LETTER TO THE EDITOR

Eight more low luminosity globular clusters in the Sagittarius dwarf galaxy

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ABSTRACT

Context. The Sagittarius (Sgr) dwarf galaxy is merging with the Milky Way, and the study of its globular clusters (GCs) is important to understand the history and outcome of this ongoing process.

Aims. Our main goal is to characterize the GC system of the Sgr dwarf galaxy. This task is hampered by high foreground stellar contamination, mostly from the Galactic bulge.

Methods. We performed a GC search specifically tailored to find new GC members within the main body of this dwarf galaxy using the combined data of the VISTA Variables in the Via Lactea Extended Survey near-infrared survey and the Gaia Early Data Release 3 optical database.

Results. We applied proper motion cuts to discard foreground bulge and disk stars, and we found a number of GC candidates in the main body of the Sgr dwarf galaxy. We selected the best GCs as those objects that have significant overdensities above the stellar background of the Sgr galaxy and that possess color-magnitude diagrams with well-defined red giant branches consistent with the distance and reddening of this galaxy.

Conclusions. We discover eight new GC members of the Sgr galaxy, which adds up to 29 total GCs known in this dwarf galaxy. This total number of GCs shows that the Sgr dwarf galaxy hosts a rather rich GC system. Most of the new GCs appear to be predominantly metal-rich and have low luminosity. In addition, we identify ten other GC candidates that are more uncertain and need more data for proper confirmation.

Key words. Galaxy: bulge – globular clusters: general – galaxies: star clusters: general – infrared: galaxies – Local Group – surveys

1. Introduction

Globular cluster (GC) systems are useful to study the formation and evolution of galaxies. A number of recent theoretical models have been recently developed to study the GCs in their galactic context (e.g., Boylan-Kolchin 2017; Bose et al. 2018; Forbes & Remus 2018; Pfeffer et al. 2018; Choski & Gnedin 2019; Hughes et al. 2019; El Badry et al. 2019; Kruisjens et al. 2019, 2020; Burkert & Forbes 2020), placing constraints on past merging events (e.g., kind of merger, galaxy masses, redshift of the accretion event, number of accreted GCs). Observationally, however, there are only a handful of very nearby galaxies (within a 100 kpc volume) that contain GCs where we can measure their properties down to the faintest possible members: the Milky Way (MW), the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), and the Fornax and Sagittarius (Sgr) dwarf galaxies, in order to compare them with the GC systems of other prototypical Local Group members, such as M31 and M33. As often occurs in Astrophysics, the knowledge of more distant systems in the Universe rests heavily on these few local standards.

In spite of their brightness, GCs can be hard to detect especially in some cases where the field stellar background density is very high and/or the reddening is high and inhomogeneous. In the Galactic bulge, these effects are combined resulting in the incompleteness of the GC sample. Large numbers of cluster candidates have been discovered, many of which still need to be confirmed (e.g., Borissova et al. 2014; Barba et al. 2015; Minniti et al. 2017a; Palma et al. 2019). In the LMC, even though the stellar density is high, the reddening is not so extreme, and the foreground halo contamination is not so severe. In consequence, LMC clusters can be more easily found and measured. Thousands of star clusters have been discovered in the LMC, exhibiting a wide range of ages, including classical old and very metal-poor GCs as well as younger and more metal-rich massive clusters (e.g., Searle et al. 1980; Da Costa 1991; Bica et al. 1996). The GC system of Sgr, another one of those known galaxies within 100 kpc volume, is less studied, probably because of the relative recent discovery of this galaxy (Ibata et al. 1994). Adding the GC system of the Sgr galaxy to the local standards would be an important step.
The primary goal of this work is to find and characterize GCs in the Sgr dwarf galaxy, located at $D = 26.5$ kpc behind the Milky Way bulge (Ibata et al. 1995; Monaco et al. 2004; Vasiliev & Belokurov 2020). However, in the case of the Sgr dwarf galaxy, finding star clusters is difficult mostly because of the high bulge stellar foreground density. Very few star clusters were previously known to be associated with this galaxy (Majewski et al. 2003; Belokurov et al. 2006; Law & Majewski 2010; Forbes & Bridges 2010; Massari et al. 2019; Myeong et al. 2019; Vasiliev 2019; Antoja et al. 2020).

According to the recent study of Bellazzini et al. (2020), there were nine GCs likely known to be Sgr members, four of them being located in the main body of this galaxy (NGC 6715, Arp 2, Ter 7, and Ter 8), and the other five being located in the extended tails (Pal 12, Whiting 1, NGC 5634, NGC 4147, and NGC 2419). Ter 7, and Ter 8, the other five being located in the extended tails. We present their positions, significance, extinctions, number of RR Lyrae, as well as their optical and near-infrared (IR) color-magnitude diagrams (CMDs).

