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How large are the globular cluster systems of early-type galaxies and do they scale with galaxy halo properties?

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ABSTRACT

The globular cluster (GC) systems of galaxies are well known to extend to large galactocentric radii. Here, we quantify the size of GC systems using the half number radius of 22 GC systems around early-type galaxies (ETGs) from the literature. We compare GC system sizes to the sizes and masses of their host galaxies. We find that GC systems typically extend to 4 times that of the host galaxy size; however, this factor varies with galaxy stellar mass from about 3 times for M^* galaxies to 5 times for the most massive galaxies in the universe. The size of a GC system scales approximately linearly with the virial radius (R_{200}) and with the halo mass (M_{200}) to the 1/3 power. The GC system of the Milky Way follows the same relations as for ETGs. For ultra diffuse galaxies (UDGs), their GC system size scales with halo mass and virial radius as for more massive, larger galaxies. UDGs indicate that the linear scaling of GC system size with stellar mass for massive galaxies flattens out for low stellar mass galaxies. Our scalings are different to those reported recently by Hudson & Robison.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: star clusters: general – dark matter.

1 INTRODUCTION

Globular clusters (GCs) can be traced to relatively large galactocentric radii, thus providing valuable probes of their host galaxy haloes (where the underlying starlight has a low surface brightness). This property has been exploited by the SLUGGS survey of 25 nearby early-type galaxies (ETGs; Brodie et al. 2014 and see sluggs.swin.edu.au) to investigate the structural properties (Kartha et al. 2016), metallicity (Usher et al. 2012), kinematics (Pota et al. 2013) and dynamical mass (Alabi et al. 2017) of GC systems over a range of host galaxy properties.

A number of scaling relations have been found between GC systems and their host galaxy. Perhaps the most remarkable is the scaling between the total mass of a GC system and the host galaxy's halo mass (Blakeslee 1997; Spitler & Forbes 2009; Georgiev et al. 2010; Hudson, Harris & Harris 2014; Harris et al. 2015, 2017b). This near-linear relation holds over a large range in halo mass with little, or no, dependence on host galaxy type.

How far do GC systems extend relative to their host galaxy and do they scale with host galaxy halo properties? GCs have been confirmed out to more than 30 times the effective (half-light) radius of their host galaxy (e.g. Alabi et al. 2016). However, defining the total radial extent of a GC system is problematic. The total radial extent of a GC system is usually defined to be the radius at which the number density of GCs per unit area, from a photometric study, decreases to a constant level, indicating that a 'background' has been reached. This constant density background is assumed to be due to contaminants in the photometric object list. This approach has been taken by Rhode et al. (2007, 2010) and Kartha et al. (2016).

However, the level of the background used is somewhat dependent on the ability of the photometry to separate bona fide GCs from contaminants. For example, imaging from the Advanced Camera for Surveys (ACS) camera onboard *Hubble Space Telescope* (*HST*) can sufficiently resolve individual GCs to measure their size to distances of about 20 Mpc, thus reducing contaminant levels to a bare minimum. At the other extreme, ground-based imaging under poor seeing conditions will result in object lists that may include significant contributions from foreground stars and distant galaxies. A better approach is to measure the effective radius of both the GC system and its host galaxy. Such measures are derived from intermediate radial scales, which are relatively less affected by contamination.

Recently, Hudson & Robison (2017; hereafter HR17) investigated the size of GC systems and trends with halo properties. They selected GC candidates around nine galaxies based on their size, *i*-band magnitude and *g*–*i* colour from the wide-field CFHT Lens Survey (Hudelot et al. 2012). They fit Sérsic profiles to the GC radial surface density profile (fixing the Sérsic *n* parameter to be 4, i.e. a de Vaucouleurs profile) to derive the half number radius (hereafter GC R_e) of the GC system. HR17 noted that this approach gave good fits to the GC density profiles but on average their GC R_e sizes were systematically larger than those in the literature

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(as they fit only in the outer regions of GC systems). HR17 also measured GC R_e for 26 other GC systems using data from the literature, including some measurements of the GC R_e from the SLUGGS survey (Kartha et al. 2014; 2016).

