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Filling the gap: a new class of old star cluster?

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ABSTRACT

It is not understood whether long-lived star clusters possess a continuous range of sizes and masses (and hence densities) or if rather, they should be considered as distinct types with different origins. Utilizing the *Hubble Space Telescope* to measure sizes and long exposures on the Keck 10 m telescope to obtain distances, we have discovered the first confirmed star clusters that lie within a previously claimed size–luminosity gap dubbed the 'avoidance zone' by Hwang et al. The existence of these star clusters extends the range of sizes, masses and densities for star clusters, and argues against current formation models that predict well-defined size–mass relationships (such as stripped nuclei, giant globular clusters or merged star clusters). The red colour of these gap objects suggests that they are not a new class of object but are related to faint fuzzies observed in nearby lenticular galaxies. We also report a number of low-luminosity ultracompact dwarfs with sizes of up to 50 pc. Future, statistically complete, studies will be encouraged now that it is known that star clusters possess a continuous range of structural properties.

Key words: galaxies: formation – galaxies: star clusters: general – globular clusters: general.

1 INTRODUCTORY REMARKS

Old, compact star clusters have traditionally been classified into several types. These include globular clusters (GCs) first discovered in 1665 by Abraham Ihle [as noted by Schultz (1866)]. They are compact (having projected half-light sizes R_h of ∼3 pc) and span a wide range of mass. All large galaxies, including our own Milky Way, host a system of GCs.

In the last decade, several new types of star clusters containing an old stellar population have been identified. Deep imaging of the nearby lenticular galaxy NGC 1023 by the *Hubble Space Telescope* (*HST*) and spectroscopic follow-up using the 10 m Keck I telescope revealed a population of low-luminosity GC-like objects with large sizes (∼10 pc) dubbed faint fuzzies (FFs) by Larsen & Brodie (2000). Objects with similar sizes and luminosities were discovered around M31 by Huxor et al. (2005) and named extended clusters (ECs). Similar extended objects have been identified in galaxies ranging from dwarfs to giant ellipticals (e.g. Peng et al. 2006; Georgiev et al. 2009) and may be related to the Palomar-type GCs found in the outer halo of the Milky Way.

Searches beyond the Local Group have revealed an additional population of star clusters called ultracompact dwarfs (UCDs; Drinkwater et al. 2000). These spherical collections of stars were first thought to be very compact dwarf galaxies but they also resemble extended (R_h > 10 pc) GCs, some 2 mag brighter than ECs/FFs. The origin of these various star clusters (GCs, ECs/FFs and UCDs) and their relationship to each other is the subject of debate (e.g. Forbes & Kroupa 2011; Willman & Strader 2012).

The size and luminosity distribution of star clusters was summarized recently by Brodie et al. (2011), to download database see: http://sages.ucolick.org/downloads/sizetable.txt. They included all types of known star clusters with old (≥5 Gyr) stellar ages. They also restricted their sample to objects with *confirmed* distances. This is important if one is exploring size and luminosity trends, but this has not always been the case in the literature. From size and luminosity, the projected surface and volume densities can also be derived.

In Fig. 1, we show the fundamental parameters of size and luminosity from this state-of-the-art compilation for long-lived star clusters. The figure shows a U-shaped distribution. The high-luminosity, extended star clusters are generally referred to as UCDs, the base of the U-shape is occupied by compact GCs and the low-luminosity, extended size regime is associated with ECs and FFs. Two extreme

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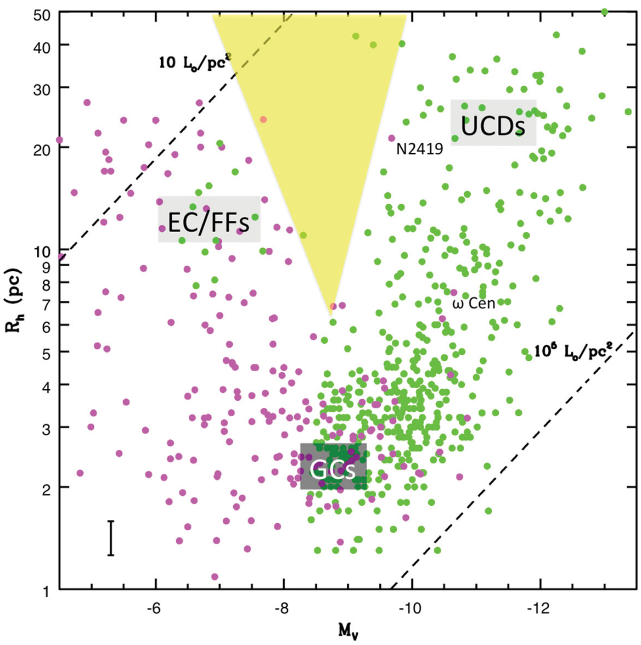