2. Data and selection of new Sgr GCs

The GC selection strategy in Sgr needs to be slightly different than the one carried out in our bulge GC searches (Minniti et al. 2017a, 2021). We pinpoint here its four main differences. The first one is due to the effect of distance. Because of their larger distances, the Sgr GCs should be roughly three times smaller than the bulge GCs and twice as large as the GCs of the Magellanic Clouds. At the distance of Sgr, the scale is $2' \approx 15$ pc. Assuming a typical size as measured from their effective radii $r_{\text{eff}}$ for the MW GCs of 5 pc (Harris 1996, edition 2010), we expect Sgr GCs to have projected sizes that are roughly smaller than 1'.

The second difference is due to the effect of extinction. Because Sgr is located at higher Galactic latitudes than the main bulge, extinction is not such a big problem. In the Galactic bulge, one has to consider the nonuniform reddening and the possibility that some of the cluster candidates may be more regions with lower extinction than their surroundings (also known as dust windows). The third difference is due to the effect of the line of sight depth. Assuming that the bulge has a radius of about 3.5 kpc, the bulge GCs can be located anywhere between 4.6 and 11.6 kpc from the Sun (adopting $R_0 = 8.18$ kpc, Gravity Collaboration 2019). However, the Sgr GCs would all be located at relatively the same distance. The fourth difference, in fact, is due to the distance moduli between the near and far side of the bulge would be in excess of 2 mag.

3. Results and discussion

All of the newly found cluster candidates are listed in Table A.1. The optical and near-IR CMDs (Fig. 3) were then inspected to select the real GCs, by comparison with the CMDs of five known Sgr GCs in the region for which we have similar data (NGC 6715, Arp 2, Pal 12, Ter 7, and Ter 8). NGC 6715 is also the largest of these GCs, with a tidal radius of $r_t = 10'$ and a mean metallicity of $[\text{Fe/H}] = -1.30 \pm 0.12$ dex (Harris 1996, edition 2010, Baumgardt & Hilker 2018; Fernández-Trincado et al. 2021). We note that Bellazzini et al. (2008) argued that NGC 6715 coincides with the nucleus of Sgr, but it is kinematically distinguished from the nucleus.

In order to estimate the statistical significance of these stellar overdensities, we applied two tests. First we followed the procedure of Koposov et al. (2007), as applied in Moni Bidin et al. (2011) and Minniti et al. 2011, 2017b) who detected new
Galactic GCs in the presence of heavy background contamination. We computed the statistical significance of the stellar overdensities from the number of stars detected in excess to the local background, whose random fluctuations are assumed to be Poissonian (Koposov et al. 2007). As a specific example, we matched the background, whose random fluctuations are assumed to be Poissonian, to the number of stars detected in excess to the local background. We computed the statistical significance of the stellar overdensity in the presence of heavy background contamination.

There are six GCs that survive the $3\sigma$ detection with this new method, and three others that maintain their status of bad candidates, so that both methods agree in the classification for nine orbits. There are three others that maintain their status of bad candidates, so that both methods agree in the classification for nine orbits. This illustrates that while the statistical significance can be computed in different ways, there are fluctuations. But in spite of these fluctuations, the really good candidates survive and the really bad ones do not, while in between a number of undefined candidates also remain. We conservatively chose to keep as real GCs only those that survive both determinations with $>3\sigma$ (Minni 332, 341, 342, 344, 348, and 349), labeled in boldface in Table A.1. We also consider the variation of the background, taking the number counts of sources included within many adjacent circles of 3 arcmin radius around a wider area from the cluster candidates and using the standard deviation of the distribution of these number counts as sigma to compute the signal to noise. There are six GCs that survive the $3\sigma$ detection with this new method, and three others that maintain their status of bad candidates, so that both methods agree in the classification for nine orbits. On the other hand, there are five gains that changed from bad to good using the new method and four losses that changed from good to bad in the new method.

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The ten unconfirmed candidates may not only be mere background fluctuations, but also real GCs in various stages of dissolution. It is not surprising to find dissolving clusters deep in the potential well of galaxies such as Sgr, as the dynamical processes that contribute to the GC demise are maximized in these inner regions (e.g., Arca-Sedda & Capuzzo-Dolcetta 2014). As argued by Minniti et al. (2017a) and Palma et al. (2019) for the case of the numerous recently discovered bulge GC candidates, these objects are worthy of following up with additional observations in order to confirm their true nature.

