_{\alpha_*} = 1.25 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -6.83 \text{ mas yr}^{-1}$, and its distance is about 3.4 kpc. These results differ from ours, because we find a GC with about 150 stars, with different PMs (see Table 1).

The nature of FSR 1767 has been debated in the past. [Froeblich et al. \(2007\)](#) concluded that it was not a star cluster. Whereas, with 2MASS photometry and PMs, [Bonatto et al. \(2009\)](#) proved that FSR 1767 was a GC located at equatorial coordinates (J2000) $RA = 17:35:44.8$, $Dec = -36:21:42$, and Galactic coordinates $l = 352.60$, $b = -02.17$, $\sim 26''$ away from our centre. These latter authors suggested that it appears to be

a detached post-collapse core, similar to those of other nearby low-luminosity GCs projected towards the bulge. On the other hand, [Buckner & Froeblich \(2013\)](#) classified FSR 1767 as an open cluster with $\mu_{\alpha_*} = 0.97 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -3.57 \text{ mas yr}^{-1}$, at a distance about 3.6 kpc. They counted 121 members. Our results agree with those of [Bonatto et al. \(2009\)](#) because we classify FSR 1767 as a GC containing about 530 stars, and place it at a distance of $\sim 10.6 \pm 0.2 \text{ kpc}$.

FSR 1775, also named MWSC 2750, was catalogued by [Buckner & Froeblich \(2013\)](#) as a possible open cluster that is poorly populated (52 members) and at equatorial coordinates (J2000) $RA = 17:56:07.9$, $Dec = -36:33:54$ and Galactic coordinates $l = 354.55$, $b = -5.79$, $\sim 30''$ away from our position space. These latter authors derived PMs of $\mu_{\alpha_*} = -9.53 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -1.00 \text{ mas yr}^{-1}$ and a distance of 4.6 kpc. Again we obtained different PMs and distances based on about 260 members (see Table 1). In addition, we exclude the open cluster nature because both FSR 1767 and 1775 contain RR Lyrae stars, suggesting relatively old ages.

6.2. VVV catalogue

All clusters named VVV-CL in this work were discovered in the VVV survey by [Borissova et al. \(2014\)](#). We report below our comments on these individual candidates.

VVV-CL110, CL128, CL131, and CL153 are located in VVV tiles b342, b317, b302, and b336, respectively. [Borissova et al. \(2014\)](#) suggest that VVV-CL110, CL128, and CL131 could be GCs or old OCs. We confirm their nature as real GCs. These latter authors suggested that VVV-CL153 could be a prominent bright cluster. Selecting a region of $r \leq 1.8'$ from the GC centre and including all stars within 1.5 mas yr^{-1} from the cluster PMs, we find a relatively dim cluster ($M_V \approx -6.8 \text{ mag}$) as indicated by [Borissova et al. \(2014\)](#).

VVV-CL119. [Borissova et al. \(2014\)](#) found this object in VVV tile b344 and classified it as a possible old open cluster. Constructing the CMDs, they located the RC and the TO point at $K_s = 13.8 \pm 0.2 \text{ mag}$ and $K_s = 17.3 \pm 0.3 \text{ mag}$, respectively. Their main physical parameters are: a mean reddening of $E(J - K_s) = 2.03 \pm 0.4$, a distance modulus of $(M - m)_0 = 14.17 \pm 0.3$ (6.8 kpc), an age of $5 \pm 1.2 \text{ Gyr}$, and a mean metallicity, calculated from five spectroscopically observed stars of $[Fe/H] = -0.3 \pm 0.18$. The main differences that we notice between our findings and those of this latter work are related to the position of the RC and TO. We identify the RC to be $\sim 0.7 \text{ mag}$ fainter than theirs and we do not reach the MSTO. Although the reddenings are in agreement, we place VVV-CL119 at 11.3 kpc from the Sun, thus $\sim 4.5 \text{ kpc}$ further out than their distance. Finally, the metallicities obtained are in agreement within the errors.

VVV-CL143. This star cluster lies in VVV tile b302. [Borissova et al. \(2014\)](#) identified a defined RGB, several RC stars at $K_s = 13.3 \pm 0.2 \text{ mag}$, and the TO point at $K_s = 16.62 \pm 0.3 \text{ mag}$. These authors estimated a reddening of $E(J - K_s) = 0.58 \pm 0.2$, a distance modulus of $(M - m)_0 = 14.45 \pm 0.6$ (7.8 kpc), an age of $4 \pm 0.7 \text{ Gyr}$, and a mean metallicity of $[Fe/H] = -0.62 \pm 0.52$, which was spectroscopically evaluated from 10 to 12 observed stars. Nevertheless, they were unable to identify the true nature of VVV-CL143, because it could be either a populated old open cluster or a young GC, especially when its relatively low metallicity and CMD morphology are taken into account. We confirm their results because this is a

Table 5. Known and well-characterised GCs used to derive the total luminosity for each GC.

Cluster ID	[Fe/H] ^(a) [dex]	$E(B - V)$ [mag]	$(m - M)_0$ [mag]	M_V ^(b) [mag]	References
NGC 6528	-0.11	0.54	16.17	-5.50	Harris (1996) (H96)
NGC 6553	-0.18	0.63	15.83	-7.01	H96
Terzan 5	-0.23	2.28	13.85	-7.08	H96
Liller 1	-0.33	3.09	14.48	-9.68	Valenti et al. (2010) (V10)
NGC 6440	-0.36	1.15	14.58	-7.70	Valenti et al. (2004) (V04)
NGC 6441	-0.46	0.52	15.65	-8.45	V04
NGC 6624	-0.44	0.31	17.33	-8.86	Siegel et al. (2011) (S11)
Terzan 6	-0.56	2.35	14.13	-5.98	Valenti et al. (2007) (V07)
Terzan 12	-0.50	2.06	12.65	-4.64	Ortolani et al. (1998)
NGC 6637	-0.64	0.22	17.35	-8.90	S11
Terzan 2	-0.69	1.40	14.30	-5.72	Christian & Friel (1992)
BH 261	-0.76	0.36	13.90	-3.16	Ortolani et al. (2006)
NGC 6569	-0.76	0.49	15.40	-7.05	V07
UKS 1	-0.98	2.2	16.01	-9.20	Minniti et al. (2011)
NGC 6638	-0.95	0.43	15.07	-6.10	V07
Terzan 9	-1.05	1.79	13.73	-5.60	V10
NGC 6642	-1.26	0.42	14.30	-4.70	Barbuy et al. (2006)
NGC 6626	-1.32	0.42	13.70	-6.04	Kerber et al. (2018)
NGC 6540	-1.35	0.66	13.57	-4.37	V10
NGC 6558	-1.32	0.50	14.59	-5.12	Barbuy et al. (2018)
NGC 6453	-1.50	0.69	15.15	-5.83	V10
NGC 6715	-1.49	0.14	17.27	-7.62	S11

Notes. ^(a)The [Fe/H] values are taken from the 2010 version of the Harris (1996) catalogue. ^(b)The M_V values are calculated using the VVV/VVVX datasets, following the same procedure as used for the clusters analysed in the present work (see Sect. 4).

well-populated GC, including 470 stars, with a metallicity of $[\text{Fe}/\text{H}] = -0.6 \pm 0.2$ at $D = 8.9 \pm 0.5$ kpc and an age of ~ 10 Gyr.

