Digging Deeper for More Curiosities: Unveiling the Reddened Bulge Globular Clusters with VVV

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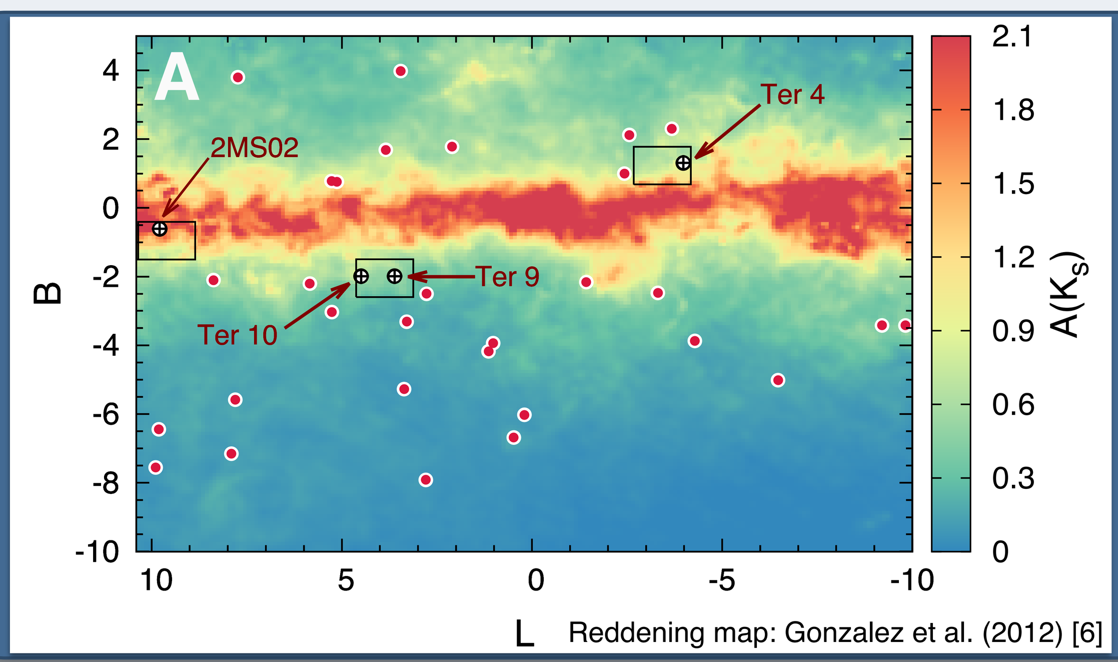


From the various anomalies found in bulge globular clusters (GCs), a picture of multiple populations of various nature has emerged, implying complicated formation/evolution histories. To understand whether these 'anomalies' are rather a main principle, and if bulge clusters commonly stand out from halo ones by wearing fingerprints of distinct evolution histories, we should extend our sample and put studies on more statistical grounds.

To this end, we explore the most obscured bulge clusters in the framework of the **VISTA Variables in the Vía Láctea (VVV) ESO Public Survey** with VISTA/VIRCAM. It provides a **ZYHJKs atlas and Ks light-curves** for most of the bulge and the southern mid-plane, covering ~560 sq.deg. Among the 34 bulge GCs covered by VVV (**Fig. A**), here we study the most extinct ones: 2MASS-GC02, Ter 4, Ter 9, and Ter 10, by means of PSF-photometry and time-series analysis techniques.

The classical analyses of these clusters, relying on snapshot images and color-magnitude distributions is hampered by extreme levels of differential extinction and field contamination [1,2,3]. VVV provides another powerful diagnostic tool: their unexplored variable star content.

