GLOBULAR CLUSTER SYSTEMS IN BRIGHTEST CLUSTER GALAXIES: A NEAR-UNIVERSAL LUMINOSITY FUNCTION?

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ABSTRACT

We present the first results from our Hubble Space Telescope brightest cluster galaxy (BCG) survey of seven central supergiant cluster galaxies and their globular cluster (GC) systems. We measure a total of 48,000 GCs in all seven galaxies, representing the largest single GC database. We find that a log-normal shape accurately matches the observed luminosity function (LF) of the GCs down to the globular cluster luminosity function turnover point, which is near our photometric limit. In addition, the LF has a virtually identical shape in all seven galaxies. Our data underscore the similarity in the formation mechanism of massive star clusters in diverse galactic environments. At the highest luminosities (L ≳ 10^5L☉), we find small numbers of “superluminous” objects in five of the galaxies; their luminosity and color ranges are at least partly consistent with those of ultra-compact dwarfs. Last, we find preliminary evidence that in the outer halo (R ≳ 20 kpc), the LF turnover point shows a weak dependence on projected distance, scaling as L0 ∼ R^−0.2, while the LF dispersion remains nearly constant.

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

Online-only material: color figures

1. INTRODUCTION

The luminosity function (LF)—the number of objects per unit magnitude or unit luminosity—is one of the most fundamental properties of globular cluster (GC) systems. The globular cluster luminosity function (GCLF) is the observational surrogate for the more astrophysically relevant GC mass function (GCMF); in turn, what we see at present is the product of the mass distribution of the clusters at their time of formation and the dynamical evolution of the GCs within their host galaxy over a Hubble time. In the Milky Way, either the GCLF or GCMF were long ago found to have a unimodal and nearly symmetric shape, often fit by a log-normal function (e.g., Harris 1996, 2010 edition, for the latest homogeneous collection of data).

Because the formation histories and tidal fields of galaxies can differ strongly from one another, it continues to be somewhat surprising that in galaxies of all morphological types and sizes, the GCLF has a nearly identical characteristic log-normal shape (e.g., Harris 2001; Brodie & Strader 2006; Jordán et al. 2007). The “turnover” luminosity L0, where the LF peaks, increases weakly with galaxy mass (Jordán et al. 2007; Villegas et al. 2010). However, to first order it remains true that the turnover is so nearly universal that it can be used as a standard candle for extragalactic distance determination to a typical accuracy of a quarter magnitude; if attention is paid to the second-order dependence of L0 on galaxy size (Villegas et al. 2010), then the accuracy can approach ±0.15 mag particularly for large galaxies (see Rejkuba 2012 for a recent review).

Although the present-day form of the GCLF is understood in a rough outline, the quantitative details are still uncertain. Since the stellar mass-to-light ratio does not vary much with luminosity for the old stellar populations of GCs, a universal GCLF translates directly to a universal GC mass function (MF). However, a peaked distribution differs radically from the observed MF of star clusters in nearby interacting and starbursting galaxies (e.g., Zhang & Fall 1999; Gieles 2009; Larsen 2009; Whitmore et al. 2010; Chandar et al. 2011), where extremely young clusters can be seen over a wide range of masses. This initial MF is typically consistent with a single power law, dN/dM ∝ M^−β with β ≈ 1.8–2.2 over a range of cluster mass from 10^5 M☉ ≲ M ≲ 10^7 M☉. Models of the dynamical evolution and disruption of GCs (e.g., Fall & Zhang 2001a; Baumgardt & Makino 2003; Gieles & Baumgardt 2008; McLaughlin & Fall 2008; Kruithsen et al. 2011, among many others) show that the fractional mass loss is strongly dependent on cluster mass; lower-mass clusters are preferentially dissolved over a Hubble time by internal evaporation coupled to the external tidal field, tidal shocking, and dynamical friction. These mechanisms seem capable of transforming an initial power-law MF into a log-normal one dominated by the highest-mass clusters, at least over the mass range that covers most clusters. Above a few 10^5 M☉, however, mass-loss rates are relatively...
slow and such massive clusters should more nearly preserve the initial MF shape.