VVV-CL150. Borissova et al. (2014) recognised this cluster as a possible new bulge GC, lying in VVV tile b350. Their CMD is well populated and they place the RC at $K_s = 13.10 \pm 0.2$, and the TO at $K_s = 17.2 \pm 0.4$ mag. They calculated reddening of $E(J - K_s) = 1.2 \pm 0.1$, distance modulus of $(M - m)_0 = 14.22 \pm 0.7$ (6.98 kpc), age of 10 ± 0.8 Gyr, and metallicity of $[\text{Fe}/\text{H}] = -0.75 \pm 0.11$. We also obtain similar results in this case. We count 383 stars belonging to VVV-CL150. We do not identify the RC, not even from inspection of the cluster LF, concluding that it is a metal-poor GC with $[\text{Fe}/\text{H}] = -1.30$. Also, we find a similar age (12 Gyr) within the errors.

VVV-CL154. Located in VVV tile b321, this object was classified as an old open cluster in close proximity to the Sun, because Borissova et al. (2014) derived a reddening of $E(J - K_s) = 1.2 \pm 0.1$, a distance modulus of $(M - m)_0 = 10.1 \pm 0.3$ (1.05 kpc), an age of 8 ± 0.2 Gyr, and a metallicity of $[\text{Fe}/\text{H}] = -0.69 \pm 0.4$ from analysis of its CMD. Aside from the metallicity, our estimates are different for this cluster. Our findings indicate an old and distant (~ 8.9 kpc) GC located near the Galactic centre ($R_G = 0.78$ kpc).

VVV-CL160. This cluster lies in VVV tile b340. The RGB and MS are well defined in the Borissova CMD, where the RC and TO are identified at $K_s = 13.1 \pm 0.3$ mag and $K_s = 14.8 \pm 0.4$ mag, respectively. Their calculated physical parameters are: reddening $E(J - K_s) = 1.72 \pm 0.1$, distance modulus $(M - m)_0 = 13.60 \pm 0.3$ (5.25 kpc), age 1.6 ± 0.5 Gyr, and metallicity $[\text{Fe}/\text{H}] = -0.72 \pm 0.21$. Borissova et al. (2014) concluded that VVV-CL160 may be an old metal-poor open cluster. Recently, Minniti et al. (2021a) found a reddening of

$E(J - K_s) = 1.95$ mag, a distance modulus of $(m - M)_0 = 13.01$ mag (4.0 kpc), a metallicity of $[\text{Fe}/\text{H}] = -1.40$, an age of 12 Gyr, and a luminosity of $M_V = -5.1$. Interestingly, Minniti et al. (2021a) concluded that VVV-CL160 may belong to a disrupted dwarf galaxy, because the kinematics are similar to those of the known GC NGC 6544 and the Hrid halo stream. Our parameters are in reasonable agreement with both works, as we find a reddening value similar to that of Borissova et al. (2014), while we agree with Minniti et al. (2021a) on the metallicity, luminosity, and age, confirming the GC nature. However, we place this cluster farther than in previous works, at 6.8 kpc from the Sun. Finally, VVV-CL119, CL143, and CL150 were also catalogued as star cluster candidates in the list of Minniti et al. (2017a).

6.3. ESO star cluster candidates

Listed in the Kharchenko et al. (2013) catalogue, ESO 393-12 and ESO 456-9 were recognised as possible globular clusters, located at RA = 17:38:40, Dec = -35:39:00 and RA = 17:53:56.4, Dec = -32:27:54, $\sim 27.40''$ and $26.90''$ from our positions, respectively. In this work, the PM values are $\mu_{\alpha_*} = 4.16$ mas yr⁻¹ and $\mu_\delta = -4.85$ mas yr⁻¹ for ESO 393-12, and $\mu_{\alpha_*} = 3.83$ mas yr⁻¹ and $\mu_\delta = -10.60$ mas yr⁻¹ for ESO 456-09. On the other hand, Dias et al. (2014) catalogued them as open galactic clusters. Our results are inline with those of Kharchenko et al. (2013), as we find two GCs, including RR Lyrae variable stars, which suggests an old age ($t > 10$ Gyr) for these clusters.

6.4. DB044

DB044 was discovered by Dutra & Bica (2000), who classified this as a possible star cluster. It was further studied by

Fig. 11. *Gaia* CMDs for the eight clusters for which we obtain reliable results in the optical passband. The black dotted line depicts the isochrone with the same age and metallicity as the VVV photometry and listed in Table 3.

Kharchenko et al. (2013), as a possible open cluster, with PMs of $\mu_{\alpha_*} = -6.38 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -11.70 \text{ mas yr}^{-1}$. We obtain very different cluster PMs, and we exclude the open cluster nature for two reasons: firstly, because it may include six RR Lyrae stars in its field, and secondly because we derive an age of $\sim 11 \text{ Gyr}$. Admittedly, this is not a clear case.

6.5. Kronberger 49

Kronberger 49, designed as DSH J1810.3-2320, was discovered by Kronberger et al. (2006). Inspections of DSS/XDSS and 2MASS images revealed a compact object, suggesting that it could be a GC core. Further, Ortolani et al. (2006) observed Kronberger 49 at the Telescopio Nazionale Galileo (TNG) using *V*, *I*, and Gunn *z* photometry, combining them with additional photometry from 2MASS, DENIS, WISE, and VVV surveys. These latter authors analysed the optical decontaminated CMD, where prominent features are a well-defined TO and an RGB with a turnover, suggesting high metallicity. Indeed, the main parameters are a distance modulus of $(m - M)_V = 18.8$, $(m_M)_I = 16.9$, and a reddening of $E(V - I) = 1.8$ (equivalent to $E(B - V) = 1.35$), and thus a heliocentric distance of $d = 8 \pm 1 \text{ kpc}$. The abso-

lute magnitude was estimated following two methods based on 2MASS photometry, and Ortolani et al. (2006) calculated $M_V = -5.4 \pm 0.5$ and -4.8 ± 0.5 . Moreover, they placed Kronberger 49 at 1.2 kpc from the Galactic centre (assuming $R_{\odot} = 8.28 \text{ kpc}$), indicating that it would be an inner bulge cluster. In conclusion, constructing a radial density profile Ortolani et al. (2006) proposed that this cluster might be a core collapse GC, similar to many others in the central part of the MW. They concluded that this is a metal-rich object with $[\text{Fe}/\text{H}] \approx -0.1$, with an age $t \gtrsim 10 \text{ Gyr}$. We find similarities between the present work and this latter: we place Kronberger 49 at $R_G = 1.14$ from the Galactic centre and at $D = 8.3 \text{ kpc}$ from the Sun, in agreement with Ortolani et al. (2006). Also, we confirm the metal-rich content and the old age, but we derive a slightly brighter luminosity.