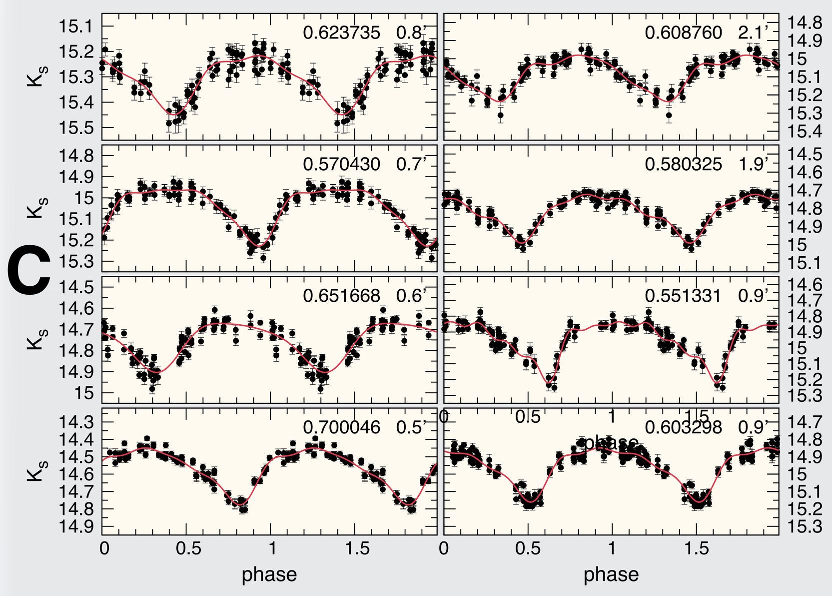
By using period-luminosity (PL) relations of RR Lyrae stars [4,5], "the Swiss army knives of astronomy", we accurately pin down their distances, coping with the differential reddening within the clusters and tracing the reddening law. We investigate their Oosterhoff properties, and reveal whether they follow the dichotomy shown by halo clusters, or else they show implications of a different origin.

2MASS-GC02

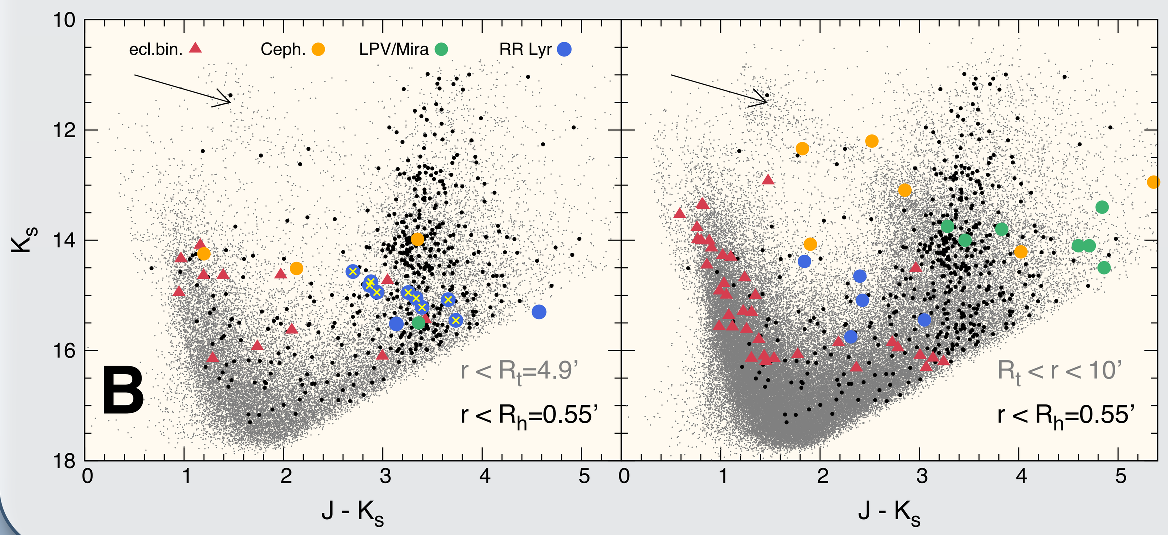
The extreme reddening of this recently discovered cluster [7] has made it invisible for optical observations. From a handful of photometric studies [e.g.,8,9], its extinction and distance remained highly uncertain. It's low metallicity of [Fe/H] = −1.08 is known from low-resolution near-IR spectroscopy [9,10].

