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

Duncan A. Forbes1,*

1Centre for Astrophysics & Supercomputing, Swinburne University, Hawthorn VIC 3122, Australia

ABSTRACT

The globular cluster 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 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× that of the host galaxy size, however this factor varies with galaxy stellar mass from about 3× for M∗ galaxies to 5× for the most massive galaxies in the universe. The size of a GC system scales approximately linearly with the virial radius (R200) and with the halo mass (M200) to the 1/3 power. The GC system of the Milky Way follows the same relations as for early-type galaxies. For Ultra Diffuse Galaxies 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 (2017).

Key words: galaxies: star clusters – galaxies: evolution – cosmology: dark matter

1 INTRODUCTION

Globular clusters (GC) can be traced to relatively large galactocentric radii, thus providing valuable probes of their host galaxy halos (where the underlying starlight has a low surface brightness). This property has been exploited by the SLUGGS survey of 25 nearby early-type galaxies (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 et al. 1997; Spitler & Forbes 2009; Georgiev et al. 2010; Hudson et al. 2014; Harris et al. 2015; Harris et al. 2017a). This near linear relation holds over a large range in halo mass with little, or no, dependence on host galaxy type.

How far do globular cluster systems extend relative to their host galaxy and do they scale with host galaxy halo properties? Globular clusters 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 ACS camera onboard 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 9 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 Sersic profiles to the GC radial surface density profile (fixing the Sersic 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 (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 early-type galaxies (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 galaxies 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 8 from the SLUGGS survey, 4 from Hargis & Rhode (2014) including the massive bulge galaxy NGC 4594 (the Sombrero), 6 GC systems fit by HR17 (but based on data from Young et al. 2012 and Hargis & Rhode 2012), and 7 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. (2017b). Relevant properties of the sample galaxies and references are given in Table 1. We also list in Table 1 three Ultra Diffuse Galaxies located in the Coma cluster, whose GC systems have recently been studied by Peng et al. (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 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 et al. 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 Figure 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 $R_e$ measurements of the GC $R_e$ through the outer regions of GC systems). H1R7 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 early-type galaxies (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 galaxies 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).

### Table 1. Galaxy and globular cluster system properties

| Galaxy | Type | Dist. [Mpc] | log $M_*$ [M$_\odot$] | $R_e$ [kpc] | GC $R_e$ [kpc] | 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        | 21.5 (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  | S0   | 9.5         | 11.41                 | 3.3         | 16.8 (1)       | 6   |
| N5813  | E1-2 | 31.3        | 11.43                 | 8.7         | 36.6 (3)       | 6   |
| N4874  | S0   | 10.0        | 10.61                 | 1.7         | 7.3 (4.8)      | 9   |
| N4889  | E7   | 10.0        | 10.61                 | 1.7         | 7.3 (4.8)      | 9   |
| N5866  | S0   | 11.7        | 10.83                 | 1.7         | 8.5 (1.8)      | 9   |
| N7332  | S0pec| 13.2        | 10.25                 | 1.9         | 14.0 (3.0)     | 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   |
| N5845  | S0   | 26.2        | 10.70                 | 2.00        | 12.9 (7.3)     | 9   |
| DIF1   | UDG  | 100         | 7.92                  | 3.4         | 5.8 (1.0)      | 10  |
| DIF4   | UDG  | 100         | 8.43                  | 4.7         | 10.3 (11)      | 11  |
| DIFX1  | UDG  | 100         | 8.26                  | 3.5         | 7.7 (11)       | 11  |

Notes: columns are (1) galaxy name where $N=NGC$ and $U=UGC$, (2) Hubble type, (3) distance, (4) stellar mass, (5) galaxy effective radius, (6) globular cluster system effective radius and uncertainty, (7) globular cluster system reference 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. (2017b), 9 = Hudson & Robison (2017); HR17, 10 = Peng et al. (2016), 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. (2017), literature galaxies with GC systems fit by HR17, new data from HR17 and Ultra Diffuse Galaxies in the Coma cluster. Stellar masses and galaxy effective are taken from Forbes et al. (2017), Cappellari et al. (2011), Harris et al. (2017), HR17, Veale et al. (2017), Vika et al. (2012), Peng et al. (2016) and van Dokkum et al. (2017). When the GC effective radii $R_e$ uncertainty is not quoted, we assume 10%.
Figure 1. The ratio of the size of a globular cluster system to its host galaxy vs galaxy size. The red filled squares are galaxies from the study of HR17; NGC 833 which a ratio of 46 is shown as a lower limit. The green filled circles are other data from the existing literature, including 3 Ultra Diffuse Galaxies. 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 early-type galaxies 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.

HR17). Ultra Diffuse Galaxies and the Milky Way lie within the general scatter.

In Figure 2 we show GC system size vs host galaxy total stellar mass. NGC 4486, an outlier in Fig. 1, lies within the general scatter. A weighted best fit to the early-type galaxy data (excluding the new HR17 data and UDGs) gives: log GC $R_e = 0.97 \pm 0.4 \log M_\star - 9.76 \pm 4.4$. This is fully consistent with a linear trend between GC system size and the stellar mass of the host galaxy. This suggests that as early-type galaxies 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 $M_\star = 10.6$ (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 $M_\star = 10.25$) 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 Figure 3 we show the ratio of GC system to host galaxy size vs 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 fit relation has the form: ratio = 2.27 ± 0.4 log $M_\star - 22.5 \pm 4.4$, where ratio = GC $R_e$ / galaxy $R_e$. In low mass early-type galaxies, GC systems extend about 2-3x the effective radius of their host galaxies; for the highest mass galaxies in the universe the GC systems are even more extended at 5x the galaxy effective radius. Again, the GC system of the Milky Way obeys the early-