Here, we investigate the central question of how large are GC systems and how they scale with host galaxy properties. We take measured sizes of GC systems around ETGs using available data from the literature. The GC system imaging for these studies comes from *HST* and/or wide-field deep ground-based observations. We include the ETGs listed in HR17 and four very massive ETGs from Harris (2017b), which extends the analysis to the highest mass galaxies in the universe. Although not ETGs, it is interesting to examine the GC systems of the new class of galaxy dubbed ultra diffuse galaxies (UDGs). Such galaxies have stellar masses similar to dwarf galaxies of around 10^8 $M_{\odot}$ but halo masses closer to giant galaxies (van Dokkum et al. 2017).

2 THE SAMPLE

Our sample consists of GC systems of ETGs using inhomogeneous data from the available literature. We exclude the GC systems of late-type galaxies as they tend to be GC poor, lacking well-defined system sizes. Our ETG sample is eight from the SLUGGS survey, four from Hargis & Rhode (2014) including the massive bulge galaxy NGC 4594 (the Sombrero), six GC systems fit from HR17 (but based on data from Young et al. 2012 and Hargis & Rhode 2012) and seven new ETGs from HR17 (we exclude the interacting pair NGC 942+943 but do include the elliptical galaxy NGC 2699, which was incorrectly identified as an Sb in HR17). All of these galaxies are listed in HR17. To this sample, we include four massive, central dominant ETGs studied by Harris et al. (2017a). Relevant properties of the sample galaxies and references are given in Table 1. We also list in Table 1 three UDGs located in the Coma cluster, whose GC systems have recently been studied by Peng & Lim (2016) and van Dokkum et al. (2017). For comparison purposes, we show the Milky Way's GC system in the figures that follow. The Milky Way's GC system has a GC R_e of 4.1 kpc (as measured by HR17). The Milky Way itself has a total stellar mass of log $M_* = 10.81$ (Mcmillan 2011) and an effective radius of 2.7 kpc (Gilmore, Wyse & Kuijken 1989).

3 RESULTS AND DISCUSSION

Before investigating the scaling of GC system size with halo properties, we examine host galaxy stellar properties, i.e. size and mass. In Fig. 1, we show the relative size of a GC system (GC R_e) to its host galaxy size (R_e). In general, the two measurements for an individual galaxy are carried out by different studies. The uncertainty in the size ratio shown is only that for the GC R_e as this tends to dominate over the quoted uncertainties in the galaxy R_e. The seven new galaxies from HR17 are highlighted in Fig. 1. They tend to have much larger quoted uncertainties than the existing literature data, and in the case of NGC 883 it lies off the plot due to its large ratio (i.e. GC $R_e/R_e = 46$), which we suspect to be a combination of an underestimated galaxy R_e (e.g. its location in the galaxy size–mass plot shown in fig. 5 of Forbes et al. 2017) and an overestimated GC R_e (see Fig. 2). The data point for NGC 4486 (M87) is also highlighted. Here, we use the galaxy R_e from Forbes et al. (2017), based on *Spitzer* 3.6 μm imaging, of around 7 kpc. However, we note that Kormendy et al. (2009) found a much larger size of around 50 kpc. If correct, the latter would reduce the ratio for NGC 4486 to 1.7. Excluding NGC 4486, and the new HR17 data, we find a mean value for the ratio of 3.7 ± 0.4 for ETGs. This indicates that the galactocentric radius corresponding to half of the GC system is ∼4 times larger than the radius containing half of the galaxy's light. HR17 found a similar mean ratio, i.e. ∼3.5. We also note a weak trend for the ratio to be higher in larger galaxies (as noted by HR17). UDGs and the Milky Way lie within the general scatter.