7. Summary and conclusions

In recent decades, many star clusters have been discovered towards the Galactic bulge. However, most of them have not yet been well studied. In this work we study 19 star clusters, recovering their main physical parameters. Reddenings and extinctions along each cluster field are calculated adopting reddening maps

Fig. 12. Spatial distribution of RR Lyrae variable stars detected within 12' from GC centres. The magenta points represent the RR Lyrae that are considered cluster members. The distance error bars are of 0.5 kpc for each point. The dotted line depicts the heliocentric distance derived from the VVV photometry.

in the NIR and measuring the RC position. We also measure their distances using the VVV photometry, including also the *Gaia* photometry in some cases. Furthermore, we first search for RR Lyrae stars in each cluster field, and we then use the variable star members to estimate the cluster distance as an independent method. Using the isochrone-fitting method with the PARSEC isochrone models we derive their metallicities and ages. We find 11 metal-rich and 3 metal-poor GCs, whereas 2 GCs show intermediate metallicity. We find that the majority of our targets are low-luminosity GCs with M_V fainter than the MW GCLF peak.

Dedicated photometric studies spread across the bulge concluded that its mean age is of ~ 10 Gyr, and in particular setting a lower limit on ages of 5 Gyr (Clarkson et al. 2011). In this context, we confirm that the clusters studied in this work are members of the Galactic bulge according to their kinematics, positions, ages ($t > 8$ Gyr), and metallicity range ($0.0 > [\text{Fe}/\text{H}] > -1.40$). We also identify three open clusters: FSR 0022, BICA 523, and BICA 524.

In conclusion, we confirm the nature of nine candidates as bona fide GCs: VVV-CL131, VVV-CL143, VVV-CL160, FSR 0009, FSR 1767, FSR 1775, ESO 393-12, ESO 456-09, and Kronberger 49. On the other hand, confirmation of the true nature of the remaining seven candidates requires further investigation, because the effect of the dust strongly reddens their CMDs. This

is especially clear in the CMDs of VVV-CL110, CL119, CL128, CL150, and CL153, which show a wider RGB –something that is not typical for bulge GCs– and a poorly defined RC. Therefore, follow-up observations are needed, including spectroscopy in order to measure their kinematics, dynamics, and chemical composition, and deeper imaging to derive their absolute age using the MSTO and calculate their structural parameters.

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Appendix A: VPMs and CMDs for each cluster

Fig. A.1. VPM, as 2D histogram diagram, of the stars in the cluster regions within the given radius r from its centre. Yellow areas are representative of over-densities, which become green and blue when the density decreases. White dot circles depict the 1σ , 2σ , and 3σ from the mean cluster PM value. On the top and on the right panels, we show the corresponding PM histograms, pmra (blue), and pmdec (red), respectively. We use a different bin size depending on the crowding of the areas. We add an insert for the VV-CL160 cluster in order to make the PM over-density much more visible.

Fig. A.1. Continued.

Fig. A.1. Continued.

Fig. A.2. *Left panel:* VVV CMD for contaminated (grey points) and PM-decontaminated samples (Hess diagram). We show the position in the CMD of the RR Lyrae stars located at 12' from the cluster centres (black squared) and those considered cluster members (magenta squared). *Middle and Right panes:* 2MASS+VVV CMDs for PM-selected members. We fit a family of isochrones (cyan, red, and yellow lines), changing metallicities and ages, respectively. The red line is the PARSEC isochrones best-fit for each cluster (see Table 3).

Fig. A.2. Continued.

Fig. A.2. Continued.

Fig. A.2. Continued.

Appendix B: Additional Table

Table B.1. Properties of RR Lyrae samples in each GC field within 12'. We highlight with a star symbol all the variables that we consider members of the respective clusters.

