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Survival in an extreme environment: Which is the closest globular cluster to the Galactic centre?

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ABSTRACT

Context. Globular clusters (GCs) are interesting probes of the Milky Way, and can be used to test different dynamical galaxy-wide processes. In particular, the inner regions of the Galaxy pose important challenges for the long-term survival of GCs, as threatening effects like dynamical friction accelerate their demise.

Aims. Our main goal is to search for the closest known GC to the Galactic centre using the VVV ESO Public Survey near-infrared database.

Methods. We investigate recently published GC candidates in a region within 2.5° from the Galactic centre using the preliminary update to the VVV Infrared Astrometric Catalogue, point-spread function photometry, and proper motions. In particular, VVV-CL002 and VVV-CL003 are located at a projected angular distance of 1.1 and 1.7° from the Galactic centre, much closer in projection than all other previously known GCs.

Results. The colour–magnitude diagrams and luminosity functions for VVV-CL002 and VVV-CL003 exhibit well-defined red giant branches and red clump peaks, and provide confirmation that both objects are metal-rich GCs. We measure their mean proper motions and distances, estimate their total luminosities, and model the orbits. In particular, we obtain $D = 8.6 \pm 0.6$ kpc and $D = 13.2 \pm 0.8$ kpc for VVV-CL002 and VVV-CL003, respectively.

Conclusions. We conclude that VVV-CL002 is a low-luminosity bulge GC, whereas VVV-CL003 is a distant background GC. Also, VVV-CL002 is the closest known GC to the centre of the Galaxy. For this cluster, the effect of dynamical friction is minimised because of the large cluster velocity, $V > 400 \text{ km s}^{-1}$, allowing the long-term survival of this GC in such a high-stellar-density medium. Furthermore, this GC has traversed through the Galactic plane very recently ($\sim 3.5 \times 10^5$ yr ago). There are many other GC candidates located within 2.5° of the Galactic centre that remain to be studied in detail: VVV-CL154, Camargo 1105, 1107, 1108, and 1109, and Minniti 20, 39, 40, 46, 47, 54, 55, 56, 57, 58, 59, and 60.

Key words. globular clusters: general – Galaxy: bulge – globular clusters: individual: VVV-CL002 – globular clusters: individual: VVV-CL003 – Galaxy: kinematics and dynamics – proper motions

1. Introduction

Globular Clusters (GCs) are important dynamical probes of the Milky Way. Whether or not there are places in the Galaxy where GCs cannot survive remains an open question. In order to answer this question, we must investigate the central regions of the Milky Way, where GCs are preferentially destroyed due to different dynamical processes; among the most important are tidal disruption and dynamical friction (e.g., Fall & Rees 1977, 1985). Dynamical friction in the high-stellar-density region of the inner bulge would accelerate the orbital decay of GCs (Chandrasekhar 1943; Tremaine et al. 1975; Mulder 1983; White 1983; Tremaine & Weinberg 1984; Gnedin & Ostriker 1997; Vesperini & Heggie 1997; Capuzzo-Dolcetta & Vicari 2005; Gnedin et al. 2014; Moreno et al. 2014; Arca-Sedda & Capuzzo-Dolcetta 2014).

Specifically, dynamical friction is proportional in strength to the background density. This acts as a drag force that for

example would require only a few gigayears to bring a globular cluster to the centre of its parent galaxy (e.g., Capuzzo-Dolcetta 1993; Lotz et al. 2001; Goerdt et al. 2006). Nevertheless, the number of Galactic GCs increases steadily towards the centre (e.g., Navarro et al. 2021), and some GCs found in the region of the Galactic centre have been clearly able to survive for a long time. It is therefore necessary to carefully study GC candidates near the centre of the Milky Way in order to provide a more comprehensive census of the MW GC system, and also to gain better insight into the destruction mechanisms that drive their evolution.

In this work we concentrate on the GCs that are located in the innermost region of our Galaxy. We analyse the candidate GCs that are located nearest to the Galactic centre, within a few degrees in projection. Previously, in the list of Harris (1996, edition 2010), Terzan 1, Terzan 2, and Palomar 6 were the closest GCs to the Galactic centre, located at a projected angular distance of about 2.5 – 2.8 deg from the centre. In the

past decade, numerous new GC candidates have arisen, mostly thanks to the near-infrared surveys like 2MASS (Hurt et al. 2000; Dutra et al. 2003; Skrutskie et al. 2006; Froebrich et al. 2007), GLIMPSE (Kobulnicky et al. 2005), WISE (Camargo et al. 2016), and VVV (Minniti et al. 2010, 2017a,b,c, 2018a, 2019; Moni Bidin et al. 2011; Borissova et al. 2014; Barba et al. 2019; Palma et al. 2019; Garro et al. 2020).

In particular, VVV-CL002 and VVV-CL003 are two new GCs located at a projected angular distance of about 1.1 and 1.7 deg from the Galactic centre that were discovered by Moni Bidin et al. (2011), who pointed out that VVV-CL002 was one of the closest known GCs to the Galactic centre. In addition, approximately two dozen new GC candidates have now been discovered that are closer to the Galactic centre in projected angular distance than Terzan 1, Terzan 2, and Palomar 6. These new candidate GCs are: Cam1105, Cam1107, Cam1108, Cam1109 (Camargo 2018; Camargo & Minniti 2019), Mi14, Mi20, Mi34, Mi35, Mi38, Mi39, Mi40, Mi42, Mi46, Mi47, Mi54, Mi55, Mi56, Mi57, Mi58, Mi59, Mi60 (Minniti et al. 2017a,b, 2019), and VVV-CL154 (Borissova et al. 2014).

