Globular Cluster Systems of Relic Galaxies

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ABSTRACT
We analyse the globular cluster (GC) systems of a sample of 15 massive, compact early-type galaxies (ETGs), 13 of which have already been identified as good relic galaxy candidates on the basis of their compact morphologies, old stellar populations and stellar kinematics. These relic galaxy candidates are likely the nearby counterparts of high redshift red nugget galaxies. Using F814W (∼I) and F160W (∼H) data from the WFC3 camera onboard the Hubble Space Telescope we determine the total number, luminosity function, specific frequency, colour and spatial distribution of the GC systems. We find lower specific frequencies (SN < 2.5) with a median of SN = 1) than ETGs of comparable mass. This is consistent with a scenario of rapid, early dissipative formation, with relatively low levels of accretion of low-mass, high-SN satellites. The GC half-number radii are compact, but follow the relations found in normal ETGs.

Key words: galaxies: star clusters: general – galaxies: evolution – galaxies: formation

1 INTRODUCTION
Massive early-type galaxies (ETGs) are host to some the most extreme formation events, and are host the end products of complex processes such as gas accretion, in-situ star formation, hierarchical merging, tidal interactions, and secular evolution (Trager et al. 2000, Thomas et al. 2005, La Barbera et al. 2013, Salvador-Rusìñol et al. 2020). ETGs experience dramatic size evolution over cosmic history (e.g. Trujillo et al. 2006, Buitrago et al. 2008, van Dokkum et al. 2010), have the most extreme initial mass functions (van Dokkum & Conroy 2010, La Barbera et al. 2013) and host the most massive black-holes in the Universe (Ferrarese & Merritt 2000). The rich variety of mechanisms that shape ETGs together with the fact that these galaxies contain ~70% of the total stellar budget in the local Universe (Fukugita et al. 1998), turn these galaxies into ideal laboratories to test galaxy formation theories.

There is theoretical and observational evidence that massive ETGs (M* > 1011 M⊙) in the local Universe have gone through two major formation phases (e.g. Hopkins et al. 2009, Oser et al. 2010, Hilz et al. 2017). In the first phase, an in situ component is formed through dissipational processes, creating a massive and compact central component. This first phase happens rapidly (< 1 Gyr) and early (at z ~ 2) (Zolotov et al. 2015), and gives rise to a population of passively evolving objects seen at high redshift (Daddi et al. 2005, Schreiber et al. 2018, Valentino et al. 2020), sometimes termed “red nuggets” (Damjanov et al. 2009). A second phase, dominated by minor mergers, then builds-up predominantly the outer regions of ETGs (Naab et al. 2009, Johansson et al. 2009). This process grows massive galaxies in size and mass, and presumably lowers their central densities (Hilz et al. 2012, Hilz et al. 2013). Simulations suggest that the second phase may initially begin concurrently with the first, but continues to operate until the present day (e.g., Wellons et al. 2015, Furlong et al. 2017).

A consequence of this formation pathway is that a small fraction of these red nuggets are expected to survive “frozen” until the present-day Universe (Trujillo et al. 2009, Poggianti et al. 2013, Spiniello et al. 2020) . These objects are thus considered relics of the first phase of ETG formation. In fact, such relic candidates have been reported to exist relatively nearby (Yıldırım et al. 2017, Ferré-Mateu et al. 2017, 2018). As relic galaxies, they are expected to have uniformly old stellar populations (> 10 Gyr, Yıldırım et al. 2017), and be

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extremely compact, as is the case for the prototypical relic galaxy NGC 1277 (Trujillo et al. 2014) and also Mrk 1216 and PGC032873 (Ferré-Mateu et al. 2017). In addition, stellar population studies indicate that relics such as NGC 1277 have extremely bottom-heavy stellar initial mass functions (IMF) which do not vary with radius. This is consistent with the picture that this class of objects generally go on to form the central regions of massive ETGs (Martín-Navarro et al. 2015).

Identification and characterization of relic galaxies is crucial to test the two-phase model, and offers the opportunity to study red nugget galaxies in the nearby Universe. In addition to the chemo-dynamical study of galaxy stellar populations, globular clusters (GCs) have proven to be uniquely powerful tools to trace the structure and history of galaxies (Brodie & Strader 2006, Pfeffer et al. 2018, Beasley 2020).

GC systems are generally thought to be old (most of them with ages > 10 Gyr, Strader et al. 2005, Chies-Santos et al. 2011), and contain the imprints of the initial conditions of galaxy formation. GC systems of ETGs in the local Universe generally show complex colour distributions. Because GCs are generally old and co-evol, differences in color are attributed to differences in metallicity, such that metal-poor GCs have "blue" colours and metal-rich GCs are "red". This correspondence has been confirmed with spectroscopy (e.g., Beasley et al. 2008, Caldwell et al. 2011, Usher et al. 2012). Furthermore, the fraction of red GCs decreases as we move to lower galaxy luminosities, reaching the extreme faint of ETGs as is the case for the prototypical relic galaxy NGC 1277 (Trujillo et al. 2014, Martín-Navarro et al. 2015, Beasley et al. 2018).

We use archival Hubble Space Telescope (HST) data from the programme GO: 13050 (PI: van den Bosch). The observations were taken with the WFC3 camera with the detectors UVIS (FOV 162×162 arcsec) and IR (FOV 123×136 arcsec) through filters F814W (=I) and F160W (=H), respectively. The data is homogeneous and all the targets have total integration time of 500 s for I and 1400 s for H. We downloaded the data from The Hubble Legacy Archive1 which offers reduced data from HST following the standard procedure.