We also examined which clusters may have associated RR Lyrae. After discarding the foreground bulge RR Lyrae on the basis of their PMs and mean magnitudes, three of these new GCs (Minni 335, 343, and 348) have four, three, and four RR Lyrae within $3\sigma$, respectively, which represents a $\approx 3\sigma$ excess above the measured background of RR Lyrae from the Sgr galaxy. All of these clusters have been classified as significant detections (Table A.1).

In addition, about half of the new GCs exhibit extended blue HBs. However, none of the new GCs appear to be significantly metal-poor. Figure 3 shows that in general the new GCs are more metal-rich than NGC 6715 ([Fe/H] = $-1.3$ dex) because of their redder giant branches (RGBs).

There are also two candidates, Minni 334 and 347, that have extended bright giant branches, indicating that they are either younger objects (more likely), or that they are located significantly in front of the Sgr dwarf galaxy (less likely). One of the new GCs, Minni 341, lies very close to the Sgr nucleus (NGC 6715), only about 15′ away. This GC is difficult to study because of the high field stellar density, but its detection is significant and its CMD is consistent with that of a typical GC (see Figs. 3 and A.1). We note that most of the new clusters are located in the central regions of this galaxy, where this search was performed, as shown in Fig. 4. If these clusters were brought...
there by dynamical friction, their structures may not be normal, as they may be dissolving.

Following Minniti et al. (2021), we also compared the new GCs with previously known Sgr GCs for which we have similar data. This comparison reveals that the new GCs are fainter than the comparison clusters Arp 2 ($M_V = -5.29$ mag), Ter 7 ($M_V = -5.01$ mag), and Ter 8 ($M_V = -5.07$ mag).

Apparently, all the previously known Sgr clusters were located to the south of NGC 6715, at the center of this galaxy. Also, only half of the Sgr GCs were located within the main body of the galaxy. The new discoveries challenge this global picture. Now most of the Sgr GCs are located within the main body of this galaxy, and with many of them located to the north of the Sgr center, where our search was performed (Fig. 4). In order to complete the spatial distribution of the Sgr GC system, however, a thorough search of the southern part of this galaxy is warranted.

### 4. Conclusions

We have carried out a new search for GCs in the main body of the Sgr dwarf galaxy using the Gaia EDR3 optical data in combination with the near-IR data from the VVVX survey. This is, as far as we know, the first systematic optical and near-IR search for GCs within the main body of this galaxy. For comparison, we used four known GCs that have compatible data: NGC 6715, Arp 2, Ter 7, and Ter 8.

In addition to the 12 new GCs found by Minniti et al. (2021), in this work we have identified eight more GCs within the main body of the Sgr dwarf galaxy. Even though the bulge field stars largely outnumber the cluster members, the exquisite Gaia EDR3 PMs allowed us to make clean optical and near-IR CMDs for the new GCs. We also present their positions, extinctions, and detection significances.

After discarding the foreground bulge RR Lyrae variables stars, we found that three of the new Sgr GCs appeared to contain RR Lyrae. Minni 335, 343, and 348 are confirmed to contain a significant overdensity ($\approx 3\sigma$) of RR Lyrae above the nearby background.

We confirm that the GC system of the Sgr dwarf galaxy is richer than previously thought. The GC system of this galaxy now contains nearly 30 members. However, from an observational standpoint, we conclude that the current census of Sgr
GCs is still incomplete, as demonstrated by the continued discovery of faint GCs in the main body of this galaxy. We stress that a complete census of these objects has yet to be done in the southern portion of the Sgr dwarf galaxy, outside of the VVVX footprint. Therefore, we predict the discovery of many more GCs with future facilities. In fact, these new GCs would also serve to train automatic detection algorithms to be applied to massive databases such as Gaia (Gaia Collaboration 2021), Pan-Starrs (Drdica-Wagner et al. 2020), and in the future the Vera Rubin Observatory (also known as Large Synoptic Survey Telescope – LSST Science Collaboration 2009; Ivezić et al. 2019) in order to find even more missing GCs.

The next step is to measure the physical parameters for the new GCs: metallicities, ages, luminosities, and structural parameters (Garro et al. 2021). It would then be possible to compare the Sgr GC system with those of other well studied nearby galaxies such as the LMC.