\[ \text{GC system size} \]
type galaxy relation but those of Ultra Diffuse Galaxies 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). Figure 3 (and to some extent Figure 2) indicate that larger, more massive ETGs host more extended GC systems. This is consistent with the idea that GCs in the outer halos 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_{vir}). Here we use values taken directly from their table 4. For the UDGs we use the halo masses of 5×10^{11} M_⊙ for DF44 and DFX1 (van Dokkum et al. 2017), and 10^{11} M_⊙ for DF17 (Peng et al. 2016), and assign approximate virial radii of 130 and 175 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 Figure 4 we show the GC system size as function of the virial radius. The literature data show a general trend of increasing GC system size in larger halos, 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 normalisation 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 halos during formation (e.g. Mo et al. 1998). Thus the size of a GC system (and the host galaxy), is to 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) suggest 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 which 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 Figure 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 galaxies...
early-type galaxies (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 vs $R_{200}$ is around unity. The virial, or halo, mass $M_{200}$ is $\alpha R_{200}^3$. 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 GC system size does not scale with $M_{200}^{1/3}$ but closer to $M_{200}^{1/2}$ 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 early-type galaxies 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 7 GC systems from Hudson & Robison (2017) as this new data shows strong deviations from the existing data. Our analysis extends to lower and higher masses compared to Hudson & Robison. We find a linear relation between the GC system size and its host galaxy stellar mass but there are indications from Ultra Diffuse Galaxies 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× for $M^*$ galaxies to around 5× 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 scalings 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 early-type galaxies. The GC system sizes of UDGs also scale with virial radius and halo mass in the same sense as more massive, larger galaxy halos. Our larger host galaxy mass range has revealed different scalings of GC system size with virial radius and halo mass to those claimed by Hudson & Robison (2017), 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 early-type galaxies, and study the blue and red GC subpopulations independently.

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6 REFERENCES

Alabi A. B., et al., 2016, MNRAS, 460, 3838
Alabi A. B., et al., 2017, MNRAS, 468, 3949
Boylan-Kolchin M., 2017, arXiv, arXiv:1705.01548
Blakeslee J. P., 1997, ApJ, 481, L59
Blom C., Spitler L. R., Forbes D. A., 2012, MNRAS, 420, 37
Brodie J. P., et al., 2014, ApJ, 796, 52
Cappellari M., et al., 2011, MNRAS, 413, 813
Forbes D. A., Spitler L. R., Strader J., Romanowsky A. J., Brodie J. P., Foster C., 2011, MNRAS, 413, 2943
Forbes D. A., Sinpetru L., Savorgnan G., Romanowsky A. J., Usher C., Brodie J., 2017, MNRAS, 464, 4611
Georgiev I. Y., Puzia T. H., Hilker M., Goudfrooij P., 2010, MNRAS, 409, 447
Hargis J. R., Rhode K. L., 2012, AJ, 144, 164
Hargis J. R., Rhode K. L., 2014, ApJ, 796, 62
Harris W. E., Harris G. L., Hudson M. J., 2015, ApJ, 806, 36
Harris W. E., Blakeslee J. P., Harris G. L. H., 2017a, ApJ, 836, 67
Harris W. E., Cicone S. M., Eadie G. M., Gnedin O. Y., Geisler D., Rohrborg B., Bailin J., 2017b, ApJ, 835, 101
Hudelot, P. et al. 2012, VizieR Online Data Catalog, 2317, 0
Hudson, M., Robison, B., 2017, arXiv:1707.02609v1, MNRAS submitted
Kartha S. S., Forbes D. A., Spitler L. R., Romanowsky A. J., Arnold J. A., Brodie J. P., 2014, MNRAS, 437, 273
Kartha S. S., et al., 2016, MNRAS, 458, 105
Kormendy J., Fisher D. B., Cornell M. E., Bender R., 2009, ApJS, 182, 216
Kravtsov A. V., 2013, ApJ, 764, L31
McMillan P. J., 2011, MNRAS, 414, 2446
Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 295, 319
Oser L., Ostriker J. P., Naab T., Johansson P. H., Burkert A., 2010, ApJ, 725, 2312
Oser L., Naab T., Ostriker J. P., Johansson P. H., 2012, ApJ, 744, 63
Peng E. W., et al., 2011, ApJ, 730, 23
Peng E. W., Lim S., 2016, ApJ, 822, L31
Pillepich A., et al., 2014, MNRAS, 444, 237
Pota V., et al., 2013, MNRAS, 428, 389
Rhode K. L., Zepf S. E., Kundu A., Larner A. N., 2007, AJ, 134, 1403
Rhode K. L., Windschitl J. L., Young M. D., 2010, AJ, 140, 430
Shen S., Mo H. J., White S. D. M., Blanton M. R., Kauffmann G., Voges W., Brinkmann J., Csabai I., 2003, MNRAS, 343, 978
Spitler L. R., Romanowsky A. J., Diemand J., Strader J., Forbes D. A., Moore B., Brodie J. P., 2012, MNRAS, 423, 2177
Spitler L. R., Forbes D. A., 2009, MNRAS, 392, L1
Usher C., et al., 2012, MNRAS, 426, 1475
Usher C., Forbes D. A., Spitler L. R., Brodie J. P., Romanowsky A. J., Strader J., Woodley K. A., 2013, MNRAS, 436, 1172
van den Bergh S., 2000, PASP, 112, 932
van Dokkum P., Conroy C., Villaume A., Brodie J., Romanowsky A. J., 2017, ApJ, 841, 68
Veale M., et al., 2017, MNRAS, 464, 356
Vika M., Driver S. P., Cameron E., Kelvin L., Robotham A., 2012, MNRAS, 421, 2264
Young M. D., Dowell J. L., Rhode K. L., 2012, AJ, 144, 103

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