Figure 1. Size–luminosity diagram for old star clusters. The half-light radius and *V*-band absolute magnitude for star clusters with known distances and old stellar ages from the compilation of Brodie et al. (2011) are shown. The purple symbols denote star clusters within the Local Group, while green symbols denote star clusters around galaxies beyond the Local Group. The general location of UCDs, GCs and ECs/FFs are labelled, as are the largest Milky Way GC NGC 2419 and the most luminous one ω Cen. A typical uncertainty in star cluster size is shown at lower left. The diagonal dashed lines denote lines of constant surface density, i.e. 10^5 and 10 solar luminosities per parsec squared. Star clusters would be easily detectable in the lower-right side of this diagram if they existed. The upper-left portion in this diagram is associated with lower densities and lower surface brightnesses; hence, objects become increasingly difficult to confirm observationally. The distribution of known old star clusters shows a U-shape with a clear lack of confirmed objects (highlighted by the yellow shaded region), which has been called the star cluster 'avoidance zone' by Hwang et al. (2011).

Milky Way GCs are highlighted in the figure: NGC 2419 (the largest Galactic GC, which lies in the region near low-luminosity UCDs) and ω Cen (the most luminous Galactic GC). The figure shows that star clusters with *V*-band magnitudes M_V brighter than −10 and projected half-light radii $R_{\rm h}$ greater than 5 pc are very rare, if not completely absent, in the Local Group of galaxies which is dominated by the Milky Way and Andromeda. Only a few objects beyond the Local Group are known with M_V fainter than −8.5. This corresponds to an apparent magnitude limit of $V < 22.5$ at the distance of the Virgo cluster (a typical limiting magnitude for spectroscopic studies on 8 m class telescopes). The exceptions are the deep *HST* and Keck telescope observations of FFs in NGC 1023 by Larsen & Brodie (2000). The figure also highlights the lack of very compact, very luminous objects, i.e. those with ultra high densities. It has been argued by Hopkins et al. (2010) that feedback from massive stars sets an upper density limit, beyond which star clusters do not form.

However, perhaps the most interesting feature of Fig. 1 is the deficiency of objects around $M_V \approx -9$ and $R_{\rm h} \geq 7$ pc, i.e. sizes and luminosities intermediate between ECs/FFs and UCDs. This gap in the size–luminosity distribution has been called the star cluster 'avoidance zone' by Hwang et al. (2011). Such a gap could be due to physical processes or due to an observational selection effect. A real gap would imply that ECs/FFs are physically distinct from low-luminosity UCDs and hence are formed by different mechanisms that have inherent upper and lower mass limits, respectively. Continuity across the gap might suggest that one family of star cluster has a wider range of properties than previously known or that a new type of star cluster exists.

Here, we briefly present the recession velocities and hence physical sizes and luminosities for extended ($R_{\rm h} > 5$ pc) star clusters around three elliptical galaxies. In particular, we investigate whether these star clusters occupy the 'avoidance zone' seen in Fig. 1 or not.

2 THE DATA

To identify potential star clusters in the 'avoidance zone' the candidates need to be resolved in order to measure their sizes. This is best achieved with the superior spatial resolution of *HST*. A small number of nearby elliptical galaxies have been imaged by *HST* in two filters (required for colour selection) and over half a dozen pointings (needed to identify a large number of candidate star clusters associated with each galaxy). In particular, half-light sizes have been measured from *g*- and *z*-bands' *HST*/ACS (Advanced Camera for Surveys) images for candidate star clusters in NGC 4278 by Usher et al. (2013) and NGC 4649 by Strader et al. (2012). In both the Usher et al. and Strader et al. works, objects were selected on the basis of having colours that matched those expected of candidate star clusters. Sizes were then determined using the ISHAPE software and visual inspection to remove obvious background galaxies. For NGC 4697 a similar procedure was used. The galaxies are located at distances of 15.6 Mpc (NGC 4278), 17.3 Mpc (NGC 4649) and 11.4 Mpc (NGC 4697). At these distances *HST* can resolve sizes as small as 1–2 pc.