In the light of all these new GC candidates, especially those discovered or confirmed from relatively contaminant-free samples, the time is ripe for a few simple questions to be addressed. Indeed, a broader scenario to validate GC destruction and evolution cannot be drawn from only one target galaxy. However, we hope to encourage further discussion by trying to address the following questions: Which are the real GCs closest to the Galactic centre? What are their physical properties? How have these GCs managed to survive in such an extreme environment? The debris of destroyed GCs would contribute to the bulge field stars. The closest GCs to the Galactic centre are of particular interest to test dynamical evolution and destruction processes. The quantitative fraction of the population contributed by the disruption of GCs is yet to be determined from observations by exploring dozens of new GC candidates found in the innermost regions of the Milky Way, and from a theoretical point of view by modelling cluster destruction as a function of their relevant main orbital and physical parameters.

This paper is organised as follows: In Sect. 2 we discuss the previously known GCs located within a few degrees of the Galactic centre. In Sect. 3 we analyse the candidate GCs recently discovered in this region. Section 4 presents the physical parameters estimated for the new GCs VVV-CL002 and VVV-CL003. Sections 5 and 6 present a discussion and our conclusions, respectively.

2. The known clusters

As mentioned above, Terzan 1, Terzan 2, and Palomar 6 were the closest GCs in projected angular distance to the centre of the Milky Way listed in the catalogue of Harris (1996, edition 2010). However, according to the same catalogue, the closest cluster to the Galactic centre in linear distance is HP1 at $R_G = 0.5$ kpc. Then there are NGC 6522 and NGC 6528 at $R_G = 0.6$ kpc, and Terzan 1 at $R_G = 0.7$ kpc. In addition, more recently the availability of *Gaia* PMs allowed different groups to map the GC orbits across our Galaxy (Vasiliev 2019; Baumgardt et al. 2019; Perez-Villegas et al. 2020). The title of the closest known GC to the Galactic centre has been disputed among different GCs located in the region, with distance determinations being the main hinderance in deciding which one is the best candidate.

According to the catalogue of Baumgardt & Hilker (2018) and Baumgardt et al. (2019), which includes recently updated

distances, the closest cluster to the Galactic centre is NGC 6522 at $R_G = 0.58$ kpc. Then there are Liller 1 at $R_G = 0.73$ kpc, UKS 1 at $R_G = 0.78$ kpc, NGC 6401 at $R_G = 0.83$ kpc, and Terzan 2 at $R_G = 0.84$ kpc (these latter authors adopt $R_0 = 8.1$ kpc). Perez-Villegas et al. (2020) also presented a catalogue of GCs, and using their adopted distances we deduce that the closest GC to the Galactic centre would be Liller 1 at $R_G = 0.73$ kpc. Then there are NGC 6528 at $R_G = 0.77$ kpc, and Djorg2 at $R_G = 0.78$ kpc (Perez-Villegas et al. adopt $R_0 = 8.2$ kpc).

We have also explored the orbital parameters of the known GCs within 2.5 deg of the Galactic centre from these different lists. Figure 1 shows the distribution of minimum orbital distances to the Galactic centre for known GCs: R_{\min} and R_{peri} from Perez-Villegas et al. (2020) and Baumgardt et al. (2019), respectively. According to Perez-Villegas et al. (2020), there are only a handful of GCs with perigalactica of less than 150 pc (~ 1 deg). These are Terzan 1, Terzan 2, Terzan 6, NGC 6528 ($R_p < 80$ pc), Liller 1, NGC 6624, Terzan 4, NGC 6440, and NGC 6642 ($80 < R_p < 100$ pc). According to Baumgardt et al. (2019) there are only three GCs with a perigalacticon of less than 200 pc: Liller 1, Terzan 2, and Terzan 9. These differences illustrate that the orbital parameters for the innermost bulge clusters are clearly still uncertain and/or incomplete, and that better data are needed in order to constrain the orbits. On the other hand, there are a number of GCs with perigalactica outside of that region of 150 pc (~ 1 deg assuming $R_0 = 8.18$ kpc, Gravity Collaboration 2019).

Figure 2 shows the position of the clusters present in the region of the sky surrounding the Galactic centre from the list of Harris (1996). In particular, we note that there were no GCs inside a circle of 2.5° . The recent reddening map of Surot et al. (2020) is reproduced for comparison to illustrate that the known clusters do not lie in the most heavily reddened regions. This high-resolution (2 arcmin to 10 arcsec) $J - K_s$ reddening map for the VVV bulge area is publicly available¹.

Figure 3 shows the orbits of all Galactic GCs on a zoomed-in area of the central region of the Milky Way covered by Fig. 1. The orbits are represented as simple ellipses projected onto the same plane (with $i = 0$) using the parameters from Perez-Villegas et al. (2020). This is a simplification because the GC orbits are more complex, but it makes no difference for the points discussed in this paper. Even though few known GCs are located in this region, many other GCs have orbits that sometimes place them inside the same region. However, no known GC penetrates what we define as the ‘death zone’, within 0.5 deg of the Galactic centre.

It also makes no difference if we separate the GCs into metal-rich and metal-poor components at $[\text{Fe}/\text{H}] = -1.0$ dex (blue and red orbits in Fig. 3, respectively). Both components are present in the region, and can reach short Galactocentric distances. This suggests that the GC metallicities do not play a significant role in the orbital dynamics of the inner regions. Despite being different populations, both metal-rich and metal-poor GCs can survive close to the Galactic centre.

Our first conclusion is to note that there are no GCs that approach the Galactic centre and come within less than 75 pc (~ 0.5 deg). The interpretation is that this is the destruction region (death zone), where GCs are foredoomed. No GCs have been able to survive passing through this region, regardless of cluster mass, size, or orbital parameters.