Current attempts to incorporate the formation and evolution of GCs in the hierarchical framework of galaxy formation have had some reasonable initial success at reproducing not only the observed GCMF but also the cluster metallicity distribution in the Milky Way (Muratov & Gnedin 2010; Griffen et al. 2010) and in giant early-type galaxies (Li & Gnedin 2014). GCs are simply the most massive star clusters and, like all star clusters, they are likely to have formed as initial high-mass gaseous clumps of typically ~1 pc scale size embedded within much more extended giant molecular clouds (GMCs; e.g., Harris & Pudritz 1994; Burgarella et al. 2001; Bromm & Clarke 2002; Beasley et al. 2002; Shapiro et al. 2010; Elmegreen et al. 2012). Detailed cosmological simulations of the formation of high-redshift galaxies predict the existence of GMCs with the right large masses, sizes, and low metallicities within which embedded proto-GCs can form and eventually evolve into the extremely dense, massive GCs of the present day (Kравtsov & Gnedin 2005). A simple sub-grid model for the creation of star clusters at gas density above a fixed threshold (10^4 M⊙ pc^{-3}) results in a GCMF consistent with the β ≈ 2 power law. Alternatively, the MF could be described by a curved log-normal shape but with very different parameters than the present-day GCMF, motivated by the probability distribution function of clumps in a turbulent interstellar medium. Both functional forms are possible when fit over a relatively narrow range of cluster mass, but differences between them may occur at the highest cluster masses. Therefore, extending the measurement of the GCLF (and GCMF) to the most massive clusters offers the potential to test models of GC formation based on supersonic turbulence in GMCs.

Although the theoretical modeling mentioned above is more advanced than in earlier years, the numerical problem is essentially that galaxy formation simulations must cover scales of ~10^3 M⊙ and ~100 kpc, while full resolution of proto-GCs requires resolving scales at least 10^2 times smaller in both quantities, an extremely steep challenge to accomplish simultaneously (see Harris 2010 for a discussion). Modeling work directed at bridging this gap is ongoing (e.g., Bournaud et al. 2008; Mashchenko et al. 2008; Howard et al. 2014), but a complete theory of GC formation is not yet in hand. It is, however, globally important because a significant fraction of star formation and stellar feedback should occur in these densest, most massive clumps.

The highest-mass GCs are especially interesting as well because of their potential connections to the populations of ultra-compact dwarf (UCD) galaxies that are typically found in rich clusters of galaxies. In structural parameter planes of effective radius, luminosity, or surface brightness, the UCDs bridge the traditional gap between the GC sequence and the dwarf ellipticals (e.g., Haşegan et al. 2005; Misgeld et al. 2011; Brodie et al. 2011; Penny et al. 2014, among many others). UCDs may be especially luminous GCs, remnant nuclei of dwarf spheroidal galaxies, remnants of multiple mergers of GCs, or genuine small-scale dwarfs. Because they are relatively rare and hard to find, their possible connections with GCs remain uncertain.

GCs with luminosities in the range L ∼ 10^4−10^6 L⊙ (i.e., the two orders of magnitude centered on the turnover luminosity) are by far the most numerous and so the shape of the GCLF is observationally well established in this middle range. The high-mass end (roughly speaking, objects like ω Centauri and above, with masses up to 10^7 M⊙ and beyond) is much less well surveyed. Because they are rare, very large statistical samples of GCs are needed to fill in this high-mass region.

The most effective way to accumulate the largest possible samples of GCs is through observation of the most luminous elliptical galaxies—the dI or brightest cluster galaxy (BCG) systems that reside at the centers of rich galaxy clusters. Because of the empirical fact that the GCLF dispersion increases systematically with galaxy size (Villegas et al. 2010), simply stacking large numbers of smaller galaxies to gain a high-n total sample is not equivalent to using a single supergiant galaxy with the same total n(GC) (see, e.g., Mieske et al. 2010 for a specific example constructed from the Virgo and Fornax surveys). In the present paper, we give a brief overview of a new Hubble Space Telescope (HST) survey of GC systems in seven BCGs and discuss our first findings for the observed GCLF. In following papers of this series, we will present the complete database along with more thorough discussions of the color–magnitude diagrams, the GC metallicity distributions, and related issues relevant to the formation histories of our target galaxies.