After selecting resolved star cluster candidates (with GC-like colours) around these three galaxies, we designed several multi-object slit masks for the DEIMOS instrument on the 10 m Keck II telescope. Typical exposures of 2 h, in 0.8–1.2 arcsec seeing conditions during the nights of 2013 January 11–12, were obtained. The resulting spectra were reduced using standard procedures and radial velocities were measured, e.g., following the method of Pota et al. (2013). For each galaxy, we confirmed several tens of GCs, with sizes of ∼3 pc, to have velocities consistent with that of their host galaxy. A small number of background galaxies, with significantly higher velocities, were confirmed in each mask. The magnitudes, colours and angular sizes of the background galaxies are provided in the appendix.

Here, we focus on the confirmed objects with sizes greater than 5 pc. Table 1 lists their magnitudes, colours and average half-light radii from the *g* and *z* bands and apparent *V*-band magnitudes from the transformation: $0.753 \times (g - z) - 0.108 + z$ (based on a large sample of GCs from Usher et al. 2013). IDs for the objects come from Strader et al. (2012), Usher et al. (2013) and this work for NGC 4278, 4649 and 4697, respectively.

3 FILLING THE GAP

In Fig. 2, we again show the data points from Brodie et al. (2011) and now include all the confirmed star clusters in NGC 4278, 4649 and 4697. Our main finding is that old star clusters do indeed occupy the 'avoidance zone' gap. The avoidance zone is therefore simply the result of a selection bias in previous works which were unable to reach low enough surface brightness levels beyond the Local Group. Here, we confirm that long-lived star clusters cover a wide and continuous range of sizes and luminosities (and hence densities).

Table 1. Confirmed star clusters with half-light radii greater than 5 pc.

ID	z (mag)	err (mag)	$(g-z)$ (mag)	err (mag)	$R_{\rm h}$ (pc)	err (pc)	M_V (mag)
N4278							
acs0320	20.78	0.030	0.845	0.041	23.23	0.51	−9.65
acs0259	20.00	0.026	0.899	0.039	21.12	0.64	−10.37
acs0498	21.11	0.012	0.882	0.019	8.47	0.10	−9.29
acs1362	20.30	0.027	0.810	0.030	8.35	0.67	−10.10
acs2305	21.95	0.026	1.260	0.039	6.34	0.55	−8.17
acs1369	18.43	0.014	1.440	0.021	6.07	0.34	−11.55
acs0965	21.13	0.016	0.970	0.023	5.83	0.32	−9.20
acs1365	21.15	0.013	0.986	0.019	5.55	0.22	−9.18
acs1606	20.59	0.014	0.906	0.020	5.53	0.30	−9.80
acs1634	22.07	0.025	0.973	0.038	5.11	0.55	−8.26
acs1381	20.66	0.010	0.823	0.014	5.09	0.15	−9.79
N4649							
D68	19.66	0.062	0.991	0.087	47.42	3.37	−10.78
A155	21.59	0.039	1.026	0.047	39.52	4.22	−8.83
A32	19.91	0.018	0.923	0.023	36.48	2.64	−10.57
E91	21.85	0.020	1.690	0.031	16.09	1.65	−8.04
C84	21.46	0.021	1.591	0.031	14.99	1.37	−8.53
C42	20.80	0.016	0.919	0.021	14.91	1.11	−9.69
A122	21.73	0.027	1.600	0.040	14.69	1.51	−8.25
A51	21.10	0.016	1.659	0.025	13.79	1.14	−8.83
C28	20.58	0.015	0.927	0.019	13.58	0.99	−9.90
B139	21.71	0.021	0.952	0.028	11.17	0.96	−8.76
J67	19.81	0.019	0.877	0.031	9.83	0.17	−10.72
J623	20.93	0.049	0.934	0.065	6.88	0.26	−9.55
B8	18.62	0.010	1.314	0.015	5.58	0.39	−11.59
J76	19.19	0.022	1.230	0.042	5.55	0.15	−11.08
A197	22.76	0.031	1.085	0.041	5.04	0.72	−7.61
N4697							
acs52	19.25	0.002	0.846	0.004	27.30	2.59	−10.49
acs580	22.09	0.017	1.342	0.059	26.42	8.43	−7.27
acs112	20.05	0.004	0.882	0.006	19.15	1.92	−9.67
acs173	20.48	0.005	1.021	0.008	19.18	1.98	−9.13
acs132	20.24	0.004	0.865	0.007	15.57	2.25	−9.49
acs486	21.79	0.012	0.960	0.017	7.85	3.03	−7.86
acs071	19.60	0.003	0.906	0.005	5.37	2.14	−10.10
acs474	21.75	0.010	0.960	0.016	4.90	1.98	−7.91
acs782	22.59	0.021	1.515	0.039	7.08	3.14	−6.65
acs270	20.99	0.008	1.300	0.012	5.29	1.00	−8.41
acs607	22.18	0.016	1.445	0.029	6.14	2.81	−7.11
acs805	22.67	0.019	1.329	0.035	5.15	1.04	−6.71