¹ <http://basti-iac.oa-teramo.inaf.it/vvexmap/>

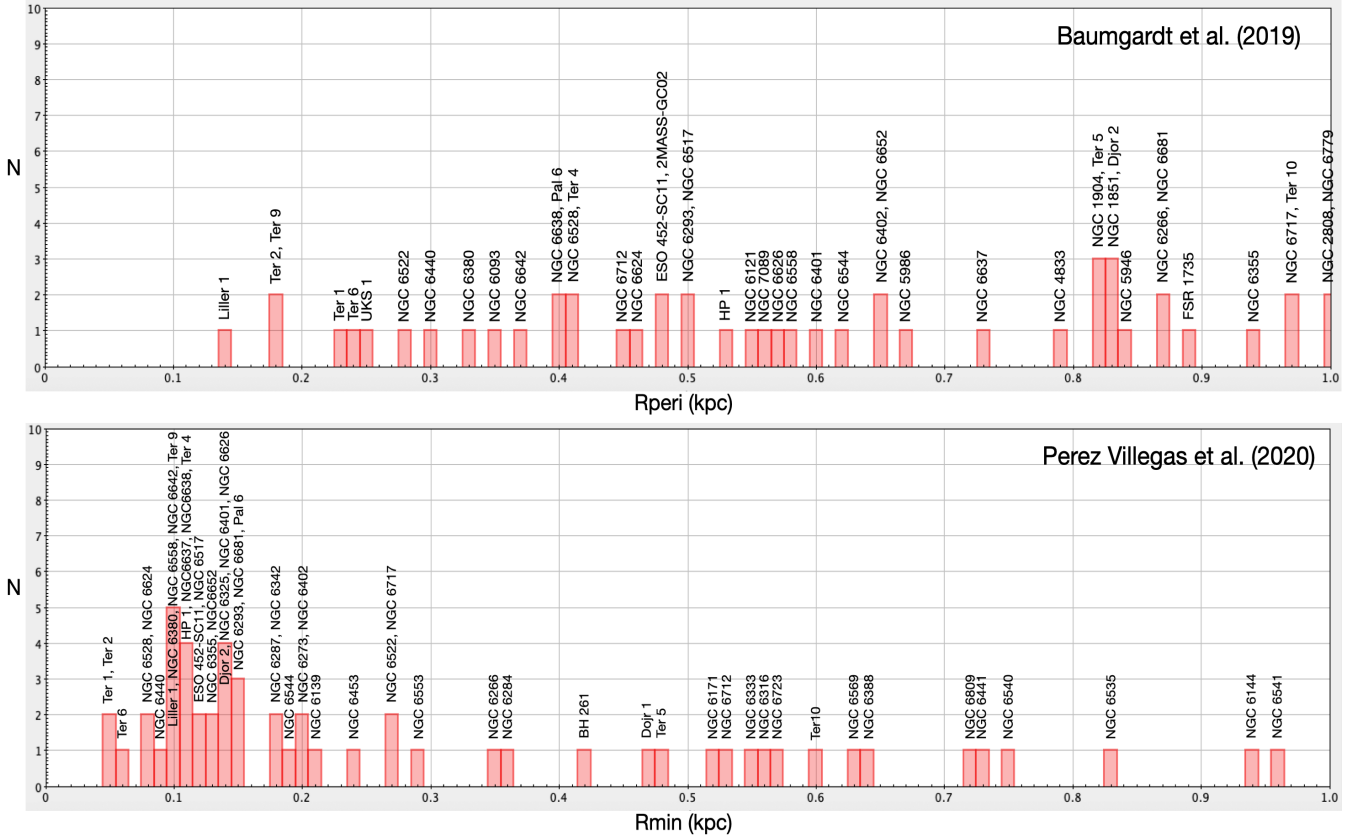


Fig. 1. Distribution of minimum orbital distances to the Galactic centre for known GCs. *Top panel:* GC perigalactica from Baumgardt et al. (2019). The perigalacticon for each individual GC is labeled. *Bottom panel:* minimum Galactocentric distance R_{\min} from Perez-Villegas et al. (2020).

In this region, the only known young massive clusters are Quintuplets and Arches, which are not going to survive more than several million years according to recent simulations (Habibi et al. 2013, 2014; Hosek et al. 2015; Rui et al. 2019; Libralato et al. 2021). There are also now a few new candidate young clusters in this zone, from the lists of Borissova et al. (2014). These are VVV-CL142 (compact open cluster or edge of nebula), VVV-CL146 (open cluster or dust window), VVV-CL147 (nebulousity, maser, infrared in dark cloud), and VVV-CL148 (embedded cluster), which remain to be studied in detail. We note that the models for the Arches and Quintuplets indicate that they may exhibit a compact core with extended tails, and therefore we do not necessarily expect the GCs travelling through this region to be normal; they may well be very distorted.

3. The new GC candidates

Observational data were acquired with the VISTA InfraRed CAMera (VIRCAM) at the 4.1m wide-field Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson & Sutherland 2012) at ESO Paranal Observatory, in the context of the VVV and VVVX ESO Public Surveys (Minniti et al. 2010; Saito et al. 2012). These surveys have been sampling the Galactic bulge and close regions of the Southern Galactic Plane since 2010 using the J ($1.25\ \mu\text{m}$), H ($1.64\ \mu\text{m}$), and K_s ($2.14\ \mu\text{m}$) near-infrared passbands. The data were reduced with the VIRCAM pipeline v1.3 at the Cambridge Astronomical Survey Unit (CASU), and with the VISTA Science Archive at the Wide-Field Astronomy Unit, within the VISTA Data Flow System (Emerson