ID Cluster	ID RR Lyrae	RA [deg]	Dec [deg]	P [day]	V [mag]	K_s [mag]	J [mag]	D_{RRLS} [kpc]	D_c [arcmin]	μ_{α_*} [mas yr ⁻¹]	μ_{δ} [mas yr ⁻¹]
VVVCL154	OGLE-BLG-RRLYR-31849	268.6284	-28.0437	0.2957846	—	15.08	16.14	8.7	9.9	-6.81	-5.119
VVVCL154	OGLE-BLG-RRLYR-31855	268.6331	-28.0206	0.526845	22.17	14.68	15.76	8.4	10.2	—	—
VVVCL154	OGLE-BLG-RRLYR-31867	268.6435	-28.2037	0.7274215	19.49	14.05	14.82	7.3	10.4	-5.545	-7.643
VVVCL154	OGLE-BLG-RRLYR-31877	268.6523	-28.2061	0.5223266	19.35	14.37	15.1	7.2	10.1	-1.585	-5.245
VVVCL154	OGLE-BLG-RRLYR-31898	268.6618	-28.0111	0.5278617	—	14.69	15.84	8.4	9.0	—	—
VVVCL154	OGLE-BLG-RRLYR-31902	268.6652	-28.2087	0.5584574	21.98	15.05	16.01	10.2	9.6	-2.194	-1.874
VVVCL154	OGLE-BLG-RRLYR-31908★	268.6681	-28.0259	0.6702737	—	14.58	15.89	9.0	8.2	1.636	-4.757
VVVCL154	OGLE-BLG-RRLYR-31938	268.6857	-28.0951	0.6323773	—	14.71	16.17	9.3	5.9	—	—
VVVCL154	OGLE-BLG-RRLYR-31941	268.6899	-28.1139	0.2558873	—	15.06	16.26	8.0	5.7	3.04	-1.083
VVVCL154	OGLE-BLG-RRLYR-31942★	268.6909	-27.9855	0.5565757	21.9	14.73	15.57	8.8	8.8	-5.832	-5.821
VVVCL154	OGLE-BLG-RRLYR-31960	268.7024	-27.9769	0.2949171	20.85	14.89	15.21	7.9	8.9	-2.572	-3.292
VVVCL154	OGLE-BLG-RRLYR-31962★	268.703	-28.0839	0.5279925	—	14.84	16.09	9.0	4.9	-3.127	-6.495
VVVCL154	OGLE-BLG-RRLYR-31966	268.7039	-28.0552	0.5208234	—	14.92	16.21	9.3	5.5	—	—
VVVCL154	OGLE-BLG-RRLYR-31967	268.7049	-28.1295	0.2869678	20.4	14.74	15.48	7.3	5.0	-2.49	1.132
VVVCL154	OGLE-BLG-RRLYR-31969	268.7058	-28.1439	0.484147	—	14.62	15.55	7.8	5.3	-5.771	-4.005
VVVCL154	OGLE-BLG-RRLYR-31971	268.7097	-28.2149	0.7063366	21.37	14.38	15.34	8.4	8.2	2.047	-1.077
VVVCL154	OGLE-BLG-RRLYR-31990★	268.7178	-28.031	0.5542389	—	14.73	15.7	8.8	5.7	-5.639	-8.718
VVVCL154	OGLE-BLG-RRLYR-32004	268.7267	-28.0066	0.4577286	20.48	13.57	14.59	4.7	6.6	-9.049	-5.778
VVVCL154	OGLE-BLG-RRLYR-32007★	268.7289	-27.9811	0.2600223	21.58	15.26	16.08	8.9	7.9	-4.066	-9.283
VVVCL154	OGLE-BLG-RRLYR-32024★	268.743	-28.1039	0.5293469	—	14.77	16.3	8.7	2.4	-2.788	-4.074
VVVCL154	OGLE-BLG-RRLYR-32029	268.745	-28.2024	0.5918788	—	15.87	16.84	15.3	6.5	—	—
VVVCL154	OGLE-BLG-RRLYR-32038	268.7515	-28.1637	0.5024584	19.88	13.9	14.7	5.7	4.3	-2.971	-5.835
VVVCL154	OGLE-BLG-RRLYR-32042★	268.7538	-28.2099	0.6431962	20.42	14.37	15.21	8.0	6.8	-0.482	-7.594
VVVCL154	OGLE-BLG-RRLYR-32046	268.7578	-28.2583	0.3334006	20.65	14.6	15.5	7.4	9.6	1.244	-0.215
VVVCL154	OGLE-BLG-RRLYR-32051	268.7624	-27.9862	0.6701652	22.26	14.39	15.54	7.2	7.0	-3.752	1.226
VVVCL154	OGLE-BLG-RRLYR-32052★	268.7626	-28.2543	0.5227533	21.4	14.73	15.57	8.3	9.3	-2.126	-6.599
VVVCL154	OGLE-BLG-RRLYR-32056	268.7638	-28.0611	0.2592107	—	15.18	15.93	8.5	2.6	—	—
VVVCL154	OGLE-BLG-RRLYR-32057	268.7676	-28.2012	0.6348947	—	14.35	15.25	8.5	6.1	1.103	-4.045
VVVCL154	OGLE-BLG-RRLYR-32067★	268.7788	-27.9733	0.2673053	22.28	15.24	16.05	8.9	7.6	-2.387	-6.92
VVVCL154	OGLE-BLG-RRLYR-32072★	268.7824	-27.9565	0.6135911	20.81	14.32	15.18	7.6	8.6	-1.541	-3.611
VVVCL154	OGLE-BLG-RRLYR-32083	268.7906	-28.2239	0.2812811	20.15	14.68	15.38	7.1	7.4	3.001	-3.569
VVVCL154	OGLE-BLG-RRLYR-32085	268.7924	-28.1722	0.4918871	20.28	14.48	15.36	7.3	4.3	-2.983	-6.053
VVVCL154	OGLE-BLG-RRLYR-32101★	268.8049	-28.2565	0.5903478	19.92	14.52	15.29	8.2	9.5	0.664	-1.73
VVVCL154	OGLE-BLG-RRLYR-32102	268.8051	-28.1453	0.4806654	2.0	14.48	15.25	7.3	3.0	-7.417	-9.068
VVVCL154	OGLE-BLG-RRLYR-32105	268.8104	-28.1677	0.3156331	21.68	15.51	16.31	10.7	4.4	-2.697	-2.515
VVVCL154	OGLE-BLG-RRLYR-32109	268.8143	-27.9695	0.5341929	—	14.59	15.37	8.1	8.1	—	—
VVVCL154	OGLE-BLG-RRLYR-32125	268.8239	-27.943	0.536193	19.92	14.22	15.03	6.8	9.7	-4.121	-4.032
VVVCL154	OGLE-BLG-RRLYR-32126	268.8254	-28.0719	0.2878272	21.53	14.86	15.78	7.8	3.0	4.409	-5.655
VVVCL154	OGLE-BLG-RRLYR-32128★	268.8265	-28.2278	0.5197572	20.42	14.64	15.41	8.1	8.1	2.003	-3.581
VVVCL154	OGLE-BLG-RRLYR-32139	268.8335	-28.2183	0.3100202	19.63	14.41	15.14	6.5	7.7	-10.32	-1.854
VVVCL154	OGLE-BLG-RRLYR-32146	268.8375	-28.1352	0.5954208	19.97	14.23	15.06	7.2	3.9	-5.873	-10.197
VVVCL154	OGLE-BLG-RRLYR-32147★	268.8379	-27.9986	0.7253929	21.84	14.74	15.67	10.1	6.9	-2.38	-4.776
VVVCL154	OGLE-BLG-RRLYR-32152	268.8392	-27.9709	0.3874457	20.26	14.44	15.18	7.4	8.5	3.413	-6.722
VVVCL154	OGLE-BLG-RRLYR-32161★	268.8439	-28.1966	0.2575597	20.99	15.29	15.99	8.9	6.8	-3.118	-5.865

Table B.1. continued.