The FWHM for I and H are 0.1 and 0.22 arcsec, respectively. We use the AB photometric system, with zero-points in I and H, $zp_I=25.12$ and $zp_H=25.95$ mag, respectively. The Galactic extinction toward each galaxy in both bands are from Schlafly & Finkbeiner (2011). For consistency with Yildrım et al. (2017), we adopt a cosmology with a Hubble constant of $H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$, a matter density of $\Omega_M = 0.27$, and dark energy density of $\Omega_{\Lambda} = 0.73$.

### 2.1 Photometry

In order to detect sources close to the centre of the galaxies, first we need to subtract the galaxy light. This is because the steepness of the galaxy luminosity is reflected as drastic changes in the background, hampering the detection of sources. To create the galaxy model we use the tasks ELLIPSE and BMODEL from IRAF (Tody 1986) and fit elliptical isophotes to the surface brightness of the galaxies. For such procedure, we mask all the sources detected (except the galaxy to be fitted) using the SEGMENTATION MAP from a first SExtractor (Bertin & Arnouts 1996) run. We then create models for both I and H bands and subtract them from the original images.

When inspecting the subtracted images, we notice significant residuals in the central regions of most of the sample galaxies, this is mainly because of dust (disks or lanes) or complex structures like rings. Another manuscript is being drafted with an in-depth structural analysis of this sample of galaxies (Flores-Freitas, in prep).

We perform source extraction on the galaxy subtracted image, by running SExtractor independently for each band with a set of parameters optimized for point source detection. We use a background grid size BACKSIZE=32 pix and FILTERSIZE=3, and an effective $\sigma$ detection larger than 5 for both bands. Then, we apply a first cut to select objects with good quality in photometry by rejecting objects with saturated pixels, truncated by being close to the edges of the

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1 https://hla.stsci.edu/
image, or, with magnitude error larger than 0.2 mag. Moreover, we estimate the concentration parameter $C_{4-10}$, which is the difference in magnitude within an aperture of 4 and 10 pixels in diameter, as it seems to be a better indicator of the luminosity profile for the faintest objects in comparison to the SExtractor CLASS_STAR parameter (Peng et al. 2011, Cho et al. 2016).

2.2 Globular Cluster Candidates Selection

We use SExtractor output MAG_AUTO as the actual magnitude of the objects, but to estimate the color we use aperture photometry within a diameter of 4 pixels (0.16′′) and apply the respective aperture correction. Finally, the sample of point sources that are taken as GC candidates are the ones detected independently in both bands (matching the coordinates within a radius < 1 arcsec). Also, the GC candidates must have magnitudes according to the expected luminosity function of GCs (see Section 3.2 for more details), and color $-0.5 < I - H < 1.5$ which is the expected color for GCs (Cho et al. 2016).

In order to have an accurate estimation of the GCs magnitude distribution and the total number of GCs for each galaxy, we need to determine the detection completeness curve as function of magnitude. To estimate the completeness curve we construct the point-spread function (PSF) using the Tiny Tim web interface. We add 20,000 artificial stars with a range in magnitude between 22 and 27 in both bands, and color $I - H = 0$. We mimic the source detection as in the original images by applying the same source detection criteria in each band independently, and then select the ones that match in coordinates. We proceed by fitting a Pritchett criteria in each band independently, and then select the ones that match in coordinates. We proceed by fitting a Pritchett function (Fleming et al. 1995) to the ratio of recovered to created artificial stars for the $I$ band, as it is the band with reliable parameters available for GC populations (Peng et al. 2011, Cho et al. 2016). As the observing strategy is the same for all the galaxies, the recovered parameters are similar but not exactly the same as the detection limit is affected by the brightness of the galaxy. The magnitude in the $I$-band where 50% of the artificial stars are recovered is in the range of 25.1 and 25.5, and with slopes in the range 3-5 for all the sample.

3 ANALYSIS

3.1 Spatial Distribution of Globular Cluster Candidates

In order to estimate the amount of contaminants by Milky Way stars and background galaxies, and to quantify the spatial incompleteness, we parametrise the spatial distribution of the GC candidates by determining the surface number density of the GC candidates as function of radius. We measure the number of GC candidates inside circular concentric annuli with a constant width of 16 arcsec each, and normalise it by the effective area. We then fit a single Sérsic function (Sérsic 1968) including a background component:

$$\Sigma_{GC}(r) = \Sigma_0 \exp\left( -b_n \left( \frac{r}{R_{e,GCS}} \right)^{1/n_{GCS}} - 1 \right) + BG_{ps} \quad (1)$$

![Figure 1. Surface number density of the GC candidates as function of radius for the galaxy NGC 1270. The error bars represent the poissonian error for the number of counts and weighted by the effective area of each annulus. The solid line shows the best Sérsic fit. The blue shaded region shows the inner population which contains mostly GCs with high certainty, while the yellow shaded region shows the outer population which might be strongly affected by contaminants.](http://tinytim.stsci.edu/cgi-bin/tinytimweb.cgi)

where $R_{e,GCS}$ is the radius that contains half of the GC population; $\Sigma_0$ is the surface number density at $R_{e,GCS}$; $n_{GCS}$ is the Sérsic index; and $BG_{ps}$ is the surface number density of background point sources. The fit is performed leaving all the parameters free but constraining $n_{GCS}$ to be between 0.5 and 4, as are the expected values for disky and spheroidal galaxies (Kormendy et al. 2009), and $R_{e,GCS}$ to be larger than the effective radius of the galaxy ($R_{e,GAL}$) as the physical extension of the GC system is generally more extended than that of the starlight (Rhode et al. 2007; Kartha et al. 2014). The error bars are estimated assuming a poissonian error for the number of counts and weighted by the effective area. As an example, in Figure 1 we show the GC surface number density for the galaxy NGC 1270, and its best Sérsic fit. For all the galaxies we obtained $R_{e,GCS}$ between 2 and 3 times $R_{e,GAL}$, in agreement with the literature (Kartha et al. 2014; Forbes 2017; Hudson & Robison 2018). In Table 1 we present the measured $R_{e,GCS}$ values.