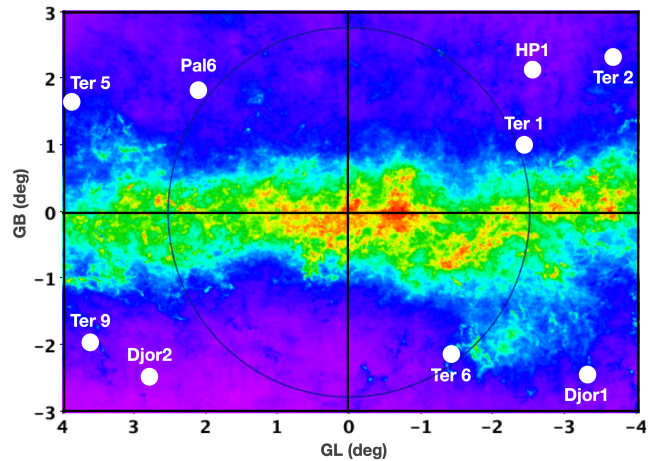


Fig. 2. Location of known GCs within a $8 \times 6^\circ$ region about the Galactic centre from the list of Harris (1996), overplotted on the reddening maps of Surot et al. (2020), where blue indicates $E(J-K_s) = 1$ mag, light blue $E(J-K_s) = 2$ mag, green $E(J-K_s) = 3$ mag, yellow $E(J-K_s) = 4$ mag, and red $E(J-K_s) = 5$ mag. The circle indicates a region of 350 pc radius in projection at the distance of the Galactic centre.

et al. 2004; Hambly et al. 2004; Irwin et al. 2004). The point-spread function (PSF) photometry that we used to build the deep near-infrared colour-magnitude diagrams (CMDs) and luminosity functions (LFs) are from VIRAC2 (Smith et al., in prep.). VIRAC2 is an updated version of the VVV Infrared Astrometric Catalogue (VIRAC, Smith et al. 2018).

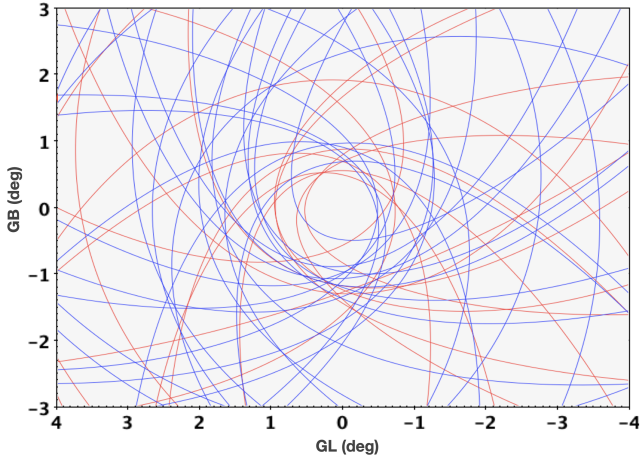


Fig. 3. Orbits of all known GCs projected on the same plane in this region using the orbital parameters listed by Perez-Villegas et al. (2020). Metal-rich ($[\text{Fe}/\text{H}] > -1.0$ dex) and metal-poor ($[\text{Fe}/\text{H}] < -1.0$ dex) cluster orbits are drawn with red and blue solid lines, respectively. The death zone where no GC can survive is clearly seen within half a degree of the Galactic centre.

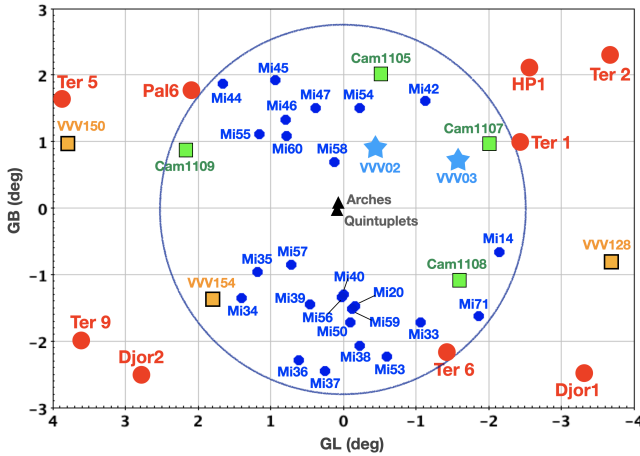


Fig. 4. Location of known GCs (large red circles) and the Quintuplets and Arches clusters (black triangles) compared with new candidate star clusters in the same region from different works: Moni Bidin et al. (2011; light blue stars), Borissova et al. (2014; orange squares), Minniti et al. (2017a; 2017b; 2019, solid blue circles), and Camargo (2018; green squares).

We explored all candidate GCs within 2.5 deg of the Galactic centre published from the lists of Froebrich et al. (2007), Moni Bidin et al. (2011), Borissova et al. (2014), Minniti et al. (2017a,b,c, 2018a, 2019), Palma et al. (2019), and Camargo (2018), Camargo & Minniti (2019), included in the recent compilation of Bica et al. (2019). Even though we are concerned with GCs, a number of young star clusters have also been found by Borissova et al. (2014). Signs of youth include nebulosity and bright members, and while they have not been confirmed spectroscopically, many of them are conspicuous in the VVV images. A trivial point that should be made is that if these young clusters are associated with the Galactic disc, they could be located anywhere along the line of sight. Old GCs on the other hand are very concentrated towards the Galactic centre.

We therefore explore the recently discovered candidate GCs, concentrating on the region within 2.5 deg of the Galactic centre, or about 350 pc in projection at that distance. There are

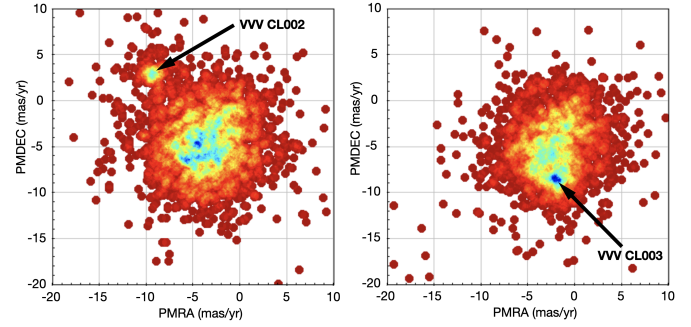


Fig. 5. Vector proper motion diagram for a 10 arcmin field centred in VVV-CL002 (left) and VVV-CL003 (right) obtained from VIRAC2 (Smith et al., in prep.). In both cases, the arrow points at the peak due to cluster members that are much more tightly concentrated than the rest of the bulge field stars.

about three dozen candidate star clusters within the 2.5 deg circle shown in Fig. 4. These need to be properly confirmed and characterised, as their physical parameters are uncertain or unknown. We are particularly interested in the distances in order to find the closest GC to the Galactic centre. While the majority of the candidates are difficult to analyse in the absence of additional data, two of them immediately stand out: VVV-CL002 and VVV-CL003. These clusters were discovered using initial VVV near-infrared photometry (Moni Bidin et al. 2011). The star members of these two clusters in particular are relatively easy to identify with our new data.