In Fig. 2, we show GC system size versus host galaxy total stellar mass. NGC 4486, an outlier in Fig. 1, lies within the general scatter. A weighted best fit to the ETG data (excluding the new HR17 data and UDGs) gives: log GC $R_e = 0.97\ (\pm 0.4)$ log $M_* - 9.76\ (\pm 4.4)$. This is fully consistent with a linear trend between GC system size

Table 1. Galaxy and GC system properties. Columns are: (1) galaxy name, where N = NGC and U = UGC, (2) Hubble type, (3) distance, (4) stellar mass, (5) galaxy effective radius, (6) GC system effective radius and uncertainty, and (7) GC system.

Galaxy (1)	Type (2)	Dist. (Mpc) (3)	log M_* ($M_{\odot}$) (4)	R_e (kpc) (5)	GC R_e (kpc) (6)	Ref
N720	E5	26.9	11.27	3.8	13.7 (2)	1
N1023	S0	11.1	10.99	2.6	3.3 (0.9)	1
N1407	E0	26.8	11.60	12.1	25.5 (1)	2
N2768	E6/S0	21.8	11.21	6.4	10.6 (2)	1
N3607	S0	22.2	11.39	5.2	14.2 (2)	3
N3608	E1-2	22.3	11.03	4.6	9.1 (1)	3
N4278	E1-2	15.6	10.95	2.1	11.3 (2)	4
N4365	E3	23.1	11.51	8.7	41.3 (8)	5
N4406	E3	17.9	11.47	8.1	28.2 (1)	6
N4472	E2	16.7	11.83	7.7	58.4 (8)	6
N4594	Sa	9.5	11.41	3.3	16.8 (1)	6
N5813	E1-2	31.3	11.43	8.7	36.6 (3)	6
N4874	cD	100	11.90	15.8	62 (2)	7
N4889	cD	100	12.09	16.3	110 (–)	8
U9799	E	150	12.00	22.7	61 (–)	8
U10143	cD	154	11.73	23.4	114 (–)	8
N3384	S0	10.9	10.61	1.7	7.3 (4.8)	9
N4486	cD	16.0	11.74	6.9	87 (56)	9
N4754	S0	16.1	10.68	2.5	8.8 (3.5)	9
N4762	S0	15.3	10.67	3.3	4.7 (1.1)	9
N5866	S0	11.7	10.83	1.7	8.5 (1.8)	9
N7332	S0pec	13.2	10.25	1.9	1.4 (0.3)	9
IC219	E	72.7	10.97	1.88	25.9 (8.8)	9
N883	S0	72.7	11.40	3.83	178 (72)	9
N2695	S0	26.5	10.54	1.15	10.3 (6.1)	9
N2698	S0	26.5	10.54	0.88	10.4 (9.9)	9
N2699	E	26.5	10.30	0.79	2.0 (1.6)	9
N5473	S0	26.2	10.72	1.58	1.56 (2.4)	9
N5485	S0	26.2	10.70	2.00	12.9 (7.3)	9
DF17	UDG	100	7.92	3.4	5.8 (1.0)	10
DF44	UDG	100	8.43	4.7	10.3 (–)	11
DFX1	UDG	100	8.26	3.5	7.7 (–)	11

References: 1 = Kartha et al. (2014), 2 = Spitler et al. (2012), 3 = Kartha et al. (2016), 4 = Usher et al. (2013), 5 = Blom et al. (2012), 6 = Hargis & Rhode (2014), 7 = Peng et al. (2011), 8 = Harris et al. (2017a), 9 = Hudson & Robison (2017; HR17), 10 = Peng & Lim (2016) and 11 = van Dokkum et al. (2017). The table is divided into five sections: SLUGGS survey galaxies, galaxies from Hargis & Rhode (2014), galaxies from Harris et al. (2017a), literature galaxies with GC systems fit by HR17, new data from HR17 and UDGs in the Coma cluster. Stellar masses and galaxy effective are taken from Forbes et al. (2017), Cappellari et al. (2011), Harris et al. (2017a), HR17, Veale et al. (2017), Vika et al. (2012), Peng & Lim (2016) and van Dokkum et al. (2017). When the GC effective radii $R_e$uncertainty is not quoted, we assume 10 per cent.