From inspection of the Sérsic fits, we define two subsamples: an inner population (sources within $1R_{e,GCS}$; blue shaded region in Fig. 1), whose sources with high certainty are dominated by GCs, and an outer population (sources out of $2R_{e,GCS}$; yellow shaded region in Fig. 1), which might be heavily contaminated by Milky Way stars and background galaxies. These subsamples are defined so that the inner subsample is well above the level of background contaminants.

3.2 Luminosity Function and total GC number

The globular cluster luminosity function (GCLF) is a property that has been extensively studied among galaxies with different morphological type, mass and environment, being

\[^2\text{http://tinytim.stsci.edu/cgi-bin/tinytimweb.cgi}\]
well described by a Gaussian (Harris 1991), albeit some departures form gaussianity in the faint end (Jordán et al. 2007a), not relevant for this study. The peak or also called turnover ($M_0^I$) and width ($\sigma_{GCLF}^I$) of the GCLF are known to depend on the luminosity of the galaxy, where brighter turnover and broader distributions are observed in brighter galaxies (Kundu & Whitmore 2001; Jordán et al. 2006). For ETGs the values are $M_0^I \approx -7.4$ and $M_0^I \approx -8.5$ in Johnson-Cousins photometric system. On the other hand, although $\sigma_{GCLF}^I$ varies with the luminosity of the galaxy, it does not vary among bands (Kundu & Whitmore 2001) where for the most massive galaxies is $\sigma_{GCLF}^I \approx 1.4$.

We adopt a GCLF turnover and width (AB system) dependent on the galaxy luminosity $M_{V,\text{GAL}}$ with the form:

$$M_0^I = -7.4 + 0.04(M_{V,\text{GAL}} + 21.3) - 1.04 + 0.436$$

(2)

$$\sigma_{GCLF}^I = 1.2 - 0.1(M_{V,\text{GAL}} + 21.3)$$

(3)

Following Harris et al. (2013) on the dependency of $M_V^0$ as function of the galaxy luminosity, and assuming $M_V^0 - M_I^0 = 1.04$ which is a mean value measured for 28 ETGs according to Kundu & Whitmore 2001, and finally to convert from Johnson-Cousins to AB photometric system we add 0.436 (Sirianni et al. 2005).

Using this transformation, for a massive galaxy with $M_{V,\text{GAL}} \sim -24$ (as it is for M87) we recover $M_I^0 = -8.112$ in agreement with Jordán et al. (2007b). On the other hand, for dwarf galaxies with $M_{V,\text{GAL}} \sim -18$, we recover $M_I^0 = -7.872$ in agreement with Miller & Lotz (2007).

As mentioned in Section 2.2, we selected point sources fainter than $3\sigma_{GCLF}$ from $M_0^I$, together with a selection by color $-0.5 < I-H < 1.5$ (Cho et al. 2016), in order to reduce the contamination by Milky Way stars and background galaxies. To derive the GCLF of our studied galaxies, we estimate the luminosity function for the inner and outer subpopulations, this to subtract the outer (dominated by contaminants) from the inner (GCs and contaminants). As we know the surface number density of background sources ($BG_{ps}$ from Equation 1) we can estimate the number of expected contaminants within the area of $1R_{GCS}$ to normalise by this number the luminosity function of the outer population. Then, our final GCLF for each galaxy is the luminosity function of the inner population minus the luminosity function of contaminants within $1R_{GCS}$, multiplied by two, as within $1R_e$ we have half of the total population.

As the GCLF that we recover is the convolution of the intrinsic GCLF and the incompleteness Pritchet function (determined in Sect 2.2), in order to obtain the total number of GCs, we estimate the area under the expected Gaussian GCLF by fitting the product of a Gaussian and the Pritchet function, with the expected $\sigma_{GCLF}^I$ and $M_0^I$. In Figure 2 we show the luminosity functions for the inner and outer subpopulations (top panel), as well as the GCLF (bottom panel) in the $I$-band. We also show the best Gaussian*Pritchet function (dotted curve), and the corresponding single Gaussian (solid curve) for the galaxy NGC 1270.

Although the data is relatively deep, it is not enough to sample the whole range of the GCLF, the faint limit we reach is about $\sim 1$ mag brighter than $M_0^I$ (depending on the distance to the galaxy). In Table 1 we show the total number of GCs corrected by incompleteness in area and photometry, and the corresponding error propagating the uncertainty in the fitted Gaussian amplitude.

4 RESULTS

In this section we explore different correlations between the GC System (GCS) and host galaxy parameters derived in this work and from the literature.