Figure 5 shows the vector PM diagram for these two clusters made using the preliminary VIRAC2 PMs from Smith et al. (in prep.) which are anchored to *Gaia* DR2. The cluster members are concentrated, showing a distinct sharp PM peak (indicated with the arrow in both panels of Fig. 5) that stands out from the bulge field stellar population and exhibits a much wider distribution of PMs. We measure mean proper motions $\text{PMRA} = -9.33 \pm 0.07 \text{ mas yr}^{-1}$, $\text{PMDEC} = 2.78 \pm 0.07 \text{ mas yr}^{-1}$ for VVV-CL002, and $\text{PMRA} = -1.93 \pm 0.05 \text{ mas yr}^{-1}$, $\text{PMDEC} = 8.33 \pm 0.05 \text{ mas yr}^{-1}$ for VVV-CL003, where the errors include the average of the systematic error of the *Gaia* PMs ($\sigma = 0.035 \text{ mas yr}^{-1}$, Gaia Collaboration 2018).

Figure 6 shows the comparison of the mean PMs with the other clusters in the Galactic bulge. While most GCs have mean PMs following the bulge field stars, we note that VVV-CL002 in particular stands out from the rest as a distinct PM cluster, indicating a large tangential velocity, along with the foreground clusters NGC 6397, NGC 6544, and NGC 6656 which show high PMs because they are located at about one-third of the distance.

4. VVV-CL002 and VVV-CL003 distances

The Moni Bidin et al. (2011) discovery paper for VVV-CL002 and VVV-CL003 concluded that they are metal-rich GC candidates, with $[\text{Fe}/\text{H}] = -0.4$ dex and $[\text{Fe}/\text{H}] = -0.1$ dex, respectively. These latter authors also estimated the distances, finding $D = 7.3$ and 13.0 kpc, respectively, and their Galactocentric distances of $R_G = 0.7$ kpc and 5.0 kpc, respectively, arguing that VVV-CL002 could be one of the closest GCs to the Galactic centre. As these two clusters are located in extremely dense and very reddened regions, more important progress made here is that we are able to select cluster members using the vector PM diagram from the preliminary VIRAC2 data (Smith et al., in prep.) to measure their distances. In order to do this we chose stars with PMs within 2 mas yr^{-1} of the mean cluster PMs. Because

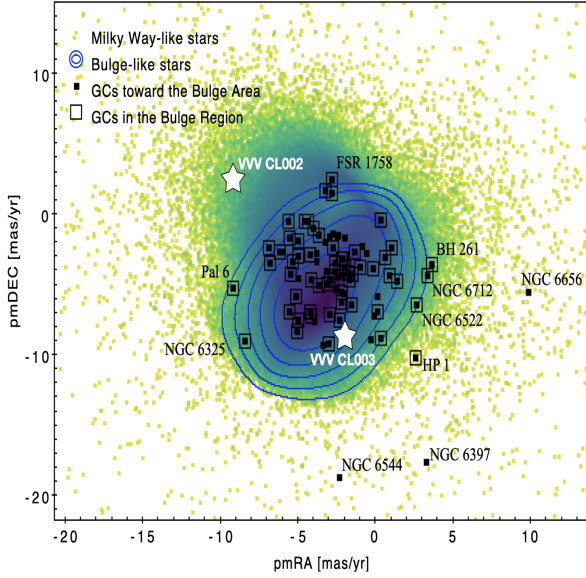


Fig. 6. Vector proper motion diagram for globular clusters in the VVV bulge fields from VIRAC2. The GCs VVV-CL002 and VVV-CL003 are highlighted with the white stars, as labelled. A sample of field Milky Way stars are shown as green dots, and the bulge density contours are indicated with the blue lines.

the PMs for GC VVV-CL003 are closer to the mean PM of the field stars, some field contamination remains, while in the case of VVV-CL002 the separation is cleaner. Based on the PM selections we estimate the field contamination for VVV-CL002 to be low ($\sim 15\%$), and more severe for VVV-CL003 ($\sim 30\%$).

The PM-selected near-infrared CMDs and their corresponding K_s -band LFs for these clusters are shown in Figs. 7 and 8, respectively. Both clusters display a red giant branch (RGB) with a prominent red clump (RC), as shown in Figs. 7 and 8, indicating that they are indeed metal-rich GCs.

The CMD of VVV-CL002 looks very clean (Fig. 7), with a narrow RGB and a well-defined RC, because there is a better PM separation from the field stars. The cluster RGB and RC match the location of the field stars, and if it were not for the PMs, it would have been hard to discriminate the field contamination. Figure 7 also shows the mean ridge line for the metal-rich GC NGC 6440 ($[Fe/H] = -0.4$ dex, $D = 8.6$ kpc) obtained using the same VIRAC2 photometry for comparison. This has been appropriately shifted to the cluster reddenings and distances. Figure 5 shows a clear and narrow peak corresponding to the cluster RC giants located at $K_s = 14.14 \pm 0.02$ mag.

The CMD of VVV-CL003 (Fig. 7, right panel) shows that some field star contamination remains even after the PM selection, because the cluster PM is close to the mean PM of the bulge field stars. The cluster RGB and RC does not match the location of the field stars in this case, as these GC sequences are fainter and redder than the typical population in this field, indicating that this GC is more reddened and more distant than the bulge. However, VVV-CL003 also presents an RGB that is narrower than the field, along with a well-defined RC located at $K_s = 14.92 \pm 0.03$ mag.