ID Cluster	ID RR Lyrae	RA [deg]	Dec [deg]	P [day]	V [mag]	K_s [mag]	J [mag]	D_{RRLS} [kpc]	D_c [arcmin]	μ_{α_*} [mas yr ⁻¹]	μ_{δ} [mas yr ⁻¹]
VVVCL154	OGLE-BLG-RRLYR-32167	268.8453	-27.9902	0.3117361	20.79	14.93	15.74	8.3	7.6	-0.512	-9.141
VVVCL154	OGLE-BLG-RRLYR-32171	268.8463	-28.0338	0.5983338	21.97	14.82	15.82	9.5	5.5	-6.168	-10.743
VVVCL154	OGLE-BLG-RRLYR-32185	268.8569	-27.965	0.2508808	21.09	15.12	15.94	8.1	9.2	-4.886	-7.319
VVVCL154	OGLE-BLG-RRLYR-32197	268.8652	-27.9533	0.6042157	20.28	14.25	15.14	7.4	10.1	-8.543	-8.788
VVVCL154	OGLE-BLG-RRLYR-32198	268.8667	-28.2269	0.2756981	20.22	14.88	15.56	7.7	9.1	-2.061	-8.591
VVVCL154	OGLE-BLG-RRLYR-32212	268.8749	-27.9691	0.3468166	20.43	14.85	15.6	8.5	9.6	-5.738	-1.765
VVVCL154	OGLE-BLG-RRLYR-32230	268.8871	-28.0332	0.3593307	20.55	14.67	15.43	7.9	7.4	-3.445	-11.858
VVVCL154	OGLE-BLG-RRLYR-32234	268.8901	-28.2309	0.5318649	20.36	14.56	15.45	7.9	10.1	-5.794	-5.428
VVVCL154	OGLE-BLG-RRLYR-32238	268.8942	-28.1385	0.6298719	21.01	14.54	15.45	8.6	7.0	-10.81	-7.612
VVVCL154	OGLE-BLG-RRLYR-32261★	268.9102	-28.1785	0.6813527	21.18	14.57	15.38	9.1	8.9	-0.447	-4.361
VVVCL154	OGLE-BLG-RRLYR-32268	268.9143	-28.156	0.3038136	20.5	14.8	15.52	7.8	8.5	3.136	-2.847
VVVCL154	OGLE-BLG-RRLYR-32283	268.9246	-28.0078	0.4927651	20.4	13.73	14.78	5.2	10.1	3.597	-9.091
VVVCL154	OGLE-BLG-RRLYR-32297	268.9327	-28.1388	0.5333822	21.27	14.9	15.91	10.0	9.3	-6.901	-6.53
VVVCL154	OGLE-BLG-RRLYR-32322	268.9521	-28.0384	0.4673814	20.69	14.47	15.47	7.6	10.8	---	---
DB044	OGLE-BLG-RRLYR-28715	266.4744	-24.8868	0.5610397	---	15.07	16.1	9.7	10.3	-6.753	-1.822
DB044	OGLE-BLG-RRLYR-28782	266.517	-24.998	0.5207337	21.32	15.43	16.45	11.0	10.0	-3.266	-5.884
DB044	OGLE-BLG-RRLYR-28794	266.5275	-24.9285	0.6581612	20.28	14.28	15.17	7.2	7.4	-4.348	-2.717
DB044	OGLE-BLG-RRLYR-28810	266.5392	-24.8102	0.810599	21.37	14.01	15.11	7.0	8.0	-1.376	-7.399
DB044	OGLE-BLG-RRLYR-28813	266.54	-24.99	0.796195	20.44	14.51	15.45	8.8	8.7	-7.253	-4.381
DB044	OGLE-BLG-RRLYR-28835	266.5514	-24.7805	0.469473	21.08	14.41	15.38	6.5	8.7	-6.122	-5.806
DB044	OGLE-BLG-RRLYR-28845★	266.5591	-25.0286	0.6161224	21.04	14.42	15.4	7.5	9.8	-6.754	-7.669
DB044	OGLE-BLG-RRLYR-28857	266.5669	-24.9776	0.4712295	20.06	14.39	15.32	6.5	7.0	-4.568	-1.2
DB044	OGLE-BLG-RRLYR-28870★	266.5759	-24.9575	0.5675825	20.91	14.64	15.67	8.0	5.8	-1.594	-7.447
DB044	OGLE-BLG-RRLYR-28875★	266.5784	-24.9967	0.4820862	20.9	14.91	15.91	8.4	7.5	-4.073	-7.89
DB044	OGLE-BLG-RRLYR-28876★	266.5787	-24.9653	0.7569609	20.73	14.43	15.42	8.3	6.0	-2.098	-7.042
DB044	OGLE-BLG-RRLYR-28878	266.5803	-24.9563	0.5827392	20.11	14.33	15.37	7.0	5.5	-7.019	-5.054
DB044	OGLE-BLG-RRLYR-28889	266.5901	-24.9258	0.5984483	20.49	14.65	15.52	8.2	3.9	-6.95	-5.86
DB044	OGLE-BLG-RRLYR-28893	266.5928	-25.0445	0.4890572	20.89	14.57	15.49	7.2	9.7	-6.943	-3.903
DB044	OGLE-BLG-RRLYR-28895	266.5934	-25.0144	0.3096242	-99.99	14.74	15.55	6.6	8.0	-1.793	-9.514
DB044	OGLE-BLG-RRLYR-28897	266.5938	-24.8594	0.4852231	20.6	14.46	15.37	6.8	3.7	-4.84	-3.493
DB044	OGLE-BLG-RRLYR-28907	266.6002	-24.8185	0.2612227	-99.99	15.24	16.17	7.7	5.1	-6.806	-5.405
DB044	OGLE-BLG-RRLYR-28916	266.6054	-24.8065	0.4890075	-99.99	14.73	16.08	7.8	5.6	-4.317	-7.519
DB044	OGLE-BLG-RRLYR-28923	266.6088	-24.7283	0.2768075	21.53	15.4	16.25	8.6	10.0	-9.282	-5.984
DB044	OGLE-BLG-RRLYR-28937	266.6158	-24.8575	0.576656	21.3	14.79	15.6	8.6	2.7	-1.577	-2.033
DB044	OGLE-BLG-RRLYR-28962	266.6258	-25.0254	0.2810044	20.51	14.45	15.43	5.6	8.1	---	---
DB044	OGLE-BLG-RRLYR-28970	266.6276	-24.7371	0.4247647	-99.99	15.79	16.63	11.8	9.3	-6.182	-6.7
DB044	OGLE-BLG-RRLYR-28972★	266.6281	-24.8412	0.5042931	20.96	14.76	15.78	8.0	3.2	-1.122	-4.27
DB044	OGLE-BLG-RRLYR-29003	266.6479	-24.9667	0.4983005	20.49	14.61	15.37	7.4	4.5	-2.112	0.292
DB044	OGLE-BLG-RRLYR-29044	266.6738	-24.8928	0.5575422	-99.99	15.24	16.36	10.4	1.7	-3.544	-10.1
DB044	OGLE-BLG-RRLYR-29085	266.7048	-24.7479	0.5266495	21.14	14.65	15.71	7.7	9.3	-2.186	-4.64
DB044	OGLE-BLG-RRLYR-29101	266.7153	-24.7527	0.5680777	21.53	14.89	16.0	8.9	9.3	-4.58	0.783
DB044	OGLE-BLG-RRLYR-29183	266.7604	-25.0117	0.5564618	22.03	14.65	15.69	7.9	10.0	-4.625	-9.005
DB044	OGLE-BLG-RRLYR-29208	266.7717	-24.9875	0.2785731	22.06	14.95	15.89	7.0	9.5	-5.679	-6.981
DB044	OGLE-BLG-RRLYR-29221★	266.7792	-24.9384	0.5040744	-99.99	14.76	15.81	8.0	8.5	-4.669	-7.874
DB044	OGLE-BLG-RRLYR-29232	266.7872	-24.8763	0.3237754	21.03	14.67	15.56	6.6	8.5	-3.856	-4.661
DB044	OGLE-BLG-RRLYR-29261	266.8099	-24.96	0.5964202	21.84	14.48	15.55	7.6	10.7	-3.333	-4.05
VVVCL131	OGLE-BLG-RRLYR-25540	265.1568	-34.4823	0.4729397	20.17	15.48	16.21	12.1	11.1	-3.886	-8.546
VVVCL131	OGLE-BLG-RRLYR-25628	265.1924	-34.5224	0.4767443	19.76	15.28	15.92	11.1	8.2	-5.057	-1.124

Table B.1. continued.