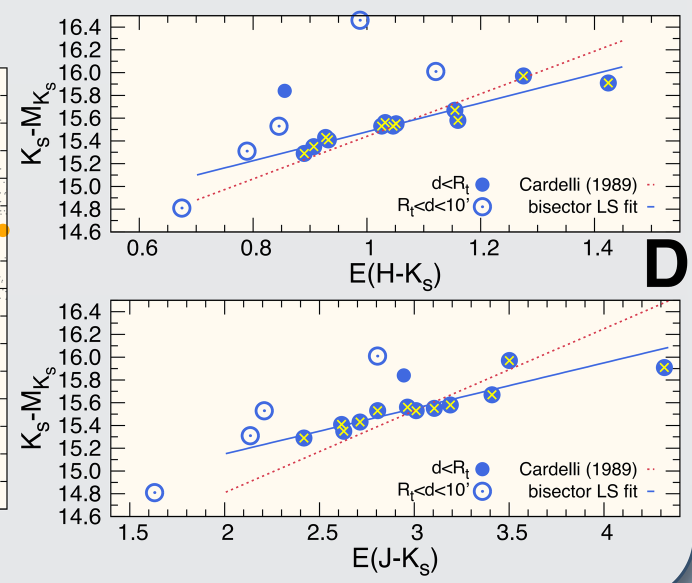
The J-K$_s$ CMD (**Fig. B**) is very broadened due to differential extinction and allows us only to distinguish the RGB of the cluster within the half-light radius (R_h=0.55'), with a clump at K$_s$ ≈ 14, J–K$_s$ ≈ 3.2. It does not reach the MS turnoff, and becomes dominated by bulge stars at r > R_h. The contribution of the disk MS is also prominent at J–K$_s$ < 2.

The cluster was observed at 43 K$_s$-band epochs in 2010-2013 by VVV. We discovered 32 new variables inside its tidal radius of R_t = 4.9' (**Fig. B**), including 13 RRab Lyrae stars (**Fig. C** shows the inner 8 of them with periods [d] and distances from the cluster center), 3 Cepheids, 4 eclipsing binaries, and 3 LPVs.



The RR Lyr apparent distance modulus—color excess distributions derived from their PL relations (**Fig. D**) shows a well-defined locus aligned with the expected reddening vector, proving the cluster membership of 12 RRab, and yielding an anomalous reddening law of: **A(K$_s$)/E(H–K$_s$)=1.27±0.29, A(K$_s$)/E(J–K$_s$)=0.55±0.15.** The mean extinction towards the cluster is A(K$_s$)≈1.17, **A(V)≈12 mag** (!). Our distance to the cluster is stemmed from the zero-point of the fitted reddening vector, and is found to be **d=7.1±1 kpc**, ~40% larger than previously