A clue to the nature of the extended size star clusters comes from their intrinsic colours. In Fig. 2, objects have been coded by their colour, i.e. red or blue for a colour separation at $(g-z) = 1.1$, which corresponds to a metallicity of [Fe/H] ~ -1. We find that the high-luminosity star clusters tend to be blue (or metal poor) and the low-luminosity ones red (metal rich). Focusing on the gap itself, the clusters are mostly red in colour indicating that they are metal rich. This suggests that they are more closely related to the lower luminosity FFs found in NGC 1023 by Larsen & Brodie (2000) and the diffuse star clusters (DSCs) of Peng et al. (2006) which are metal rich and red in colour. These objects are typically associated with the discs of lenticular galaxies that reveal signs of a past interaction. Burkert, Brodie & Larsen (2005) suggest that FFs form in metal-rich discs as the result of an interaction and subsequent starburst. Goudfrooij (2012) has argued that the intermediate-aged DSCs in the merger remnant NGC 1316 may evolve to resemble FFs after the continued disruption by tidal shocks. Although all three host galaxies studied here are classified as ellipticals, we note that NGC 4278 contains a large H I ring (Raimond et al. 1981) that is perhaps a remnant of a past interaction, NGC 4649 reveals strong rotation in its outer region as might be expected after a major merger (Hwang et al. 2008) and NGC 4697 is highly flattened (E6) and so may be a misclassified S0 (Dejonghe et al. 1996).