4.1 GCs Color ($I-H$) correlations

The colours of the GC populations contain significant amounts of embedded information. They give us insights into ages and metallicities of the GCs (Brodie & Strader 2006), key parameters to infer the star-formation history of the host galaxy. Spectroscopic analyses indicate that most GCs are old and co-eval (Cohen et al. 2003; Puzia et al. 2005; Beasley

\[ M_{V,\text{GAL}} = -24 \]

\[ M_{I,\text{GAL}} = -8.112 \]

\[ M_{I,\text{GAL}} = -7.872 \]

\[ M_0^I = -7.4 + 0.04(M_{V,\text{GAL}} + 21.3) - 1.04 + 0.436 \]

\[ \sigma_{GCLF}^I = 1.2 - 0.1(M_{V,\text{GAL}} + 21.3) \]
et al. 2008; Caldwell et al. 2011), implying that color differences are mainly due to differences in metallicity. Unlike the relative homogeneity of the GCLF shape, the color distribution of GCs shows more variety among different galaxies. In optical colors, more massive galaxies exhibit more complex GC color distributions (dominated by bimodal distributions with different blue-to-red fractions, see Lee, Chung & Yoon 2019) and turn gradually unimodal with a blue dominant population as the mass of the galaxy decreases (Peng et al. 2006).

Even though the optical colors of GC systems have been extensively studied, their interpretation is still debated. Here, we do not attempt to study in detail the nature or the existence of bimodality of the near-IR color distribution of GCs (for that, see Blakeslee et al. 2012, Chies-Santos et al. 2012, Cho et al. 2016) mainly because we are not sampling the entire population of GCs in any of the bands. Instead, we perform a rough characterization of the $I - H$ color distribution of our sample by estimating the mean and the standard deviation of the GC candidates for each galaxy. The rationale here is that even such simple metrics can encode useful information about the GC systems and their host galaxies. In order to avoid outliers, we calculate the mean and standard deviation within interquartiles 1 and 3, for the inner (within 1$R_e$), outer (out of 2$R_e$), and within 2$R_e$. It is well known that the mean metallicity of a galaxy and its GCs increases for more massive galaxies (Kundu & Whitmore 2001); together with the fact that the fraction of red GCs increases for brighter galaxies (Peng et al. 2006), we expect redder GCs colors for brighter galaxies. However, for a single galaxy, inner GCs have higher metallicities than the outer ones (Geisler, Lee & Kim 1996; Harris 2009), thus, in order to avoid a bias for selecting only the inner GCs, the GC color of our sample is determined using the population within 2$R_e$ where we have ~90% of the detected GC candidates. In Figure 3 we show the color $I - H$ distribution for galaxy NGC 1270, plotting the inner, outer and within 2$R_e$ sub-populations.

In Figure 4 we plot the mean $I - H$ color versus galaxy metallicity and galaxy stellar mass ($M_\star$) obtained from Yıldırım et al. (2017) where we can see a trend that more massive and metal-rich galaxies have GCs with on average redder mean $I - H$ colours, mimicking the effect of the GC peak metallicity, galaxy luminosity relation (see eg. Brodie & Strader 2006). We also explore any dependence of the standard deviation of the $I - H$ GC color with galaxy properties, identifying an interesting possible correlation when plotting it versus the stellar angular momentum, $J_\star$, from Yıldırım et al. (2017). We can see tantalizing evidence for an anti-correlation between $J_\star$ and $I - H$ color standard deviation. This trend may be explained in a hierarchical scenario where successive merging events decrease $J_\star$ (Rodriguez-Gomez et al. 2017) while the final merged system in turn will tend to have a more complex, wider GC color distribution. In this sense, the right hand panel of Figure 4 may show a progression of the “degree of relieveness” of a system, where the least evolved (most relic-like) systems will be located to the right of the plot with higher $J_\star$ and a narrower colour width.

### 4.2 GC total number correlations

One of the first parameters defined to quantify the richness of a GC population is the called specific frequency, $S_N$ (Harris & van den Bergh 1981), which is the number of GCs per unit galaxy luminosity, normalised to a galaxy with absolute $V$ magnitude of -15:

$$S_N = 10^{0.4(M_{V_{\text{GAL}}}-15)}.$$  

Harris & van den Bergh (1981) found values in the range 2<$S_N$<10 for elliptical galaxies, noticing that the number of GCs do not scale with the luminosity of the galaxy. Since then, the $S_N$ has been extensively studied among galaxies with different masses, morphological types and environments (Harris & Harris 2001; Peng et al. 2008; Georgiev et al. 2010; Alamo-Martinez & Blakeslee 2017), where the behaviour of $S_N$ as function of $M_{V_{\text{GAL}}}$ can be described by an U-shape, where $S_N$ increases with luminosity on the bright side, and increases as the luminosity decreases on the faint side with a minimum of $S_N \sim 1$ for galaxies around $L_\star^*$, and large scatter on the edges.

The fact that the number of GCs seems to scale linearly with the halo mass of the host galaxy (Blakeslee 1999; Kravtsov & Gnedin 2005; Spitler & Forbes 2009; Hudson, Harris & Harris 2014; Harris, Blakeslee & Harris 2017) suggests that $S_N$ scales inversely with the stellar-to-halo mass relation, or the total star-formation efficiency, where high star-formation efficiencies would imply low values of $S_N$. On the other hand, because $S_N$ can be high in both giants and dwarf galaxies, but is uniformly low at the intermediate-mass regime, an explanation for the high $S_N$ values in giant galaxies is that the large amounts of GCs are an accreted population that once belonged to dwarf galaxies. Recently, Beasley et al. (2018) reported that the GCS of NGC 1277, in the Perseus cluster is made up of almost exclusively red GCs, with only a small (<10\%) fraction of blue GCs by studying the optical color $g - z$ with deep HST imaging. This finding supports the
idea from other studies based on the age of its stellar population (Ferré-Mateu et al. 2018) and its IMF (Martín-Navarro et al. 2015) that this galaxy is a relic. Furthermore, the $S_N$ of NGC 1277 is low ($< 2$), in accordance with a high star-formation efficiency as would be for a rapidly early dissipative formation and a lack of a accretion of high-$S_N$, low-mass satellites.