For the reddening determinations we use the latest extinction maps of Surot et al. (2020) based on the VVV PSF photometry. The mean reddenings for VVV-CL002 and VVV-CL003 are $E(J - K_s) = 1.55 \pm 0.15$, and 1.34 ± 0.16 mag, respectively, where the error is given by the reddening scatter in a region of 2 sq arcmin centred on the clusters. Assuming the extinction

law of Cardelli et al. (1993) for consistency with Moni Bidin et al. (2011), their extinctions are $A_K = 1.07$, and 0.92 mag, respectively.

A caveat regarding the distance determinations is that the shape of the extinction law can vary in the central regions of the Milky Way (e.g., Gonzalez et al. 2012; Schultheis et al. 2014; Majaess et al. 2016; Nataf et al. 2016; Alonso-Garcia et al. 2017; Surot et al. 2020). Adopting a shallower extinction law like that of Nishiyama et al. (2009) with a slope of $A_K/E(J - K_s) = 0.528$ would make the cluster distances nearly 10% larger. Nonetheless, we can conclude that VVV-CL002 is a serious contender for being the closest GC to the Galactic centre.

We also note that the maps of Schlafly & Finkbeiner (2011) give extinction values of $A_K = 1.05$, and 1.94 mag for VVV-CL002 and VVV-CL003, respectively. While the extinction of VVV-CL002 is nearly identical to the value $A_K = 1.07$ mag adopted here, the difference is very large in the case of VVV-CL003, for which our extinction value is one magnitude brighter.

The cluster distances can be derived given the observed RC magnitudes, and adopting the mean absolute magnitude for RC giant stars $M_{K_s} = -1.601 \pm 0.009$ mag (Ruiz-Dern et al. 2018). We obtain $D = 8.6 \pm 0.6$ kpc for VVV-CL002, which places it at a Galactocentric distance of $R_G = 0.4$ kpc. This makes VVV-CL002 potentially (given our error $\sigma_D = 0.6$ kpc) the closest GC to the Galactic centre, not only in projection (located at a projected angular distance of 1.1 deg), but also in Galactocentric distance (located at $R_G = 0.4$ kpc). On the other hand, for VVV-CL003 we find $D = 13.2 \pm 0.8$ kpc, indicating that this is a distant background cluster merely projected onto the Galactic centre region.

We calculate the integrated luminosity of the clusters by considering: $L_{K_{\text{obs}}} = \sum_i 10^{-0.4 K_i}$ and then converting this summed luminosity of selected cluster members into absolute magnitude by using our previously derived distances and extinction values A_K . We estimate $M_K = -7.71$ and $M_K = -9.92$ for VVV-CL002 and VVV-CL003, respectively. Undoubtedly, our integrated luminosities shall be considered as rough estimates only, because neither radial extrapolation nor correction for undetected low-mass stars has been attempted. Assuming a colour of $V - K_s = 3.1$ for old, metal-rich GCs (see e.g., Obasi et al. 2020) this translates into integrated V -band magnitudes of $M_V = -4.61$ and $M_V = -6.82$, respectively. Comparing with the luminosity function of known Galactic GCs (from the lists of Harris 1996; Baumgardt et al. 2019), these luminosities are consistent with VVV-CL002 being a very low-luminosity bulge GC, while VVV-CL003 is a GC of relatively normal luminosity located closer to the peak of the luminosity function.

We note that there are no spectroscopic observations for these GCs. Especially desirable are measurements of the radial velocities for VVV-CL002, which are needed to map its orbital path and establish how this GC was able to survive in such a harsh environment. Despite a lack of precise radial velocities for these clusters, interesting conclusions can be drawn about their range of possible orbits. We simulate the orbits of both clusters assuming a range of radial velocity (RV) values. We use the 3D steady-state gravitational potential model implemented in the new state-of-the-art orbital integration package GravPot16² developed by Fernández-Trincado et al. (2020a). We adopt the same model configuration as described in Fernández-Trincado et al. (2020a), except for the bar pattern speed, for which we adopt the recommended value of $41 \text{ km s}^{-1} \text{ kpc}^{-1}$ (see, e.g., Sanders et al. 2019). The uncertainties on the input data

² <https://gravpot.utinam.cnrs.fr>

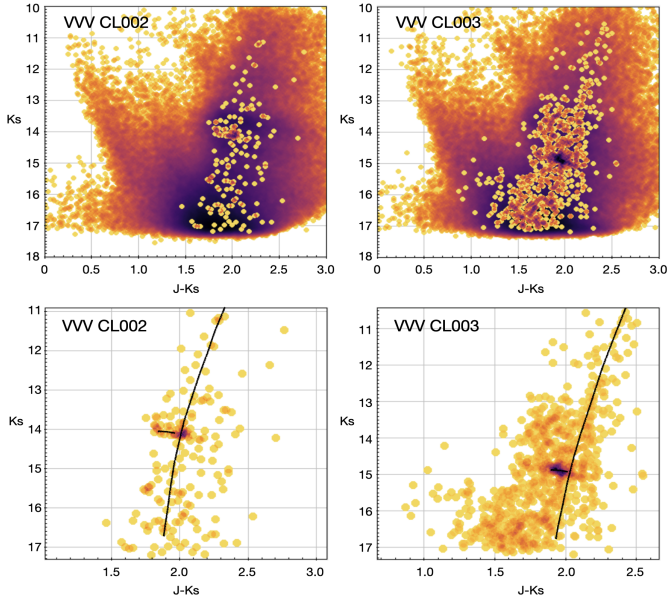


Fig. 7. *Top panels:* near-infrared CMDs for a 10-arcmin field radius centred on VVV-CL002 (*left*) and VVV-CL003 (*right*), with the cluster members shown in lighter colours, from VIRAC2 PSF photometry (Smith et al., in prep.). The large scatter in the background populations is due to the combined effect of the line of sight depth and the differential reddening. *Bottom panels:* similar zoomed-in CMDs for the PM selected cluster members. The position of the RC giants is clearly seen for both clusters. The mean ridge line of the metal-rich GC NGC 6440 from VIRAC2 photometry is shown for comparison (solid line), shifted to match the clusters reddenings and distances.