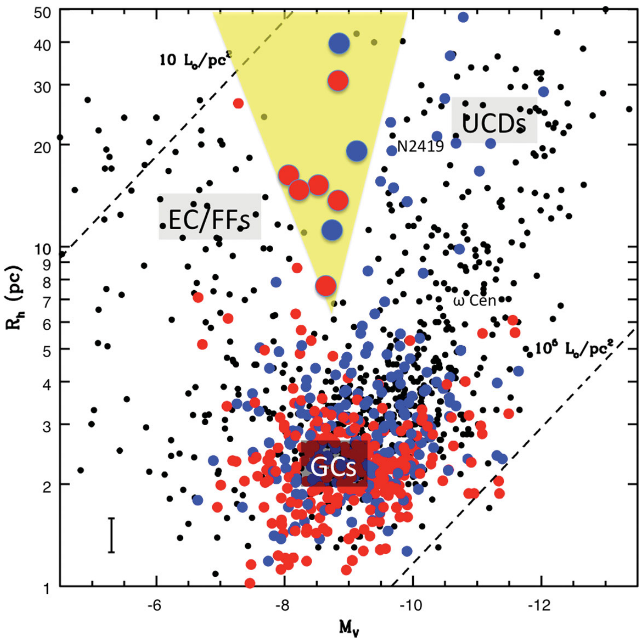

Figure 2. Size–luminosity diagram for old star clusters including newly confirmed objects around the early-type galaxies NGC 4278, 4649 and 4697. The data of Brodie et al. (2011) from Fig. 1 are shown as small black dots. The labels are as in Fig. 1. New star cluster measurements (with sizes from the *HST* and distances from the Keck telescope) are shown as blue and red symbols (corresponding to a division at colour $(g-z) = 1.1$, equivalent to metallicity [Fe/H] $= -1$). Several new objects, with the largest symbols, occupy the yellow shaded 'avoidance zone' of Fig. 1; thus, long-lived star clusters cover a wide and continuous range in size and luminosity. The new data also include two objects with sizes and luminosities similar to the Milky Way GC NGC 2419, several additional objects that might be classified as low-luminosity UCDs, one very low density object that appears to be similar to an EC and/or FF, an object of similar luminosity (and hence mass) to ω Cen but six times larger, as well as numerous compact GCs. Most of the extended high-luminosity objects are intrinsically blue while the low-luminosity ones, including those in the 'avoidance zone' gap, tend to be red.

We have also confirmed the existence of several other interesting objects. They include a number of blue low-luminosity UCDs, similar to those found originally by Strader et al. (2011) and listed in their table 9. Two of these have sizes and luminosities very similar to the Milky Way GC NGC 2419, the largest known GC in the Milky Way. Like other massive GCs in the Milky Way, NGC 2419 contains multiple stellar populations, e.g. Cohen & Kirby (2012), which are traditionally associated with galaxies (Forbes & Kroupa 2011; Willman & Strader 2012). Indeed, Cohen & Kirby (2012) have suggested that NGC 2419 is not in fact a GC but the remnant nucleus of a stripped dwarf galaxy. If it was once part of a dark matter-dominated dwarf galaxy, that dark matter appears to have been largely stripped away as none is detected today in its outer regions (Conroy, Loeb & Spergel 2011; Ibata et al. 2013).

We also confirm an object (acs580) around NGC 4697 with a similar luminosity to the red FFs, but with a larger size (26 pc). This object has the lowest surface density of any confirmed old

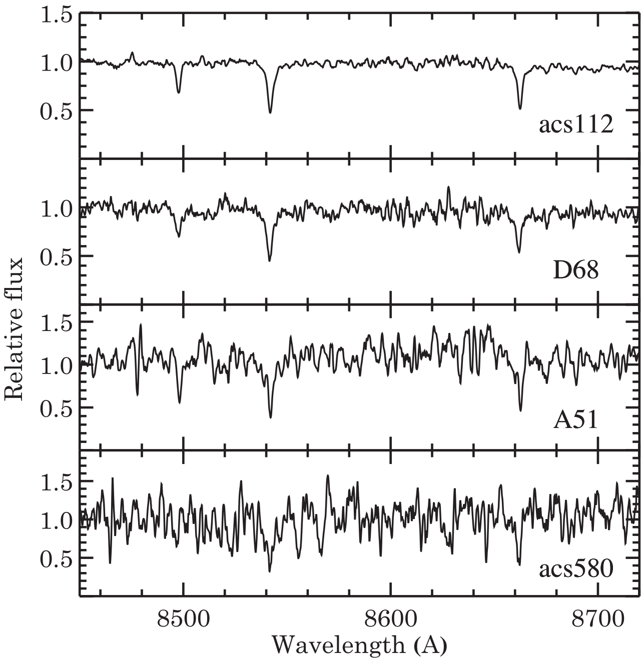

Figure 3. Keck spectra of selected star clusters. The three calcium triplet lines used for redshift determination are visible near 8498, 8542 and 8662 Å. The plot shows from top to bottom in decreasing signal-to-noise ratio: objects acs112 associated with NGC 4697 ($M_V = -9.67$, $R_{\rm h} = 19$ pc), D68 in NGC 4649 ($M_V = -10.78$, $R_{\rm h} = 47$ pc), A51 in NGC 4649 ($M_V = -8.83$, $R_{\rm h} = 14$ pc) and acs580 in NGC 4697 ($M_V = -7.27$, $R_{\rm h} = 26$ pc). acs112 has a size and luminosity similar to that of the Milky Way GC NGC 2419. D68 is the largest star cluster confirmed in this work. A51 is a red star cluster located in the 'avoidance zone'. acs580 is a large FF analogue in NGC 4697.

star cluster beyond the Local Group. Finally, we note that one star cluster (D68) has a luminosity of $M_V = -10.8$, similar to that of ω Cen (the most massive GC or remnant nucleus in the Milky Way), but with a half-light radius some six times larger at 47 pc and hence a lower surface density by a factor of ~35.