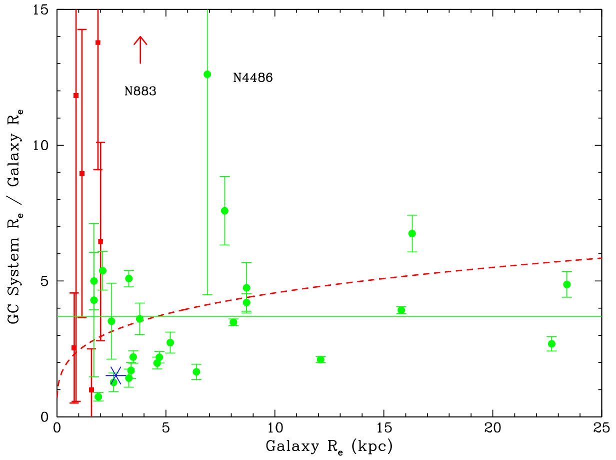

Figure 1. The ratio of the size of a GC system to its host galaxy versus galaxy size. The red filled squares are galaxies from the study of HR17; NGC 833 with a ratio of 46 is shown as a lower limit. The green filled circles are other data from the existing literature, including three UDGs. The blue asterisk represents the Milky Way's GC system. The UDGs and the Milky Way follow the general trend. Excluding the HR17 data and NGC 4486 (M87), the mean ratio for ETGs is 3.7 (shown by a green solid line) with a mild trend for an increasing ratio in larger galaxies. The relation found by HR17 for their sample of 35 early- and late-type galaxies is shown by the red dashed line.

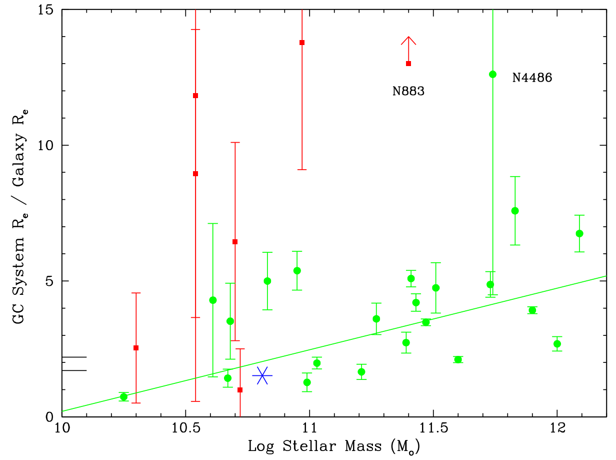

Figure 3. The ratio of the size of a GC system to its host galaxy versus galaxy stellar mass. The red filled squares are galaxies from the study of HR17; NGC 833 with a ratio of 46 is shown as a lower limit. The green filled circles are other data from the existing literature. Excluding the HR17 data and the UDGs, we find that the ratio of GC system to galaxy size increases for more massive galaxies. The green line shows a best fit of slope 2.27 ± 0.4. The blue asterisk represents the Milky Way's GC system, which follows the general trend. The three UDGs, all with log stellar masses around 8, are indicated by short horizontal lines. The UDGs do not follow an extrapolation of the best fit to lower mass.