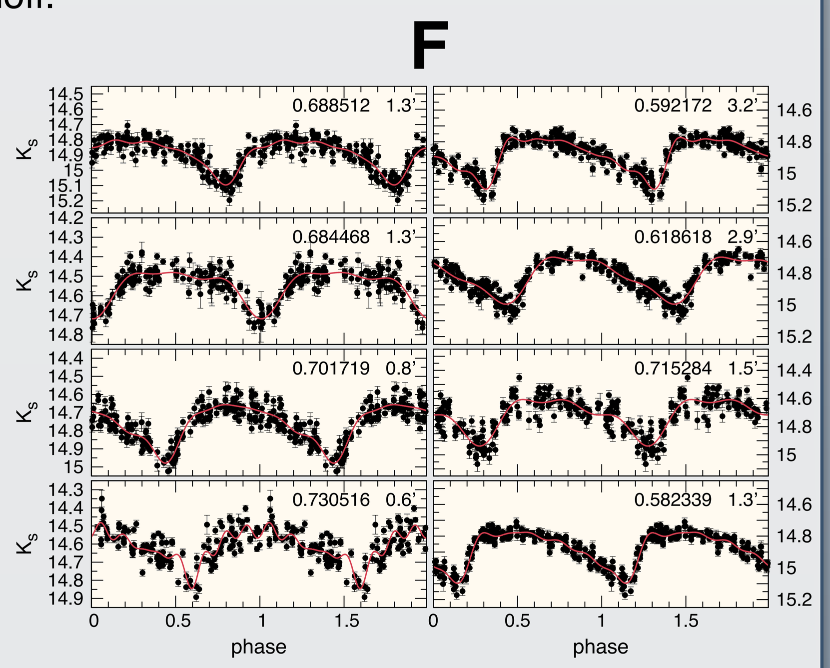


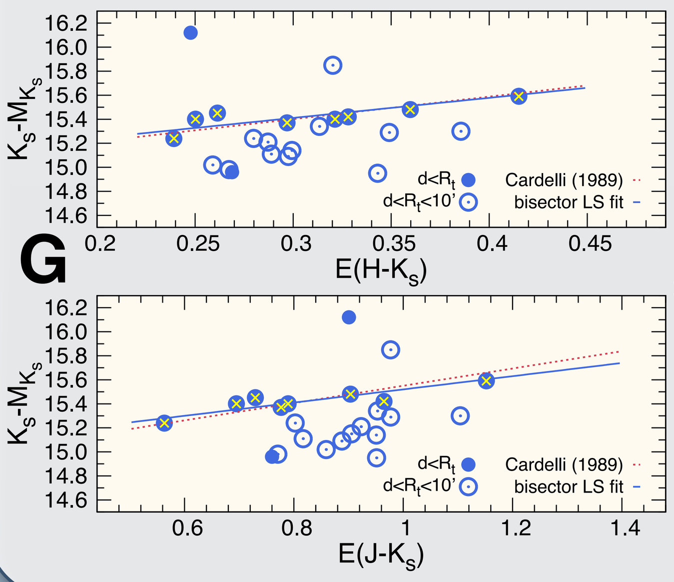
Terzan 10

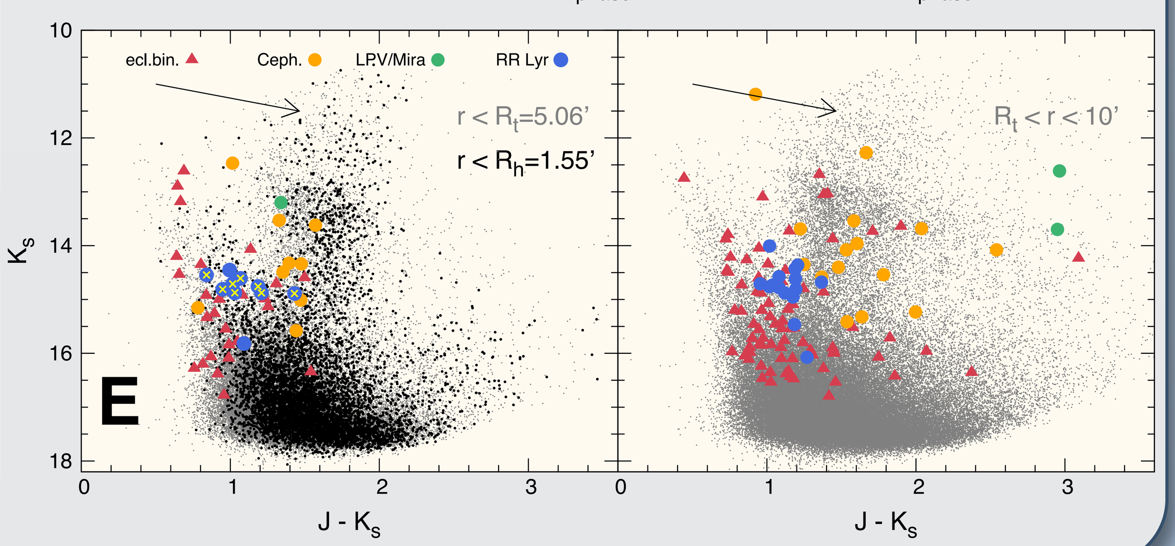
Without any previous time-domain observations, only a few photometric CMD studies of Ter 10 exist in the near-IR [12] and in the optical [13], and just one spectroscopic study using integrated spectra [14], resulting in [Fe/H] = −1.2. Earlier reddening and distance estimations were inaccurate, ranging from E(B-V) = 1.7 to 2.6 and d = 4.5 to 8 kpc, respectively.