2. BRIGHTEST CLUSTER GALAXY SURVEY

BCGs contain the most populous GC systems, but they are also a rare type of galaxy and so we must look much further afield than the closest galaxy clusters to find more than just the few that have been studied to date (Bassino et al. 2006; Harris 2009a, 2009b; Wehner et al. 2008; Peng et al. 2011). The paradigm of a GC system in a BCG-type galaxy is that in M87, which holds 13,000 clusters (e.g., Harris 2009b). However, larger systems are known (see Harris et al. 2013), such as the Coma central dI NGC 4874 that may hold as many as 30,000 GCs (Peng et al. 2011). An even larger system may be that around A1689 at cz = 54,000 km s^{-1} (Alamo-Martínez et al. 2013). Many more BCG targets of the size of NGC 4874 or even larger have GC systems that are within reach of HST.

2.1. Observational Material

In this paper, we present the first results of photometry for GCs in seven BCG galaxies, all of which are examples of the largest galaxies that exist in the present-day universe. Each of these was already known from previous deep ground-based imaging to contain a rich GC population (Harris et al. 1995; Bridges et al. 1996; Blakeslee et al. 1997). Our targets, listed in Table 1 in order of increasing distance, were imaged during program GO-12238 (PI: Harris) with the exception of the F814W exposures for the three European Space Observatory (ESO) galaxies, which came from program GO-10429 (PI: Blakeslee). The table lists in successive columns the galaxy ID, the Abell cluster for which it is the central BCG, coordinates, redshift of the galaxy cz normalized to the cosmic background (CBR) reference frame, apparent distance modulus, foreground extinction (from NED on the Landolt scale), and V-band luminosity, where V_T is taken from NED. All the foreground extinctions are small and have no effect on the following analysis. Throughout the following discussion, we adopt a distance scale of H_0 = 70 km s^{-1} Mpc^{-1}. The uncertainties in the conversion to the CBR frame and possible motion of the BCG relative to the Abell cluster center may make the true cz differ by up to ~400 km s^{-1}, or 0.05–0.10 in distance modulus depending on distance.

The primary camera for all targets was the Advanced Camera for Surveys (ACS)/Wide Field Camera (WFC), with the Wide Field Camera 3 (WFC3) being used in parallel; exposures in both cameras were through the F475W and F814W filters.
advantage for our photometry is that the GCs are therefore easily distinguished from the faint, nonstellar background galaxies that constitute the main source of sample contamination.

In the last column of Table 2, we also give the radial range $R(\text{min}) - R(\text{max})$ from galaxy center covered by the ACS field. This $R(\text{max})$ is determined both by the distance to the galaxy and its placement relative to the center of the ACS/WFC field of view. The innermost radii sampled for any of the galaxies are typically ~20 arcsec, corresponding to $R(\text{min}) \sim 10-20$ kpc depending on distance; at smaller radii, the object detection and photometry are more severely limited by the higher surface brightness of the central galaxy. These numbers show that the bulk of our GC sample is drawn from the mid- to outer-halo regions of these supergiant galaxies.

The calibration of our data is in the VEGAMAG system, and uses the most recent filter-based zeropoints given on the HST webpages to define the $F475W$ and $F814W$ natural magnitudes. For the purposes of the present discussion and ease of comparison with previous work (e.g., Harris et al. 2006; Harris 2009a), we use conventional $(B, I)$ magnitudes converted from $(F475W, F814W)$ defined by the transformations in Saha et al. (2011). Using the reddening corrections for each galaxy from the NED database (listed in Table 1), we convert the preliminary color–magnitude distributions to absolute magnitude $M_I$ and intrinsic color $(B-I)_0$.