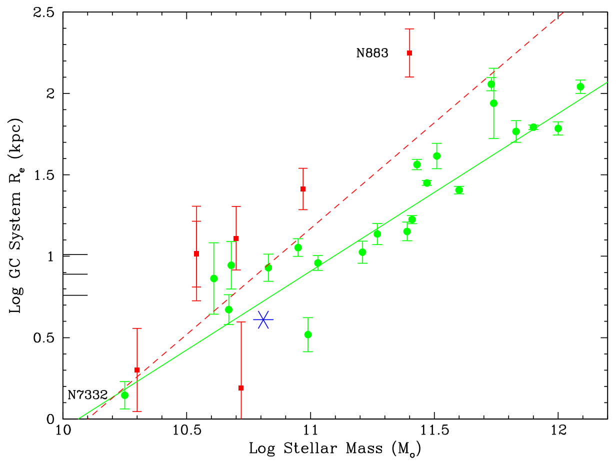

Figure 2. Effective radius of the GC system versus host galaxy stellar mass. Red squares represent data from HR17 and filled green circles represent data from the existing literature. The blue asterisk represents the Milky Way's GC system, which follows the general trend. The three UDGs, all with log stellar masses around 8, are indicated by short horizontal lines. The green solid line shows a best-fitting relation between the GC system size and galaxy mass for the existing literature data for ETGs (i.e. excluding the HR17 data, UDGs and the Milky Way). The slope of 0.97 ± 0.4 is fully consistent with a linear relation. The UDGs do not follow an extrapolation of the best fit to lower mass. The red dashed line shows the fit of HR17 (slope = 1.30 ± 0.14) to their sample of 35 early- and late-type galaxies.

and the stellar mass of the host galaxy. This suggests that as ETGs grow in stellar mass, their GC systems grow proportionally in size. HR17 measured a slope of 1.30 ± 0.14 between GC R_e and galaxy stellar mass for their sample of 35 early- and late-type galaxies; thus the two slopes agree within the combined uncertainties. The GC system of the Milky Way is consistent with the trend in Fig. 2. However, the UDGs indicate that they follow a different scaling with stellar mass than a simple extrapolation to lower masses. We suspect that the relation flattens out for low galaxy masses with an inflection point around log $M_* = 10.6$ (i.e. at the same mass associated with the change in the slope of the galaxy size–stellar mass relation; Shen et al. 2003). We note that NGC 7332 (with log $M_* = 10.25$) is a disturbed galaxy and the only one for which the quoted GC R_e is less than the galaxy R_e; it warrants further study to confirm its GC system size.

In Fig. 3, we show the ratio of GC system to host galaxy size versus host galaxy stellar mass. Again excluding the new HR17 data from our analysis, we find that although the ratio has a mean value of around 4, it is larger for more massive galaxies. A weighted best-fitting relation has the form: ratio = 2.27 (±0.4) log M_* – 22.5 (±4.4), where ratio = GC system R_e/galaxy R_e. In low-mass ETGs, GC systems extend about 2–3 times the effective radius of their host galaxies; for the highest mass galaxies in the universe, the GC systems are even more extended at 5 times the galaxy effective radius. Again, the GC system of the Milky Way obeys the ETG relation, but those of UDGs do not obey a simple extrapolation to log masses of ∼8.

In the two-phase picture of ETG formation, more massive galaxies contain a larger fraction of accreted material from satellites (e.g. Oser et al. 2010). This accreted material serves to build up the halo of the host galaxy, so that the more massive galaxies tend to have shallower, more extended surface brightness profiles (Pillepich et al. 2014). Fig. 3 (and to some extent Fig. 2) indicates that larger, more massive ETGs host more extended GC systems. This is consistent with the idea that GCs in the outer haloes of ETGs are largely accreted from disrupted satellite galaxies (Georgiev et al. 2010; Forbes et al. 2011; Blom et al. 2012). This may also indicate that massive galaxies accrete a larger fraction of low mass compared to high-mass satellites which are disrupted at relatively large galactocentric radii (e.g. Oser et al. 2012).