In Figure 5 (upper panel) we show $S_N$ vs. $M_{\text{V,GAL}}$ for our sample and the compilation of galaxies from Harris et al. (2013), which comprises a sample of 422 ETGs, S0s and late-type galaxies with $-24 < M_v < -14$. We find low values of $S_N$ for our sample, $< 2.5$ with a median of 1. Assuming that the behaviour of the bright side of $S_N$ vs. $M_{\text{V,GAL}}$ plot is dominated by accretion, and that the faint side is consequence of dissipative processes, then, relic galaxies would be the largest seeds formed by dissipative processes. A massive galaxy with low $S_N$ could also be the consequence of a post-starburst due to a recent gas accretion with high luminosity dominated by young stellar population, as it seems to be the case for the second brightest galaxy in Fornax cluster (Liu et al. 2019).

A quantity harder to derive than $S_N$ but with more physical meaning is the specific mass, $S_M$ (Peng et al. 2008), which is the fraction of baryonic mass turned into GCs ($M_{\text{GCS}}$):

$$S_M = 100 \frac{M_{\text{GCS}}}{M_{\text{baryonic}}}$$

(5)

where for non-star forming galaxies we can assume $M_{\text{gas}} \sim 0$ and then $M_{\text{baryonic}} \sim M_*$, valid for our sample of early-type galaxies. As we know the total number of GCs, we just have to multiply by the mean GC mass, $\langle M_{\text{GC}} \rangle$. As mentioned in Section 3.2, the mean and standard deviation of the GCLF depend on the luminosity of the galaxy, being brighter and broader as the galaxy luminosity increases. This is reflected in larger $\langle M_{\text{GC}} \rangle$ for more luminous galaxies. By using the relation $M_{\text{V}}^0 = -7.4 + 0.04(M_{\text{V,GAL}} + 21.3)$ and $(M/L)_V = 2$ from Harris et al. (2013), we derive $\langle M_{\text{GC}} \rangle$. To estimate the dynamical mass, we use:

$$M_{\text{dyn}} = \frac{4 R_{\text{e,GAL}} \sigma_e^2}{G}$$

(6)

where $R_{\text{e,GAL}}$ is the effective radius of the galaxy, and $\sigma_e$ is the stellar velocity dispersion within $R_{\text{e,GAL}}$, both obtained from Yildirim et al. (2017). In Figure 5 (bottom) we show $S_M$ vs. $M_{\text{dyn}}$ for our sample and Harris et al. (2013) compilation.

Similar to the results for $S_N$, the relic galaxy sample lies below the relation for “normal” mass-matched ETGs in the...
(M_{GC})-M_{dyn} plot. Again, this reinforces the notion that relic galaxies are maximally efficient in forming stars relative to GCs, and the process that might be responsible for lower this efficiency (i.e., satellite accretion) are less important in these galaxies.

By exploring the relation between $N_{GC}$ and $M_{dyn}$ for different morphological types, Harris et al. (2013) found that for ellipticals with $M_{e} > 10^{10}M_{\odot}$ the number of GCs increases almost in direct proportion to $M_{dyn}$, while S0s and spirals show an offset of 0.2 and 0.3 dex, respectively, below the trend of ellipticals. They claim that for the same mass, the disky galaxies (higher angular momentum) have a lower fraction of GCs, or have higher fraction of field stars. In Figure 6 we show $N_{GC}$ versus $M_{dyn}$, $R_{e,GAL}$, and $\sigma_{e}$ for our sample and Harris et al. (2013) compilation without applying any offset according the morphological type as their Figure 9. We can see that indeed, our sample, which is biased towards very high velocity dispersions, is dominated by low $S_N$ values, which is a consequence of either a smaller fraction of GCs, or a higher fraction of field stars. Again, the minimal accretion of low mass, high $S_N$ satellites could result in this higher fraction of field stars. Nevertheless, it is worthwhile mentioning that the offset $N_{GC}$ versus $M_{dyn}$ for late-type galaxies vs. ETGs could also be a direct result of using such a virial mass estimator. Late-type galaxies have far more of their orbital energy tied up in rotationally supported orbits, so by using Eq. 6 we are likely to bias their dynamical mass estimates to the low side if we do not correct for this in a more detailed dynamical model.

4.3 GCS effective radius correlations

Numerical simulations predict that accreted stars are preferentially deposited at large galactocentric distances (Naab, Johannsson & Ostriker 2009; Font et al. 2011; Navarro-González et al. 2013). This has been supported observationally from metallicity and age radial gradients (Greene et al. 2015; Pastorrello et al. 2014), as well as kinematics and low surface brightness structures (e.g., Mackey et al. 2013). As the accreted galaxies not only contain stars but also GCs, the deposition of stars and GCs at large galactocentric distances causes increases in both $R_{e,GCS}$ and $R_{e,GAL}$.