The J–K$_s$ CMD (**Fig. E**) suffers from lower extinction broadening than 2MS02, but contamination from both the bulge and disk fields is severe even within its half-light radius R_h. The cluster's RGB with its clump at K$_s$ ≈ 13.5, J–K$_s$ ≈ 1.5, is mixed with bulge giants. All but the brightest disk stars, as well as the bulge ones cause a high level of confusion at the SGB and the upper MS of Ter 10, preventing us from defining its MS turnoff.

Using our 101-epoch VVV K$_s$-band photometry, we have discovered new 48 variables within the tidal radius R_t = 5.06' of Ter 10 (**Fig. E**), including 10 RRab stars, 8 Cepheids, 6 eclipsing binaries and 1 LPV. Similarly to 2MS02, 8 of the RRab's (**Fig. F**) are distributed in a linear locus along the reddening vector (**Fig. G**), proving their GC membership, and indicating a reddening law of: **A(K$_s$)/E(H–K$_s$)=1.67±0.28, A(K$_s$)/E(J–K$_s$)=0.55±0.1**, in full consistency with the Nishiyama law [15]. The RRab stars yield a distance of **d=9.8±0.5 kpc** to Ter 10, (~70% larger than previous estimates) making it the **first known GC in the far side of the bulge** with **A(V)≈4.5 mag.**