ID Cluster	ID RR Lyrae	RA [deg]	Dec [deg]	P [day]	V [mag]	K_s [mag]	J [mag]	D_{RRLS} [kpc]	D_c [arcmin]	μ_{α_*} [mas yr ⁻¹]	μ_{δ} [mas yr ⁻¹]
VVVCL131	OGLE-BLG-RRLYR-25655	265.2024	-34.6035	0.5628037	20.67	14.86	15.78	9.9	7.4	-6.032	-6.195
VVVCL131	OGLE-BLG-RRLYR-25672	265.2114	-34.6037	0.4413626	21.34	13.41	14.90	4.5	6.9	-3.129	-4.654
VVVCL131	OGLE-BLG-RRLYR-25782	265.2531	-34.6631	0.7436588	18.87	14.14	14.96	8.2	7.0	-0.3417	-3.671
VVVCL131	OGLE-BLG-RRLYR-25821★	265.2686	-34.5599	0.2920761	19.09	15.14	15.71	9.4	3.2	-1.422	-4.31
VVVCL131	OGLE-BLG-RRLYR-25829	265.2734	-34.4837	0.4050738	19.54	15.12	15.78	9.5	5.8	-6.684	-3.091
VVVCL131	OGLE-BLG-RRLYR-25844	265.2776	-34.5019	0.3265574	18.95	14.99	15.62	9.3	4.7	-6.927	-3.983
VVVCL131	OGLE-BLG-RRLYR-25850	265.2807	-34.4797	0.2144367	19.16	15.02	15.60	7.6	5.8	-3.007	-2.984
VVVCL131	OGLE-BLG-RRLYR-25872	265.2895	-34.6289	0.4121736	19.04	14.73	15.38	8.0	4.2	-5.189	-9.796
VVVCL131	OGLE-BLG-RRLYR-25879	265.2913	-34.5464	0.5483412	18.65	14.44	15.15	8.1	2.2	-5.606	-1.293
VVVCL131	OGLE-BLG-RRLYR-25979	265.3297	-34.6453	0.6133653	18.36	14.27	14.92	7.9	4.7	-7.074	-7.687
VVVCL131	OGLE-BLG-RRLYR-25989	265.3362	-34.5353	0.5697337	18.20	14.38	15.05	8.0	2.1	-7.4	-8.295
VVVCL131	OGLE-BLG-RRLYR-26062	265.3587	-34.5604	0.2868744	18.26	14.88	15.48	8.3	2.3	0.4802	-2.474
VVVCL131	OGLE-BLG-RRLYR-26148	265.3902	-34.5821	0.9635919	18.21	14.02	14.73	8.9	4.3	-6.718	-0.7498
VVVCL131	OGLE-BLG-RRLYR-26154★	265.3918	-34.5918	0.5227194	19.05	14.73	15.40	9.0	4.5	-1.806	-4.457
VVVCL131	OGLE-BLG-RRLYR-26323	265.4554	-34.5359	0.5784567	18.23	14.19	14.83	6.7	7.4	-4.292	-7.745
VVVCL143	OGLE-BLG-RRLYR-1808	266.0056	-33.819	0.3161524	19.4	14.65	15.37	7.9	9.9	-3.677	-2.274
VVVCL143	OGLE-BLG-RRLYR-1810	266.0078	-33.7866	0.6267657	19.12	12.98	14.19	4.5	9.0	--	--
VVVCL143	OGLE-BLG-RRLYR-1816	266.0225	-33.8636	0.4897335	20.92	15.07	15.9	10.3	10.7	0.697	-7.379
VVVCL143	OGLE-BLG-RRLYR-1817	266.0233	-33.8149	0.4998257	18.67	12.98	14.05	4.0	8.9	-1.148	-2.604
VVVCL143	OGLE-BLG-RRLYR-1840	266.0564	-33.7357	0.3622305	19.46	14.59	15.28	8.2	5.6	-3.585	-1.964
VVVCL143	OGLE-BLG-RRLYR-1842	266.0594	-33.604	0.5501256	18.82	14.48	15.19	8.3	9.7	-4.875	-2.943
VVVCL143	OGLE-BLG-RRLYR-1843	266.0605	-33.6834	0.4862021	19.47	14.92	15.52	9.6	6.3	-0.562	-9.28
VVVCL143	OGLE-BLG-RRLYR-1856	266.0751	-33.6656	0.4861809	19.92	14.49	15.2	7.9	6.3	-6.761	-2.469
VVVCL143	OGLE-BLG-RRLYR-1871	266.0927	-33.819	0.4876707	19.54	14.89	15.6	9.5	5.9	-10.98	-5.435
VVVCL143	OGLE-BLG-RRLYR-1902	266.1483	-33.6071	0.2530813	18.81	14.84	15.42	7.7	7.9	3.832	-5.825
VVVCL143	OGLE-BLG-RRLYR-1921	266.1687	-33.7774	0.5616153	18.47	14.44	15.06	8.3	2.6	0.135	-9.054
VVVCL143	OGLE-BLG-RRLYR-1930	266.1828	-33.7096	0.2128831	18.72	15.32	15.88	8.8	2.6	-2.31	-1.229
VVVCL143	OGLE-BLG-RRLYR-1934	266.1884	-33.6093	0.5451788	18.28	13.1	14.12	4.4	8.1	--	--
VVVCL143	OGLE-BLG-RRLYR-1951	266.212	-33.6885	0.4103589	18.01	14.48	14.98	7.2	4.8	-7.108	-7.203
VVVCL143	OGLE-BLG-RRLYR-1952	266.2131	-33.8177	0.5854312	18.23	14.25	14.9	7.7	6.1	--	--
VVVCL143	OGLE-BLG-RRLYR-1953★	266.2132	-33.8861	0.5645519	18.33	14.6	15.29	8.9	9.6	-2.369	-5.567
VVVCL143	OGLE-BLG-RRLYR-1981	266.2543	-33.8232	0.266701	18.98	15.74	16.24	12.0	8.1	-5.475	-7.227
VVVCL143	OGLE-BLG-RRLYR-2019★	266.2908	-33.7593	0.5942394	18.32	14.22	14.89	7.7	8.5	-0.392	-6.068
VVVCL143	OGLE-BLG-RRLYR-2033	266.3029	-33.8348	0.3189595	18.39	14.71	15.3	8.2	10.8	0.363	-8.91
VVVCL143	OGLE-BLG-RRLYR-2083	266.3386	-33.6841	0.6098489	18.09	14.32	14.96	8.2	11.8	-3.406	-7.908
VVVCL143	OGLE-BLG-RRLYR-28294★	266.2448	-33.7902	0.2950622	18.77	15.18	15.71	9.7	6.5	-0.488	-3.132
VVVCL143	OGLE-BLG-RRLYR-28382★	266.2947	-33.7378	0.8623781	17.83	14.09	14.75	8.8	8.7	-7.268	-2.622
FSR1775	OGLE-BLG-RRLYR-07563★	268.9155	-36.5419	0.6295925	17.12	14.62	15.31	9.9	6.6	-2.367	-4.914
FSR1775	OGLE-BLG-RRLYR-07686	268.9768	-36.6496	0.3468452	16.44	14.26	14.73	7.2	5.7	-2.295	-0.841
FSR1775	OGLE-BLG-RRLYR-07854	269.0391	-36.6278	0.4896602	16.51	14.41	14.77	7.9	3.9	-0.138	-3.219
FSR1775	OGLE-BLG-RRLYR-07909★	269.0592	-36.6091	0.2832088	16.84	14.92	15.39	8.8	3.4	-2.154	-5.334
FSR1775	OGLE-BLG-RRLYR-07941	269.0744	-36.4699	0.3388444	16.17	13.90	14.59	6.0	6.6	-0.630	-12.885
FSR1775	OGLE-BLG-RRLYR-08075	269.1244	-36.6262	0.5052062	16.92	14.66	15.39	9.0	7.1	-5.536	2.243
FSR1775	OGLE-BLG-RRLYR-08080	269.1257	-36.4505	0.5689601	17.30	14.63	15.35	9.4	9.3	-0.821	-5.112
FSR1775	OGLE-BLG-RRLYR-32595	269.2184	-36.5455	0.5800306	16.30	14.17	14.84	7.7	11.8	-3.126	-1.385
FSR1767	OGLE-BLG-RRLYR-21653	263.7614	-36.3636	0.5382471	19.26	14.35	15.21	6.7	10.1	-3.061	-4.352
FSR1767	OGLE-BLG-RRLYR-22035★	263.9167	-36.3381	0.6364407	19.64	14.80	15.50	9.0	1.4	-2.334	-5.879
FSR1767	OGLE-BLG-RRLYR-22054	263.9221	-36.2895	0.5399269	20.15	14.45	15.20	7.0	4.1	4.402	-10.080