Importantly, we are uncovering a new GC system of a very nearby galaxy that can be studied in detail. The Sgr galaxy is merging with the MW and its GCs may help to reveal the past history and also the future of this event, and of other GC systems of more distant galaxies as well. The discovery of a populous GC system in the Sgr dwarf enables a variety of studies: a comparison of the LMC and MW GC systems, which have widely different masses, potentials, and tidal fields; a measurement of their orbital and structural parameters to explore their kinematical and dynamical evolution; a measurement of their ages and metallicities to unveil their star formation history and chemical evolution as well as to compare the age-metallicity relationship for these galaxies; and a census of their variable star populations, including the RR Lyrae, to name a few.

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Appendix A: Sgr GCs data

Table A.1 below lists the data for all the GC candidates analyzed. We give the IDs, positions in equatorial coordinates (J2000), near-IR extinctions $A_{Ks}$, number of RR Lyrae within 3′ and 10′ from the cluster centers ($N_3$ and $N_{10}$), significance of the overdensity, and data provenance VVVX or MD (McDonald et al. 2013). Confirmed GCs ($\sigma > 3.0$) are in boldface.

Figure A.1 below shows the optical CMDs for the best clusters listed in Table A.1 compared with their respective field CMDs (with only PM-selected Sgr members and equal areas being considered). We looked for differences that can be appreciated with respect to the Sgr field stars, including the following, for example: the width of the RGB, which is larger in the Sgr dwarf than in the typical GCs; the presence of young and intermediate age stars in the Sgr body, which are absent in old GCs, and in some cases of metal-poor GCs; and the presence of an extended HB. In fact the CMDs for the well populated GCs are different than the typical Sgr population, showing instead similar features to the known Sgr GCs used for comparison (NGC 6715, Arp 2, Pal 12, Ter 7, and Ter 8), with CMDs shown by Minniti et al. (2021).

Table A.1. New GC candidates in the Sgr galaxy.

| ID     | RA (J2000) | Dec (J2000) | $A_{Ks}$ (mag) | $N_3$ | $N_{10}$ | $S/N_1$ | $S/N_{10}$ | Survey |
|--------|------------|-------------|----------------|-------|----------|----------|-------------|--------|
| Minni 332 | 18 47 43.2 | −29 23 06 | 0.045 | 1 | 7 | 6.4 | 5.2 | VVVX |
| Minni 333 | 18 58 07.2 | −29 45 36 | 0.051 | 1 | 8 | 2.2 | 6.7 | VVVX |
| Minni 334 | 18 59 57.6 | −30 16 12 | 0.038 | 1 | 9 | 2.6 | 1.7 | VVVX |
| Minni 335 | 18 47 16.8 | −30 15 36 | 0.054 | 4 | 12 | 5.5 | 2.2 | VVVX |
| Minni 336 | 18 51 48.0 | −31 39 36 | 0.049 | 0 | 2 | 2.7 | 3.4 | VVVX |
| Minni 337 | 18 52 16.8 | −31 37 12 | 0.050 | 0 | 2 | 1.8 | 2.3 | VVVX |
| Minni 338 | 18 54 52.8 | −31 40 48 | 0.047 | 0 | 1 | 3.7 | 2.0 | VVVX |
| Minni 339 | 18 45 55.2 | −29 49 12 | 0.042 | 0 | 8 | 2.7 | 4.9 | VVVX |
| Minni 340 | 18 50 55.2 | −30 27 36 | 0.046 | 2 | 22 | 3.4 | 1.9 | VVVX |
| Minni 341 | 18 53 57.6 | −30 31 48 | 0.043 | 2 | 11 | 4.9 | 4.8 | VVVX |
| Minni 342 | 18 54 19.2 | −31 07 12 | 0.042 | 1 | 5 | 4.6 | 3.9 | VVVX |
| Minni 343 | 18 55 36.0 | −31 06 36 | 0.045 | 3 | 13 | 4.6 | 2.4 | VVVX |
| Minni 344 | 18 56 38.4 | −31 06 36 | 0.045 | 1 | 15 | 3.2 | 3.8 | VVVX |
| Minni 345 | 18 56 45.6 | −30 58 12 | 0.044 | 2 | 11 | 1.6 | 12.5 | VVVX |
| Minni 346 | 18 56 21.6 | −30 43 48 | 0.044 | 2 | 12 | 1.4 | 0.1 | VVVX |
| Minni 347 | 18 58 36.0 | −30 37 48 | 0.042 | 1 | 15 | 2.0 | 3.4 | MD |
| Minni 348 | 18 59 57.6 | −29 22 12 | 0.046 | 4 | 14 | 4.4 | 8.1 | VVVX |
| Minni 349 | 19 04 57.6 | −28 26 24 | 0.061 | 0 | 3 | 3.5 | 3.3 | MD |
Fig. A.1. GC CMDs from Gaia EDR3 photometry compared with their respective field CMDs.