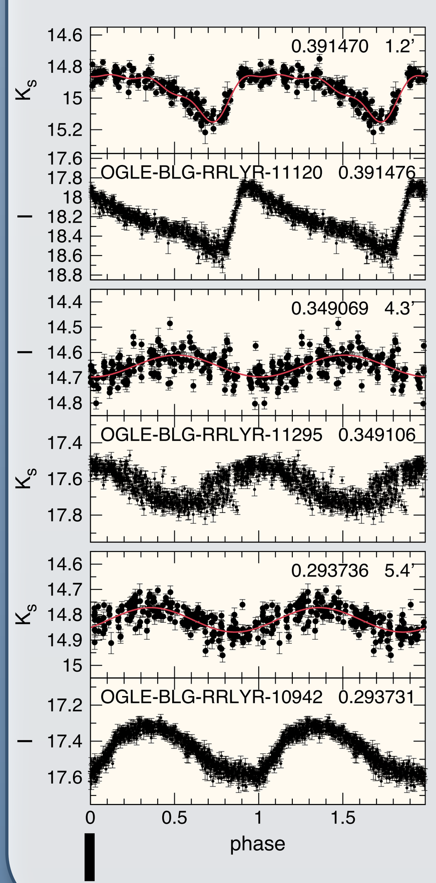


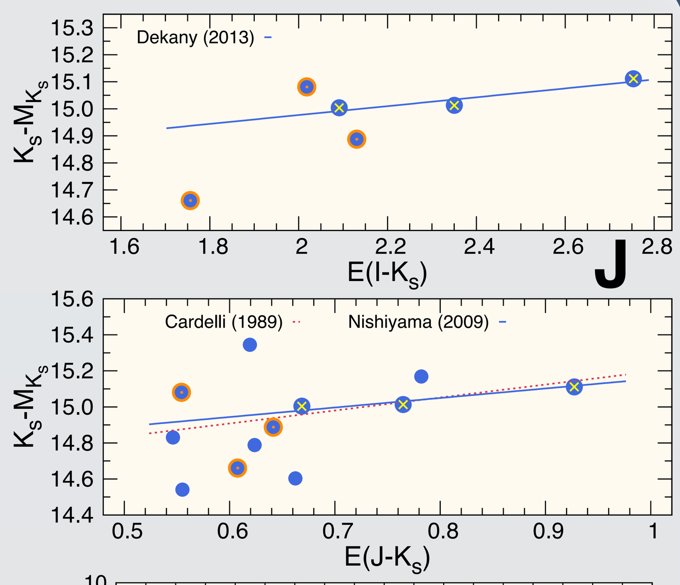


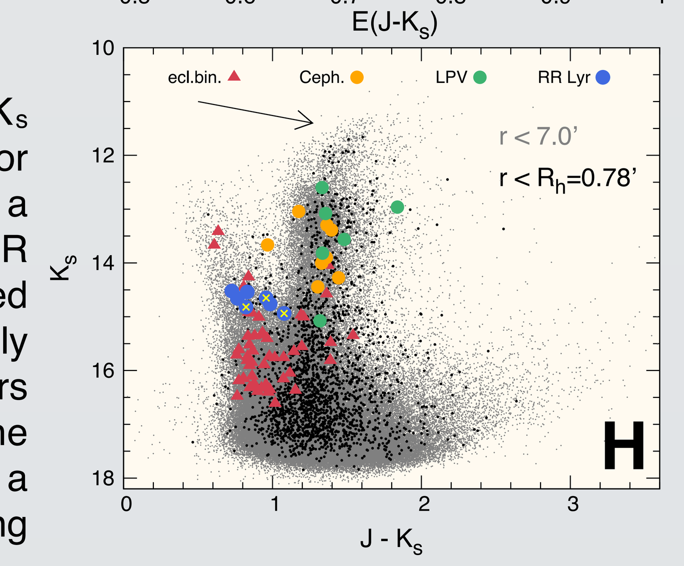
Terzan 9

Another heavily reddened inner bulge GC, Ter 9 has a collapsed core [11] and an extended tidal radius of R_t = 9.5' [11]. Estimates of its [Fe/H] range from −1 dex [14] to −1.2 [1]. An earlier high-res. near-IR CMD study [1] of its inner core obtained E(B–V) = 1.8 and a distance of 5.5 kpc by characterizing its RGB.

Being diffuse outside of its compact core, its VVV CMD is totally dominated by the bulge and disk fields (**Fig. H**). From a preliminary analysis of the VVV K$_s$ photometry with the same sampling as for Ter 10, we discovered 96 variables up to a radius of 7' from its core, including 17 RR Lyrae candidates, 7 of which were detected by OGLE-III which is in partial overlap. Only 3 of these, one RRab and 2 RRc stars (**Fig. I**) are precisely aligned with the Nishiyama reddening vector (**Fig. J**), with a mean reddening of **A(V) ≈ 4.4**, suggesting that they are cluster members.