Although $R_{e,GCS}$ is commonly measured to correct for spatial incompleteness, it is a GCS property little explored. Studies of the spatial extension of the GCS, measured as the radial distance at which the GC surface density reaches the background levels (Rhode et al. 2007; Rhode, Windschitl & Young 2010; Kartha et al. 2014) showed that the extension of the GCS is proportional to the host stellar mass and $R_{e,GAL}$ (but see also Saifollahi et al. (2020) for the case of ultra-diffuse galaxies). However, as pointed out by Kartha et al. (2014), the extension of the GCS is strongly dependent on the quality of the data and the width of FOV, and claimed that the correlations should be considered more as a general trend than a quantitative relation. Similarly, studies of $R_{GC}$ scaling relations (Forbes 2017; Hudson & Robson 2018) reported not unexpectedly correlations between $R_{e,GCS}$ and host galaxy properties. However, although is consistent the claim that $R_{e,GCS}$ scales with $R_{e,GAL}$, the scaling factor is significantly different among authors.

In Figure 7 we show $R_{e,GCS}$ as function of $R_{e,GAL}$ and stellar mass of the host galaxy for our sample and data from the literature. Our data follow the general trend where the spatial extension of the GCS is proportional to galaxy stellar mass and $R_{e,GAL}$ but with a closer distribution to ETGs in the Fornax galaxy cluster (Liu et al. 2019). We note that there is no evidence for stripping in these relic candidates, i.e., all of the correlations between the GC and system sizes reflect the co-evolution of both due to merging (or lack thereof) modulating the orbits/sizes of both the field stars and GCs.

5 CONCLUSIONS

In this study we analyze the GC systems of a sample of 15 massive compact early-type galaxies from which 13 are relic galaxy candidates (Yıldırım et al. 2017). By using archival HST imaging in the $I$ and $H$ bands, we determine the GCLF, $N_{GC}$: color and spatial distribution of the GCS, $S_N$, $S_M$ and, look for correlations with host galaxy properties from the literature, such as, $M_\star$, $M_{dyn}$, $\lambda_R$, stellar velocity dispersion and metallicity. Our main findings are:

(i) The compact galaxy sample has low GC specific frequencies, $S_N < 2.5$ with a median of $S_N = 1$, whereas normal ETGs of the same mass typically have $2 < S_N < 10$. This is in agreement with the picture that the galaxies in our sample experienced high star-formation efficiencies as would be the case for a rapid, early dissipative formation, together with relatively low levels of accretion of high-$S_N$, low-mass satellites.

(ii) The GCS spatial distributions are similar to those in normal ETGs in that they are more extended than the starlight, and $R_{e,GCS}$ correlates with the galaxy properties $R_{e,GAL}$, $M_\star$ and $M_{dyn}$.

(iii) Intriguingly, we find a mild, but significant anti-correlation between the standard deviation of the $I-H$ colour distribution and the galaxy specific angular momentum, $\lambda_R$. While the present dataset is relatively small, if confirmed this result might be expected from hierarchical merging models whereby galaxies which have undergone less accretion/merging activity might be expected to preserve their initial $\lambda_R$ and have less complex GCS colour distributions.

Future simulations can help constrain the diagnostic power of $\lambda_R$ when allied to the width of the colour distributions of GC systems for understanding of merger histories of galaxies. Moreover, quantification of the globular cluster color distributions of this sample with optical HST photometry would be extremely valuable to better constrain the accreted mass fractions in these systems.

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**Figure 6.** Number of GCs versus dynamical mass, velocity dispersion and effective radii of their host galaxies. Circles are from Harris et al. 2013, while the squares (relics) and diamonds (non-relics) are the galaxies studied in this work. The colour-code indicates the $S_N$.

**Figure 7.** GCS effective radius, $R_{e, GCS}$ as function of: $R_{e, GAL}$ (left) and stellar mass of the galaxy (right).

**Table 1.** Globular cluster system parameters.

| Galaxy     | $N_{GC}$ | $R_{e, GCS}$ [kpc] | $\Sigma_0$ | $n_{BGCS}$ | $BG_{ps}$ | $S_N$ | $T-H$ | $\sigma_{T-H}$ |
|------------|----------|---------------------|------------|------------|-----------|-------|-------|----------------|
| NGC 0384   | 356 ± 47 | 6.04 ± 8.7          | 0.02       | 1.10       | 0.01      | 1.21  | 0.64  | 0.09           |
| NGC 0472   | 328 ± 37 | 6.52 ± 8.0          | 0.02       | 0.50       | 0.00      | 0.74  | 0.59  | 0.11           |
| MRK 1216   | 1013 ± 80| 8.24 ± 0.7          | 0.03       | 0.50       | 0.00      | 1.43  | 0.59  | 0.10           |
| NGC 1270   | 485 ± 64 | 5.82 ± 0.8          | 0.03       | 0.50       | 0.01      | 0.88  | 0.78  | 0.13           |
| NGC 1271   | 180 ± 84 | 5.23 ± 1.1          | 0.02       | 0.70       | 0.00      | 0.27  | 0.69  | 0.09           |
| NGC 1281   | 360 ± 30 | 4.5 ± 0.5           | 0.03       | 0.70       | 0.00      | 1.13  | 0.70  | 0.09           |
| NGC 1282   | 184 ± 27 | 4.04 ± 1.5          | 0.02       | 0.60       | 0.00      | 1.37  | 0.58  | 0.11           |
| UGC 2698   | 547 ± 100| 8.57 ± 1.4          | 0.03       | 0.50       | 0.00      | 0.62  | 0.64  | 0.14           |
| NGC 2767   | 389 ± 49 | 7.96 ± 2.5          | 0.02       | 0.80       | 0.00      | 1.47  | 0.49  | 0.11           |
| UGC 3816   | 253 ± 20 | 6.31 ± 2.5          | 0.02       | 0.80       | 0.00      | 0.55  | 0.51  | 0.09           |
| NGC 3990   | 6 ± 2    | 1.6 ± 1.4           | 0.00       | 0.50       | 0.00      | 0.17  | 0.54  | 0.09           |
| PGC 11179  | 200 ± 43 | 8.42 ± 3.0          | 0.01       | 0.50       | 0.00      | 0.42  | 0.65  | 0.10           |
| PGC 12562  | 31 ± 13  | 5.6 ± 8.8           | 0.00       | 0.50       | 0.01      | 0.13  | 0.84  | 0.21           |
| PGC 32873  | 745 ± 238| 18.4 ± 119.5        | 0.00       | 1.50       | 0.00      | 1.06  | 0.42  | 0.07           |
| PGC 70520  | 183 ± 70 | 8.52 ± 2.4          | 0.01       | 0.50       | 0.00      | 0.36  | 0.51  | 0.08           |
DATA AVAILABILITY