HR17 used weak lensing results to connect their measured stellar masses to halo masses (M_{200}) and virial radii (R_{200}). Here, we use values taken directly from their table 4. For the UDGs, we use the

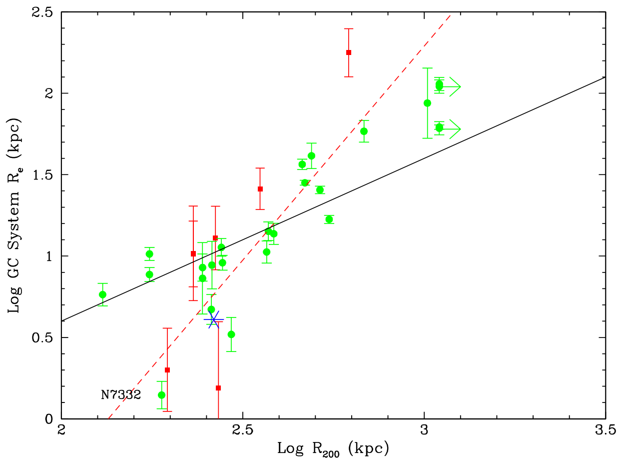

Figure 4. GC system size versus virial radius (R_{200}) of the halo. The red filled squares are galaxies from the study of HR17. The green filled circles are other data from the existing literature. The blue asterisk represents the Milky Way's GC system, which follows the general trend. The three galaxies with the smallest virial radii are the UDGs. The four most massive galaxies in our sample lack virial radii, and so are shown as lower limits. The solid line is not a fit but shows the linear relation of Kravtsov (2013) between galaxy size and virial radius scaled up by a factor of 3.7 (i.e. the mean GC system to galaxy size ratio). The red dashed line is the fit of HR17 (slope = 2.63 ± 0.38) to their sample of 35 early- and late-type galaxies.

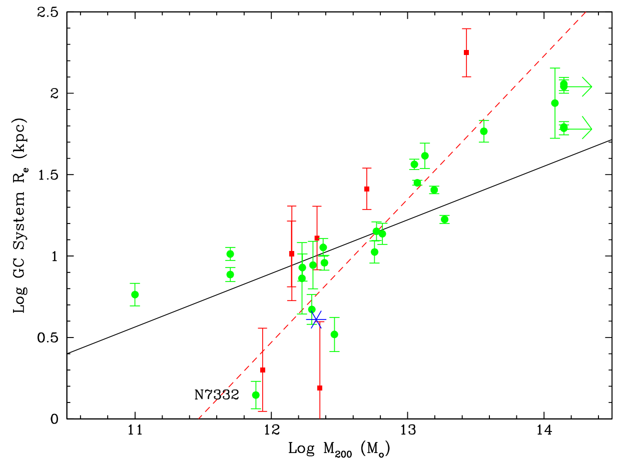

Figure 5. GC system size versus the halo mass (M_{200}). The red filled squares are galaxies from the study of HR17. The green filled circles are other data from the existing literature. The blue asterisk represents the Milky Way's GC system, which follows the general trend. The three galaxies with the smallest halo masses are the UDGs. The red dashed line is the fit of HR17 (slope = 0.88 ± 0.10) to their sample of 35 early- and late-type galaxies. The solid line is not a fit but shows a relation of slope 1/3 based on the predictions of Kravtsov (2013).

halo masses of 5×10^{11} M$_\odot$ for DF44 and DFX1 (van Dokkum et al. 2017) and 10^{11} M$_\odot$ for DF17 (Peng & Lim 2016), and assign approximate virial radii of 175 and 130 kpc, respectively. The four most massive galaxies in our sample lack halo masses and virial radii. As they have stellar masses comparable to, or greater than NGC 4486, we show them as having virial radii and halo masses larger than NGC 4486 in the following figures.

In Fig. 4, we show the GC system size as a function of the virial radius. The literature data show a general trend of increasing GC system size in larger haloes, with the HR17 data having a large scatter. HR17 measured a slope of 2.63 ± 0.38, which is a reasonable representation for the GC systems in intermediate-mass galaxies. However, as can be seen in Fig. 4, their relation tends to overpredict the GC system size of the largest galaxies and underpredict those of UDGs. We also include in Fig. 4 the predicted linear relation from Kravtsov (2013), based on halo abundance matching, between the 2D projected galaxy effective radius and virial radius, i.e. $R_e = 0.011\, R_{200}$ but scaled up by a factor of 3.7 to account for the typical GC system to galaxy size ratio. The resulting linear relation has a reasonable normalization and slope compared to the data, including the largest galaxies (which have lower limits on their size) and the smallest galaxies (the UDGs).