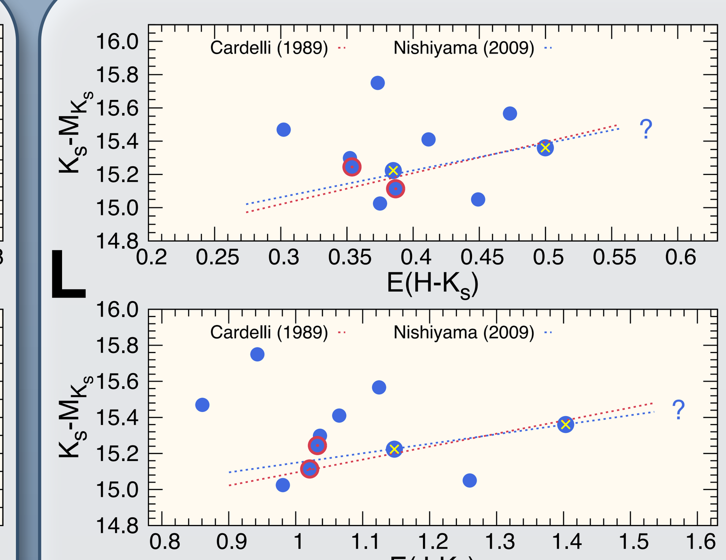


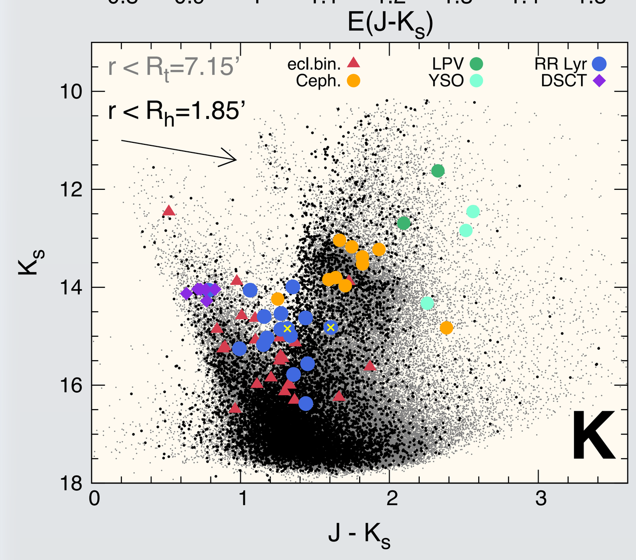


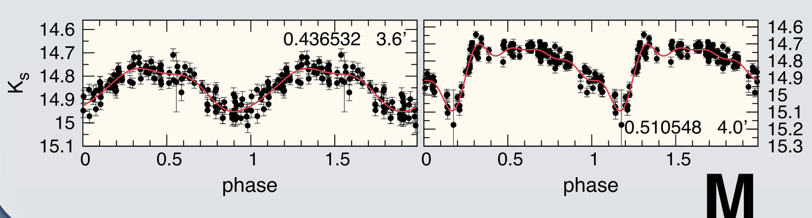


The fitted distance to the cluster using the above 3 stars is **d=8.5±0.3 kpc**, placing the **cluster at the far side of the bulge**, as opposed to earlier results of ~5.6 kpc [1].