In Fig. 3, we show several examples of our Keck spectra for selected star clusters. The examples include: acs112 which has a size and luminosity similar to that of the Milky Way GC NGC 2419; D68, the largest star cluster confirmed in this work; A51, a red star cluster located in the 'avoidance zone' and acs580 a large FF analogue around NGC 4697.

We remind the reader that it becomes increasingly difficult with decreasing brightness and increasing size to confirm low-density star clusters (the upper left-hand side of Fig. 2) and so a reduction in the number of star clusters in that region of the figure is probably due to current observational limitations. Future deep surveys may rectify this, finding that the region is well populated.

4 CONCLUDING REMARKS

A number of theories have been put forward to explain the origin of the different types of extended star clusters with corresponding predictions for their structural properties. For example, if UCDs are simply giant GCs (Murray 2009) or the remnant nuclei of stripped dwarf galaxies (Bekki et al. 2001), then a well-defined size–luminosity trend of near constant density is predicted. In the merging star cluster simulations of Bekki et al. (2004) the resulting UCDs are also predicted to have a well-defined size–luminosity relationship. Although a distinct size–luminosity relation may exist for more luminous objects (such as compact ellipticals), for luminosities fainter than $M_V = -13.5$, we find a continuous range in size and luminosity for old star clusters. With the introduction of an external tidal field and exploring a larger range of masses, the simulations of Brüns et al. (2011) produced merged star clusters with a large range of size and luminosity. However, their work indicated an upper limit to the maximum size that increased with star cluster mass. This is not generally seen in our data.

Individual star clusters were assumed to follow a distinct initial size–mass relationship in the simulations of Gieles et al. (2010), but the effects of stellar evolution, binaries and two-body relaxation over time resulted in their old clusters having large ($R_{\rm h} \sim 10$ pc) sizes. Tidal effects would tend to reduce this size further. While matching some aspects of our data, this model has difficulty reproducing the largest ($R_{\rm h} > 10$ pc) star clusters.

In summary, we find a continuity of structural properties across a gap in size and luminosity called the 'avoidance zone'. The red colour of these gap objects suggests that they are not a new class of object, but are related to the FFs observed in nearby lenticular galaxies. We also report a number of low-luminosity UCDs with sizes of up to 50 pc. No single model for the formation of extended star clusters can currently reproduce the diversity of structural properties now observed for old star clusters.

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APPENDIX A: BACKGROUND OBJECTS

We caution that some researchers have attempted to explore the size–luminosity distribution of star clusters without having a confirmed distance to each object. This is a dangerous practice and can lead to incorrect conclusions. For example, some have been tempted to explore mean size trends with luminosity and to make subsequent comparisons with theoretical predictions. In Table A1, we list the objects which have similar apparent sizes and magnitudes to our confirmed objects, but our spectroscopic redshifts indicate that they are actually distant background galaxies. The columns are ID, z magnitude and error, $(g-z)$ colour and error, and half-light radius and error.

Table A1. Background galaxies.

ID	z (mag)	err (mag)	$(g-z)$ (mag)	err (mag)	$R_{\rm h}$ (arcsec)	err (arcsec)
N4278						
acs2464	22.18	0.02	0.84	0.03	0.07	0.003
acs0284	21.86	0.05	1.49	0.08	0.14	0.017
N4649						
A78	21.14	0.020	1.56	0.028	0.23	0.026
E86	21.68	0.023	0.61	0.029	0.18	0.015
E123	22.14	0.029	1.85	0.048	0.17	0.025
A221	22.48	0.033	1.33	0.048	0.17	0.024
N4697						
acs836	22.76	0.022	0.92	0.022	0.19	0.009
acs868	22.84	0.023	1.49	0.030	0.15	0.009

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