The data underlying this article are available from the corresponding author, upon reasonable request.

REFERENCES

Alamo-Martínez K. A., Blakeslee J. P., 2017, ApJ, 849, 6
Beasley M. A., 2020, Globular Cluster Systems and Galaxy Formation. pp 245–277, doi:10.1007/978-3-030-38509-5_9
Beasley M. A., Bridges T., Peng E., Harris W. E., Harris G. L. H., Forbes D. A., Mackie G., 2008, MNRAS, 386, 1443
Beasley M. A., Trujillo I., Leaman R., Montes M., 2018, Nature, 555, 483
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Blakeslee J. P., 1999, AJ, 118, 1506
Blakeslee J. P., Cho H., Peng E. W., Ferrarese L., Jordán A., Martel A. R., 2012, ApJ, 746, 88
Brodie J. P., Strader J., 2006, ARA&A, 44, 193
Buitrago F., Trujillo I., Conselice C. J., Bouwens R. J., Dickinson M., Yan H., 2008, ApJ, 687, L61
Caldwell N., Schiavon R., Morrison H., Rose J. A., Harding P., 2011, AJ, 141, 61
Chies-Santos A. L., Larsen S. S., Kuntschner H., Anders P., Chies-Santos A. L., Larsen S. S., Kuntschner H., Anders P., Chies-Santos A. L., Larsen S. S., Cantiello M., Strader J., 2010, ApJ, 725, 2312
Pastorello N., Forbes D. A., Foster C., Brodie J. P., Usher C., Romanowsky A. J., Strader J., Arnold J. A., 2014, MNRAS, 442, 1003
Peng E. W., et al., 2006, ApJ, 639, 95
Peng E. W., et al., 2008, ApJ, 681, 197
Peng E. W., et al., 2011, ApJ, 730, 23
Poggianti B. M., Moretti A., Calvi R., D’Onofrio M., Valentinuzzi R., 2012, MNRAS, 425, 3119
Geisler D., Lee M. G., Kim E., 1996, AJ, 111, 1529
Fukugita M., Hogan C. J., Peebles P. J. E., 1998, ApJ, 503, 518
Furlong M., et al., 2017, MNRAS, 465, 722
Geisler D., Lee M. G., Kim E., 1996, AJ, 111, 1529
Georgeiev I. Y., Puzia T. H., Goudfrooij P., Hilker M., 2010, MNRAS, 406, 1967
Greene J. E., Janish R., Ma C.-P., McConnell N. J., Blakeslee J. P., Thomas J., Murphy J. D., 2015, ApJ, 807, 11
Harris W. E., 1991, ARA&A, 29, 543
Harris W. E., 2009, ApJ, 699, 254
Harris W. E., Harris G. L. H., 2001, AJ, 122, 3065
Harris W. E., van den Bergh S., 1981, AJ, 86, 1627
Harris W. E., Harris G. L. H., Alessi M., 2013, ApJ, 772, 82
Harris W. E., Blakeslee J. P., Harris G. L. H., 2017, ApJ, 836, 67
Hill A. R., et al., 2017, ApJ, 837, 1147
Hilz M., Naab T., Ostriker J. P., Thomas J., Burkert A., Jessee R., 2012, MNRAS, 425, 3119
Hilz M., Naab T., Ostriker J. P., 2013, MNRAS, 429, 2924
Hopkins P. F., Bundy K., Murray N., Quataert E., Lauer T. R., Ma C.-P., 2009, MNRAS, 398, 698
Hudson M. J., Robison B., 2018, MNRAS, 477, 3869
Hudson M. J., Harris G. L. H., Harris W. E., 2014, ApJ, 787, L5
Johansson P. H., Naab T., Ostriker J. P., 2009, ApJ, 697, L38
Jordán A., et al., 2006, ApJ, 651, L25
Jordán A., et al., 2007a, ApJS, 171, 101
Jordán A., et al., 2007b, ApJS, 171, 101
Kartha S. S., Forbes D. A., Spitler L. R., Romanowsky A. J., Arnold J. A., Brodie J. P., 2014, MNRAS, 437, 273
Kormendy J., Fisher D. B., Cornell M. E., Bender R., 2009, ApJS, 182, 216
Kraus M. G., Gnedin O. Y., 2005, ApJ, 623, 650
Kundu A., Whitmore B. C., 2001, AJ, 121, 2950
La Barbera F., Ferreras I., Vazdekis A., de la Rosa I. G., de Carvalho R. V., Trevisan M., Falcón-Barroso J., Ricciardelli E., 2013, MNRAS, 433, 3017
Lee S.-Y., Chung C., Yoon S.-J., 2019, ApJS, 240, 2
Liu Y., Peng E. W., Jordán A., Blakeslee J. P., Côté P., Ferrarese L., Puzia T. H., 2019, ApJ, 875, 156
Mackey A. D., et al., 2013, MNRAS, 429, 281
Martín-Navarro I., La Barbera F., Vazdekis A., Ferré-Mateu A., Trujillo I., Beasley M. A., 2015, MNRAS, 451, 1081
Miller B. W., Lotz J. M., 2007, ApJ, 670, 1074
Naab T., Johansson P. H., Ostriker J. P., 2009, ApJ, 699, L178
Navarro-González J., Ricciardelli E., Quilis V., Vazdekis A., 2013, MNRAS, 436, 3507
Oser L., Ostriker J. P., Naab T., Johansson P. H., Burkert A., 2010, ApJ, 725, 2312
Pastorello N., Forbes D. A., Foster C., Brodie J. P., Usher C., Romanowsky A. J., Strader J., Arnold J. A., 2014, MNRAS, 442, 1003
Peng E. W., et al., 2006, ApJ, 639, 95
Peng E. W., et al., 2008, ApJ, 681, 197
Peng E. W., et al., 2011, ApJ, 730, 23
Pfeffer J., Kruijssen J. M. D., Crain R. A., Bastian N., 2018, MNRAS, 475, 4309
Poggianti B. M., Moretti A., Calvi R., D’Onofrio M., Valentianni T., Fritz, J., Renzini A., 2013, ApJ, 777, 125
Puzia T. H., Kissler-Patig M., Thomas D., Maraston C., Saglia R. P., Bender R., Goudfrooij P., Hempel M., 2005, A&A, 439, 997
Rhode K. L., Windschitl J. L., Young M. D., Strader J., Arnold J. A., 2014, MNRAS, 442, 1003
Rhode K. L., Windschitl J. L., Young M. D., 2010, AJ, 140, 430
Rodriguez-Gomez V., et al., 2017, MNRAS, 467, 3083
Saifollahi T., Trujillo I., Beasley M. A., Peletier R. F., Knapen J. H., 2020, MNRAS,
Salvador-Rusínol N., Vazdekis A., La Barbera F., Beasley M. A., Ferreras I., Negri A., Dalla Vecchia C., 2020, Nature Astronomy, 4, 252
Schlafly E. F., Finkbeiner D. P., 2011, ApJ, 737, 103
Schreiber C., et al., 2018, A&A, 618, A85
Sersic J. L., 1968, Atlas de Galaxias Australes
Sirianni M., et al., 2005, PASP, 117, 1049
Spinelli et al., 2020, arXiv e-prints, p. arXiv:2011.05347
Spitzer L. R., Forbes D. A., 2009, MNRAS, 392, L1
Strader J., Brodie J. P., Cenarro A. J., Beasley M. A., Forbes D. A., 2005, AJ, 130, 1315