Terzan 4

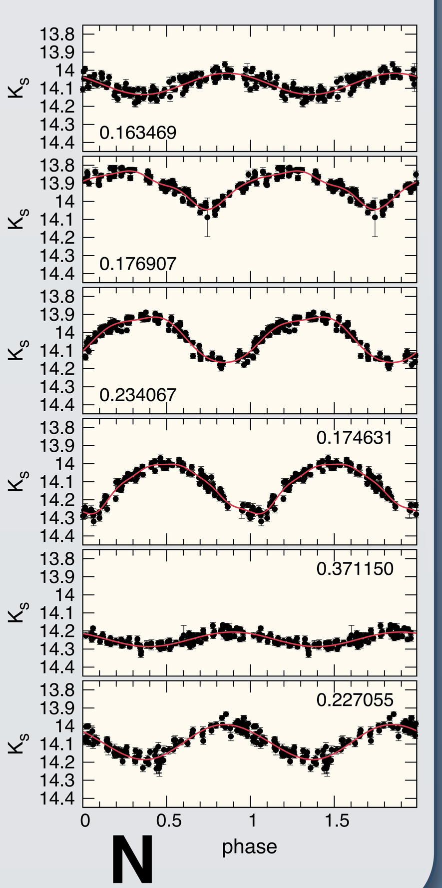


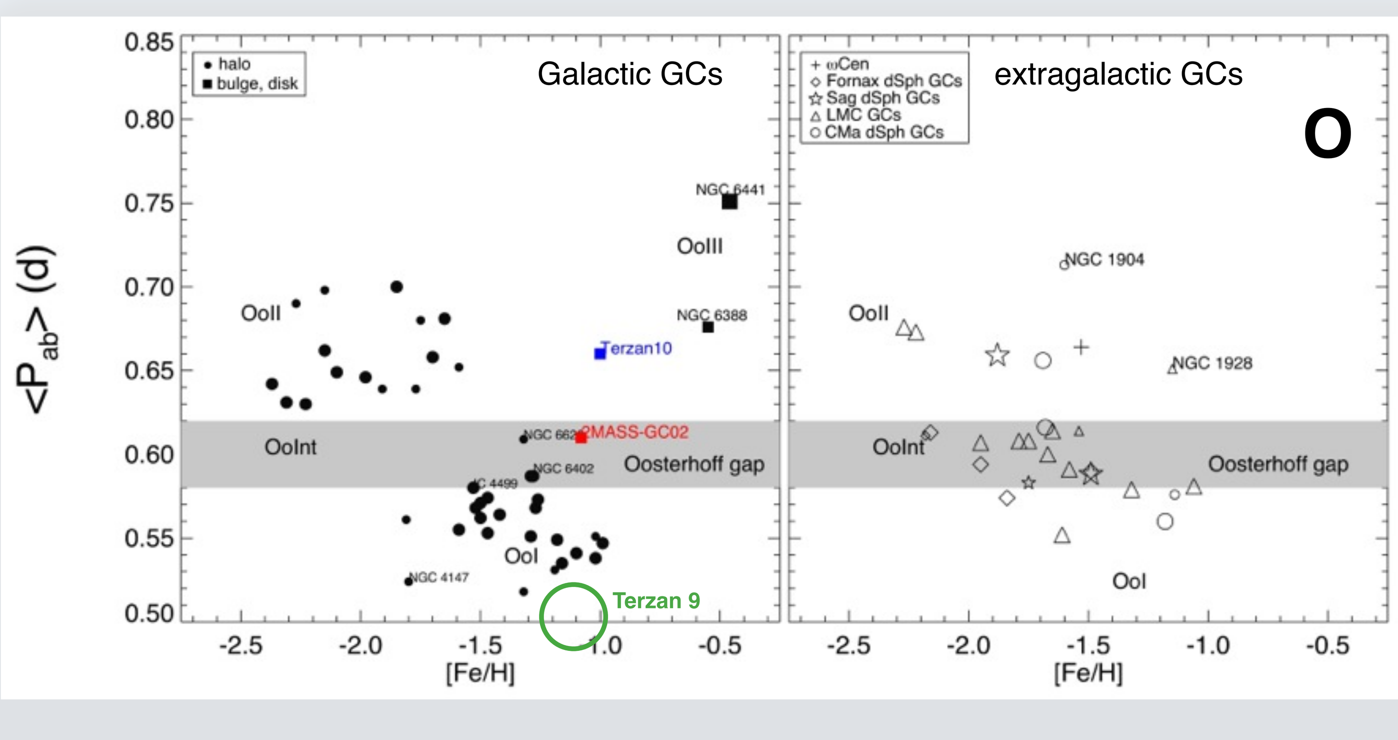




Surrounded by obscuring dark nebulae, the CMD of the heavily reddened Ter 4 features a spread and bent RGB, and very contaminated SGB and MS (**Fig. K**). It has a moderately compact core, surrounded by diffuse outskirts up to a wide tidal radius of R_t ~ 7' [11]. A high-resolution near-IR CMD study of its core [1] yielded a distance of d = 6.7 kpc with a high mean reddening of A(V) ≈ 5.2. Ter 4 also has a high-res. near-IR spectroscopic metallicity of [Fe/H]≈-1.6 [16].

The preliminary analysis of the VVV K$_s$ data with 64 epochs resulted in the discovery of 66 variables up to a radius of 7.1' from the cluster core (**Fig. K**), including 16 RR Lyrae, among which only 2 are suspected cluster members due to the similarity of their distances (**~8.3 kpc, Fig. L**). We also discovered a sample of 6 delta Scuti candidates (**Fig. N**) at a well-defined locus on the disk MS at K$_s$ ~ 14^m (**Fig. K**, purple diamonds), indicating the presence of an open cluster in the foreground of Terzan 4.





Oosterhoff properties

The average period of the 12 cluster RRab candidates in 2MASS-GC02 used in the reddening and distance fit is ⟨P_{ab}⟩ = 0.59±0.05 days, which puts **2MS02 in the Oosterhoff (Oo) gap (Fig. O)**. Based on the absence of Galactic GCs in this gap, and their high incidence rate of Oo gap GCs in nearby extragalactic systems, this feature suggests an extragalactic origin for 2MASS-GC02 [17].

The average period of the 8 RRab stars in Ter 10 is ⟨P_{ab}⟩ = 0.66±0.06 days, which would make it an Oo II cluster. However, its iron content (averaged value from 2 studies) is significantly higher than the ones of Galactic (and even extragalactic) Oo II GCs (**Fig. O**), making **Ter 10 the third known Oo III cluster**, implying a possible He self-enrichment scenario, in analogy to the other Oo III GCs [18,19].

Both the metallicity and the periods of its 3 RR Lyrae stars in are consistent with (even a bit short for) **Ter 9 being an Oo type I GC**, but it obviously suffers from small number statistics.

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