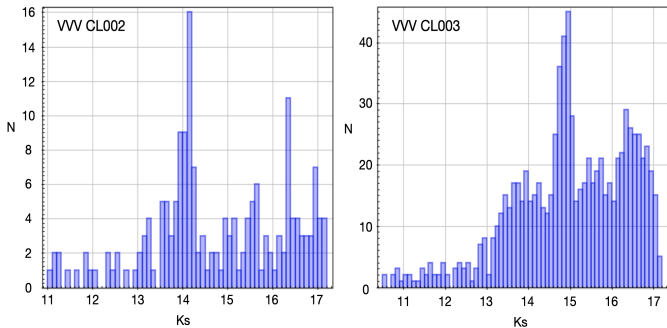


Fig. 8. *Ks*-band luminosity functions for the PM-selected cluster members for VVV-CL002 (*left*) and VVV-CL003 (*right*). The conspicuous peaks clearly mark the position of the cluster RC giants that are used to determine the distances for both clusters.

(RA, Dec, distance, PMs) were randomly propagated as 1σ variation in a Gaussian Monte Carlo re-sampling, adopting a range of line-of-sight velocities within $-250 < RV < 250 \text{ km s}^{-1}$. The orbits were computed backwards and forwards in time over 50 Myr, and the results are shown in Fig. 9.

This dynamical study shows that VVV-CL002 shares the typical orbital properties of the MW bulge, having perigalactocentric and apogalactocentric distances, and maximum vertical excursion from the Galactic plane inside the bar region. Indeed, VVV-CL002 appears to be a resilient GC that has survived in the innermost MW regions. On the other hand, VVV-CL003 appears to belong to the MW disc GC population, with small departures from the Galactic plane, except for the most extreme negative RVs.

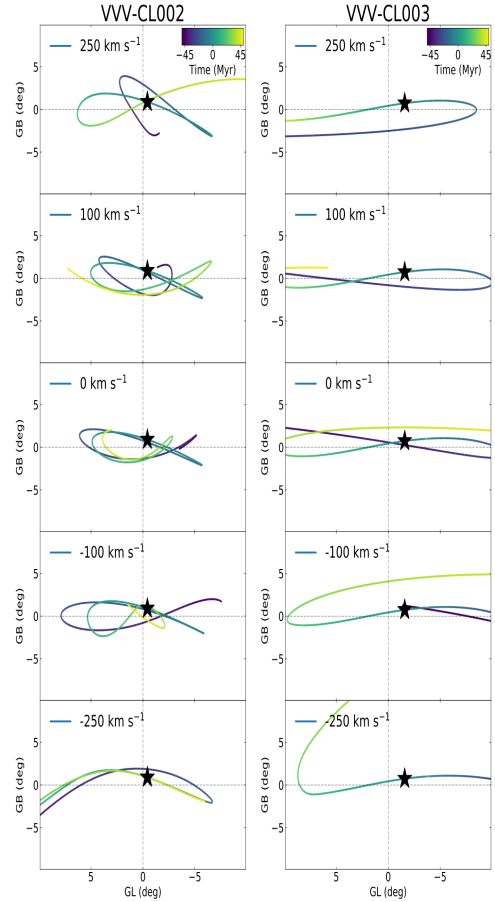


Fig. 9. Orbital integrations computed using the package GravPot16 (Fernández-Trincado et al., in prep.) assuming different RVs as labelled for VVV-CL002 (*left*) and VVV-CL003 (*right*). The black stars indicate the current GC positions, and their respective orbital paths are coloured according to the scale shown on top, ranging from -50 Myr in the past to 50 Myr in the future.

5. Discussion

New ground-based near-infrared imaging surveys like the VVVX provide a detailed panorama of the central region of the Milky Way within $R_G < 2 \text{ kpc}$. They lend themselves to the study of GCs in the Galactic centre region thanks to their high resolution, deep multicolour photometry, PM measurements, and variability information.

There are some questions about GCs that can only be answered in the Milky Way: What are the most resilient Galactic globular clusters? What physical properties make them tough and long lasting? We cannot answer questions like these using external galaxies like M 31 because their completeness is poorer than that obtained for the Milky Way. In addition to the differential extinction, for the inner regions of external galaxies, crowding is an insurmountable difficulty in detecting low-luminosity GCs.

Perhaps one of the secrets of the survival of VVV-CL002 is its high velocity. Figure 7 shows that this cluster has high velocity compared not only with the field stars but also with the known GCs in the region (except for a couple of foreground GCs). The tangential motion of VVV-CL002 of $|PM| = 9.74 \text{ mas yr}^{-1}$ yields a transverse velocity of $V_t = 397 \text{ km s}^{-1}$ at the distance of $D = 8.6 \pm 0.6 \text{ kpc}$, which seems too large at first sight. However, such high velocities are expected for clusters

close to their perigalacticon, which is consistent with its estimated short Galactocentric distance. The transverse speed of this GC with respect to the mean motion of the field stars is about $\Delta V_t = 408 \text{ km s}^{-1}$. While the RV of this GC is unknown, this large relative motion would make the cluster less prone to dynamical friction, as this effect is proportional to the GC mass and the density of the surrounding stellar medium, but inversely proportional to RV with respect to the medium squared (e.g., Chandrasekhar 1942, 1943).