Table B.1. continued.

ID Cluster	ID RR Lyrae	RA [deg]	Dec [deg]	P [day]	V [mag]	K_s [mag]	J [mag]	D_{RRLS} [kpc]	D_c [arcmin]	μ_{α_*} [mas yr ⁻¹]	μ_{δ} [mas yr ⁻¹]
FSR1767	OGLE-BLG-RRLYR-22325	264.0311	-36.4791	0.2938189	19.34	14.48	15.25	6.1	9.5	-4.658	-2.448
FSR1767	OGLE-BLG-RRLYR-22342★	264.0370	-36.3327	0.6084582	20.43	15.02	15.77	9.7	6.6	-2.221	-7.208
FSR1767	OGLE-BLG-RRLYR-22385	264.0524	-36.4410	0.6041570	19.45	14.71	15.43	8.4	8.9	-3.999	-7.417
FSR1767	OGLE-BLG-RRLYR-22500	264.0981	-36.3759	0.3061927	19.33	14.79	15.41	7.2	10.2	-0.119	-6.111
ESO393-12	OGLE-BLG-RRLYR-24232	264.7043	-35.6632	0.2833770	16.46	14.52	15.20	7.0	3.0	-8.679	-3.248
ESO393-12	OGLE-BLG-RRLYR-24016	264.6437	-35.6989	0.5980570	17.68	15.46	16.22	13.6	3.0	-3.970	-5.946
ESO393-12	OGLE-BLG-RRLYR-23892★	264.6068	-35.6957	0.6708310	16.63	14.26	15.00	8.3	4.0	-3.258	-6.625
ESO393-12	OGLE-BLG-RRLYR-24326	264.7361	-35.6510	0.8650970	15.74	13.60	14.35	6.9	4.8	-2.407	-9.103
ESO393-12	OGLE-BLG-RRLYR-23793	264.5673	-35.6081	0.2892410	17.89	15.43	16.14	10.7	5.9	-6.695	-6.716
ESO393-12	OGLE-BLG-RRLYR-24380	264.7588	-35.6008	0.4282180	15.90	14.10	14.78	6.1	6.8	-3.239	2.426
ESO393-12	OGLE-BLG-RRLYR-24366	264.7513	-35.7116	0.6268510	17.11	14.57	15.51	9.2	6.8	--	--
ESO393-12	OGLE-BLG-RRLYR-24146	264.6791	-35.7649	0.7082520	17.13	14.83	15.64	11.0	7.0	0.839	-6.124
ESO393-12	OGLE-BLG-RRLYR-23808★	264.5715	-35.5553	0.5479670	16.43	14.33	15.08	7.7	7.7	-3.690	-6.456
ESO393-12	OGLE-BLG-RRLYR-24391	264.7647	-35.7579	0.7508770	16.93	14.40	15.20	9.3	9.1	-1.188	-4.613
ESO393-12	OGLE-BLG-RRLYR-23846★	264.5873	-35.5193	0.3340570	16.82	14.58	15.27	7.8	8.9	-0.903	-5.977
ESO393-12	OGLE-BLG-RRLYR-23596	264.4851	-35.6136	0.5379749	16.86	14.50	15.40	8.2	10.5	-1.604	0.090
ESO393-12	OGLE-BLG-RRLYR-23789	264.5656	-35.7756	0.6234820	16.89	14.57	15.36	9.2	9.3	-9.734	-5.777
ESO393-12	OGLE-BLG-RRLYR-23717	264.5355	-35.5366	0.6613420	16.13	13.93	14.73	7.0	10.0	-10.553	-2.703
ESO393-12	OGLE-BLG-RRLYR-23580	264.4784	-35.5976	0.5232100	17.72	14.88	15.81	9.7	11.2	-8.638	-8.047
ESO456-09	OGLE-BLG-RRLYR-6584	268.506	-32.469	0.300182	17.149	14.28	14.72	5.8	1.79	-3.947	-18.124
ESO456-09	OGLE-BLG156.7-119095	268.4357	-32.4728	0.315771	17.861	14.57	15.15	6.8	2.47	-5.932	-1.305
ESO456-09	OGLE-BLG156.7-63639	268.4594	-32.5136	0.311188	17.748	14.67	15.23	7.1	3.02	-2.437	-9.79
ESO456-09	OGLE-BLG-RRLYR-6416	268.4456	-32.5115	0.278815	18.016	14.98	15.47	7.8	3.29	-6.086	-10.437
ESO456-09	OGLE-BLG-RRLYR-6615★	268.5186	-32.5158	0.610167	17.915	14.32	14.99	7.8	3.92	-0.695	-5.337
ESO456-09	OGLE-BLG-RRLYR-6298★	268.4025	-32.5029	0.316274	17.996	14.55	15.25	6.8	4.95	-5.133	-6.141
ESO456-09	OGLE-BLG-RRLYR-6695★	268.5483	-32.5099	0.351545	17.584	14.5	15.05	7.0	5.06	-4.435	-2.27
ESO456-09	OGLE-BLG-RRLYR-6751	268.57	-32.4531	0.622606	17.963	14.48	15.12	8.5	5.68	0.919	-8.021
ESO456-09	OGLE-BLG-RRLYR-6490★	268.4704	-32.5564	0.571457	17.714	14.35	15.03	7.7	5.43	-3.512	-4.738
ESO456-09	OGLE-BLG155.2-118495★	268.3918	-32.5255	0.540373	18.036	14.54	15.11	8.2	6.2	-4.244	-4.546