Kravtsov (2013) argues that the near-linear galaxy size–virial radius relation is consistent with the idea that galaxy sizes are set by the angular momentum imparted to haloes during formation (e.g. Mo et al. 1998). Thus, the size of a GC system (and the host galaxy) is, to the first order, set at early times in this model with subsequent evolution moving galaxies along the relation. A similar situation may exist for the linear relation between GC system mass and halo mass. For example, Boylan-Kolchin (2017) suggests that this relation is established at high redshift with (metal-poor) GCs forming in direct proportion to the dark matter content of their host galaxy's halo and that mass growth over time maintains the linear relation.

Galaxy growth over time is a function of galaxy mass with more massive galaxies accreting a larger fraction of their mass compared to lower mass galaxies that are dominated by *in situ* star formation (e.g. Oser et al. 2010; Pillepich et al. 2014). These two modes of stellar mass growth are also relevant for GC systems, with GCs expected to form *in situ* and to be accreted along satellite galaxies. The relative importance of *in situ* to accreted GCs would be expected to vary as a function of host galaxy mass, as would tidal stripping and the destruction of GCs. Future simulations, that include these processes, will help our understanding of how such linear relations can be maintained over time.

In Fig. 5, we show the GC system size as a function of halo mass. HR17 found a slope of 0.88 ± 0.10 for their sample, which again provides a reasonable representation for our intermediate halo mass galaxies. However, our inclusion of higher mass ETGs (with lower limits on their halo mass) and three lower mass UDGs suggests that the actual relation is much shallower. In Fig. 4, we found that the slope of the GC system size versus R_{200} is around unity. The virial, or halo, mass $M_{200} \propto R_{200}^3$. So based on Fig. 4, and the predictions of Kravtsov (2013), we would expect GC system size to scale with $M_{200}^{1/3}$. A relation of this slope is included in Fig. 5 and it indeed provides a good representation of the data over the full mass range. This suggests that the GC system size does not scale with $M_{200}^{0.88}$ but closer to $M_{200}^{0.33}$ and that the most massive galaxies in the universe and UDGs follow this scaling relation.

4 CONCLUSIONS

Here, we have examined the size of GC systems of 22 ETGs using a measure of their half number effective radii from fits to GC surface density profiles. We exclude late-type galaxies and the most recent new data for seven GC systems from HR17 as this new data show strong deviations from the existing data. Our analysis extends to lower and higher masses compared to HR17. We find a linear relation between the GC system size and its host galaxy stellar mass but there are indications from UDGs that the relation may flatten for log stellar masses less than 10.6 M$_\odot$. We measure the ratio of the GC system size to that of its host galaxy, finding a mean value of 3.7 for our sample. However, this ratio increases from around 3 times for M* galaxies to around 5 times for the most massive galaxies in the universe.

Our main result is that GC system size has an approximately linear relation with virial radius and halo mass to the 1/3 power. This is consistent with the galaxy scalings predicted by Kravtsov (2013) and suggests that the relation is set during the initial phases of galaxy formation. Thus, complementary to the known linear scaling of GC system mass with halo mass, we also find a near-linear scaling of GC system size with virial radius. These indicate a strong connection between GC systems and host galaxy dark matter properties. The GC system of the Milky Way appears to follow the same scalings as the GC systems of ETGs. The GC system sizes of UDGs also scale with virial radius and halo mass in the same sense as more massive, larger galaxy haloes. Our larger host galaxy mass range has revealed different scalings of GC system size with virial radius and halo mass to those claimed by HR17, but these scalings should still be verified with a more homogeneous sample. Future work should also attempt to bridge the gap in mass between UDGs and massive ETGs, and study the blue and red GC subpopulations independently.

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