In a dense stellar medium like the central regions of our Galaxy, as studied here, dynamical friction would decelerate the GC in its direction of motion, causing the orbit to decay ever more rapidly. In the case of VVV-CL002, this effect is minimised due to the large cluster velocity, allowing its long-term survival. On the other hand, clusters of similar mass but lower velocity might have already been disrupted, becoming part of the bulge stellar medium. This tangential speed of VVV-CL002 is mostly perpendicular to the Galactic plane. The projected component of the proper motion along Galactic latitude would be $V_b = 391 \text{ km s}^{-1}$. This GC is located at only $z = 134 \text{ pc}$ above the Galactic plane, and is therefore just emerging from the plane, through which it sped very recently (only $\sim 3.5 \times 10^5 \text{ yr}$ ago).

Even though there are no RV measurements for VVV-CL002, and we have explored a wide range of possible values, we predict that its RV should be smaller than the measured tangential velocity. We find that this GC has recently traversed across the Galactic plane in the central region at high velocity ($V > 400 \text{ km s}^{-1}$). VVV-CL002 would therefore be a prime target to compute detailed dynamical models in order to estimate its survival time before it is dissolved or dragged into the innermost Galactic region.

An interesting consequence is that GCs that have been disrupted in the past yield their stars to the field, and some of this stellar debris may still penetrate the death zone. These stars could in principle be recognised using detailed element abundance patterns that are similar to those of the Galactic GCs. Interestingly, Fernández-Trincado et al. 2019, 2020a,b, and in prep.) identified such potential GC debris as N-rich stars, and Fernández-Trincado et al. (in prep.) also found Al-rich stars with orbital parameters that bring them inside the death zone. Other interesting stellar debris to search for would be RR Lyrae variable stars that may have recently escaped from bulge GCs (e.g., Minniti et al. 2018b).

Another interesting consequence is that existing GCs that would never plunge through the death zone along their orbits would leave the central molecular zone (Jenkins & Binney 1994; Rodríguez-Fernández & Combes 2008) undisturbed during their passages through the Galactic plane. Outside of that region it is likely that GCs, thanks to their massive size, would probably disturb the ISM in their passages through the plane when close to perigalacticon. This effect may affect the stability and size of the innermost molecular zone, and needs to be modelled properly. This also shows that GCs have to be considered an integral part of the ecosystem in the inner Galaxy, along with the central molecular zone, the nuclear stellar bulge, and the supermassive BH.

So far, VVV-CL002 appears to be the closest known GC to the Galactic centre. However, aside from the distance uncertainties due to the extinction law, there are two other caveats: (1) There are a number of candidate GCs to be confirmed in these regions; and (2) many of the known GCs in the Galactic bulge still have uncertain orbital parameters.

As pointed out in Sect. 1, a few dozen candidate GCs were recently discovered in the Galactic centre region. We would also

like to stress the existence within this sample of other candidate GCs very close to the Galactic centre, like Mi58, which is located at a Galactocentric angular distance of only 0.7° . In this paper we have taken advantage of the distinct kinematics of VVV-CL002 and VVV-CL003, because their high PMs allow us to cleanly separate them from the bulge field stellar population. The other clusters located in the region require further work, as their PMs are not as easily distinguishable from the field stars. While these candidate GCs warrant exploration, we think that there should be even more GCs missing in this region. The main reasons are that the orbits of known GCs bring them close to the Galactic centre, the number density of GCs increases steadily towards the Galactic centre (e.g., Pérez-Villegas et al. 2020; Navarro et al. 2021) without a sign of a break in this GC distribution, and the regions of highest reddening apparently contain no clusters so far, simply because they have not yet been explored in depth. The high-extinction zones that are beyond the reach of ground-based observations can be mapped with the Roman Space Telescope (WFIRST; Green et al. 2012; Spergel et al. 2015) at higher resolution in the near-infrared.

6. Conclusions

A large number of new candidate GCs have been discovered in the Galactic bulge in the past decade. Here, we investigated the GCs in the innermost regions of the Milky Way, searching for the closest cluster to the Galactic centre. In particular, we present optical and near-infrared CMDs that confirm that VVV-CL002 and VVV-CL003 are real GCs (Moni Bidin et al. 2011). We also measured the absolute proper motions and accurate distances, estimated the luminosities, and predicted the orbits of these inner GCs.

We conclude that VVV-CL002 is a metal-rich GC located at only 1.1 deg from the Galactic centre, at $D = 8.6 \pm 0.6 \text{ kpc}$, and $R_G = 0.4 \text{ kpc}$. We also find that VVV-CL003 is a metal-rich GC lying in projection only 1.7 deg from the Galactic centre, but situated in the background at $D = 13.2 \pm 0.8 \text{ kpc}$, and $R_G = 5.0 \text{ kpc}$.

Therefore, VVV-CL002 is an excellent candidate for being the closest GC to the Galactic centre. However, some astronomical records like this should soon be broken by new observations, and the long-lasting message of this work is to point out the large number of new candidate GCs in the innermost regions of the Milky Way (within 2.5° of the Galactic centre) that still need to be properly observed, such as for example VVV-CL154, Cam 1105, 1107, 1108, and 1109, and Mi 20, 39, 40, 46, 47, 54, 55, 56, 57, 58, 59, and 60. Their proper physical characterisation would be important to model Galactic dynamical effects and GC survival. In particular, we also note that the GC candidate Mi58 lies in projection at only 0.7° from the Galactic centre, and is of particular interest for follow-up observations.

The fact that there are GCs in the innermost region indicates that some of them can survive their passages close to the Galactic centre, as their orbits bring them within a few tens of parsecs from the supermassive black hole. There also appears to be a forbidden zone, where GCs are crushed, and only young clusters can be seen (although these would presumably not last long). This ‘death zone’ within $R_G = 0.1 \text{ kpc}$ is where the debris of destroyed GCs might be found, some of which may have helped to build the massive star cluster at the centre of our Galaxy (e.g., Capuzzo-Dolcetta 1993; Arca-Sedda & Capuzzo-Dolcetta 2014), and such potential GC debris may be identified spectroscopically as N or Al-rich stars (Fernández-Trincado et al. 2019, 2020a,b, and in prep.).

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