Globular Cluster Systems of Relic Galaxies
APPENDIX A: INDIVIDUAL GC SYSTEMS

In Figures A1 to A15 we show for each individual GC system several derived properties: the spatial distribution of the GC candidates, the surface number density of the GC candidates as function of radius with the best Sersic fit, the $I - H$ color distributions for the population at different galactocentric radii, the I-band luminosity function, the H-band luminosity function of the GC candidates within $2R_e$ and the $I - H$ color magnitude diagram of the GC candidates within $2R_e$.

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Figure A1. Derived parameters for the individual GC system of NGC 384 (a) the spatial distribution of the GC candidates highlighting with blue and yellow the sources belonging to the inner and outer population according to the Sérsic profile (panel b). The gray regions show masked areas due to bright stars, galaxies and pixels with bad quality. The circles show the annuli on which the surface number density of GCs was determined. (b) Surface number density of the GC candidates as function of radius. The solid line shows the best Sérsic fit. (c) \(I-H\) color distributions for the population within \(R_{e,\text{GCS}}\) (solid blue), outer to \(2R_{e,\text{GCS}}\) (dashed yellow), and within \(2R_{e,\text{GCS}}\) (solid gray). (d) I-band luminosity function of the inner population corrected for contaminants. The dotted line shows the best Gaussian*Pritchet function, the solid line is the corresponding single Gaussian. (e) H-band luminosity function of the GC candidates within \(2R_e\). (f) \(I-H\) vs. \(I\) color magnitude diagram of the GC candidates within \(2R_e\) with the mean error bars per magnitude bin.

Figure A2. Same as in Fig A1.
Figure A3. Same as in Fig A1.

Figure A4. Same as in Fig A1.
Figure A5. Same as in Fig A1.

Figure A6. Same as in Fig A1.
Figure A7. Same as in Fig A1.

Figure A8. Same as in Fig A1.
Figure A9. Same as in Fig A1.

Figure A10. Same as in Fig A1.
Figure A11. Same as in Fig A1.

Figure A12. Same as in Fig A1.
Figure A13. Same as in Fig A1.

Figure A14. Same as in Fig A1.
Figure A15. Same as in Fig A1.