ESO456-09	OGLE-BLG-RRLYR-6728	268.5599	-32.5266	0.506702	17.735	14.41	14.9	7.23	7.5	-0.407	2.563
ESO456-09	OGLE-BLG-RRLYR-6411★	268.4411	-32.5591	0.564064	17.837	14.37	15.04	7.7	5.96	-6.211	-3.367
ESO456-09	OGLE-BLG-RRLYR-6252	268.3881	-32.5391	0.304918	18.609	15.1	15.69	8.6	6.87	-4.113	-1.387
ESO456-09	OGLE-BLG-RRLYR-6837	268.6056	-32.4733	0.567208	17.551	14.24	14.85	7.3	7.77	-6.73	-3.89
ESO456-09	OGLE-BLG-RRLYR-6150	268.3549	-32.5128	0.38559	17.908	14.51	15.16	7.3	7.81	-6.775	-5.161
ESO456-09	OGLE-BLG156.6-83017	268.5593	-32.3778	0.552816	18.354	14.69	15.35	8.9	7.27	-2.005	-5.778
ESO456-09	OGLE-BLG-RRLYR-6167	268.3616	-32.4072	0.359044	18.238	14.4	14.95	6.7	7.74	4.06	-8.893
ESO456-09	OGLE-BLG156.6-82844	268.5573	-32.3724	0.604871	17.76	14.12	14.99	7.5	7.43	-7.102	-9.897
ESO456-09	OGLE-BLG-RRLYR-6132	268.3475	-32.5136	0.425433	17.97	14.54	--	7.1	8.23	-4.151	-2.051
ESO456-09	OGLE-BLG-RRLYR-6858	268.615	-32.4994	0.362771	18.539	15.44	15.89	10.9	8.56	-1.862	-7.522
ESO456-09	OGLE-BLG-RRLYR-6129	268.3473	-32.5331	0.453186	17.684	14.66	15.27	7.9	8.72	-3.085	-10.76
ESO456-09	OGLE-BLG155.3-115521	268.3891	-32.3584	0.586622	17.97	13.76	14.58	5.9	8.32	-1.075	-6.056
ESO456-09	OGLE-BLG-RRLYR-6909	268.6336	-32.4844	0.373116	18.085	15.0	15.49	9.0	9.5	-0.379	-9.96
ESO456-09	OGLE-BLG-RRLYR-6876	268.6214	-32.5274	0.450459	17.195	14.2	14.7	6.4	9.45	-2.977	-7.047
ESO456-09	OGLE-BLG-RRLYR-6946	268.6491	-32.4545	0.333187	18.153	14.5	15.12	6.8	10.39	-3.125	-6.396
ESO456-09	OGLE-BLG-RRLYR-6037	268.3141	-32.5283	0.552234	19.01	15.15	15.72	11.0	10.42	-3.69	-7.714
ESO456-09	OGLE-BLG-RRLYR-6770	268.5753	-32.3411	0.328324	18.026	14.6	15.24	7.1	9.57	-4.925	-6.035
ESO456-09	OGLE-BLG-RRLYR-6191	268.3691	-32.3428	0.612561	19.268	14.59	15.47	8.9	9.81	-2.602	-10.055
ESO456-09	OGLE-BLG-RRLYR-6665	268.5381	-32.3206	0.44545	18.322	14.51	15.3	7.4	9.49	3.671	-10.405
ESO456-09	OGLE-BLG156.7-220529	268.6605	-32.4684	0.567581	17.512	14.3	14.93	7.5	11.05	-2.41	-4.895
ESO456-09	OGLE-BLG-RRLYR-6176	268.3644	-32.3409	0.523935	19.07	14.81	15.77	9.1	10.08	-6.319	-5.821
Kronberger49	OGLE-BLG-RRLYR-34383	272.6635	-23.2415	0.5003454	21.59	15.76	16.9	13.6	7.1	-2.327	-5.113
Kronberger49	OGLE-BLG-RRLYR-34323	272.5573	-23.2705	0.7306612	20.87	14.33	15.39	8.5	4.9	-8.198	-10.083
Kronberger49	OGLE-BLG-RRLYR-34315	272.5391	-23.2814	0.3609994	20.0	13.85	14.8	5.5	5.1	-7.674	-4.365
Kronberger49	OGLE-BLG-RRLYR-34337★	272.5835	-23.3502	0.5724149	20.51	14.51	15.39	8.2	1.1	-7.552	-7.456
Kronberger49	OGLE-BLG-RRLYR-34377	272.6478	-23.4044	0.5973248	20.3	14.23	15.19	7.3	4.8	-5.479	-18.806
Kronberger49	OGLE-BLG-RRLYR-34382	272.6582	-23.3706	0.6176361	20.48	14.7	15.66	9.3	4.0	-6.111	-9.491
Kronberger49	OGLE-BLG-RRLYR-34334★	272.5812	-23.4668	0.6591129	21.4	14.33	15.34	8.1	7.7	-1.381	-2.298
Kronberger49	OGLE-BLG-RRLYR-34340	272.5896	-23.5045	0.50217	--	14.67	15.89	8.2	9.9	--	--
Kronberger49	OGLE-BLG-RRLYR-34416★	272.7239	-23.429	0.2826901	20.92	15.04	15.96	8.5	9.2	-5.338	-7.442