Figure 1 shows the color–magnitude diagrams for all seven galaxies. The huge GC populations around each one are evident, and to first order the distributions in luminosity and color are similar. To quantify the limits of the photometry, we carried out an extensive series of artificial star tests on every field through daophot/addstar. The limiting magnitudes quoted in Table 2 (not de-reddened and in the natural filter-based VEGAMAG scale) for each field and filter are the levels at which the artificial star tests show that the completeness of detection falls to 50%. At levels $\gtrsim 0.5$ mag brighter, the completeness approaches 100%. We find that within the radial range $R \gtrsim 20$ kpc that contains the vast majority of our measured GCs, the surface brightness of the BCG itself has fallen to low enough levels that the limiting magnitudes do not depend noticeably on $R$. As noted above, crowding effects are also negligible in this same radial range. It is worth noting that this situation is in strong contrast to imaging of much closer galaxies such as the Virgo members at $d \approx 16$ Mpc (e.g., Peng et al. 2008), where the ACS field of view covers a maximum radius of only $R \sim 10$ kpc and the surface brightness gradient of the central galaxy across the detector is more of a concern.

In Figure 2, we show the trend of photometric measurement uncertainties for each galaxy, plotted as a function of absolute magnitude $M_{F814W} \simeq M_I$. The exposure times were planned to yield fairly uniform limits in absolute magnitude, so these curves are similar for all galaxies in the sample. As will be seen below,

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**Table 1**

| Galaxy  | Cluster | R.A.  | Decl. | $cz$ (km s$^{-1}$) | $(m - M)_{I}$ | $A_I$ | $M_{I}'$ |
|---------|---------|-------|-------|------------------|---------------|-------|---------|
| NGC 7720 | A2634   | 23:38:29 | +27:01:53 | 8714           | 35.61         | 0.107 | −23.35 |
| NGC 6166 | A2199   | 16:28:38 | +39:33:06 | 9125           | 35.60         | 0.017 | −23.7 |
| UGC 9799 | A2052   | 15:16:44 | −07:01:18 | 10500          | 35.95         | 0.056 | −23.1 |
| UGC 10143 | A2147   | 16:02:17 | +15:58:29 | 10741          | 35.99         | 0.047 | −23.0 |
| ESO509-G008 | A1736  | 13:26:44 | −27:26:22 | 10848          | 36.06         | 0.079 | −23.35 |
| ESO383-G076 | A3571   | 13:47:28 | −32:51:54 | 11832          | 36.24         | 0.082 | −24.1 |
| ESO444-G046 | A3558  | 13:27:57 | −31:29:44 | 14345          | 36.65         | 0.075 | −23.8 |

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**Table 2**

| Galaxy  | $F475W$ Time (s) | $F814W$ Time (s) | $R$ Range (kpc) |
|---------|-----------------|-----------------|-----------------|
| NGC 7720 | 5282            | 5278            | 12–110          |
| NGC 6166 | 5370            | 4885            | 12–100          |
| UGC 9799 | 7977            | 5253            | 15–105          |
| UGC 10143 | 10726          | 5262            | 15–130          |
| ESO509-G008 | 10758         | 18567           | 15–20          |
| ESO383-G076 | 10830         | 21081           | 16–130         |
| ESO444-G046 | 21660         | 34210           | 20–170         |

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In choosing these targets, to save orbits we took advantage of the long exposures in $F814W$ of the three ESO galaxies that were already in the HST archive. The luminosities of these giant galaxies are comparable with or even higher than the two brightest BCGs whose GC systems have previously been studied to similar depth, namely, NGC 4874 in Coma and NGC 4696 in Centaurus (Harris 2009a).

In Table 2, we summarize the raw exposure data for the ACS/WFC pointings, including the total exposure times and the limiting magnitudes that resulted. Two or more orbits were used for each filter, subdivided into sequences of half-orbit exposures. The total exposures were designed to reach a limit in absolute magnitude close to the expected GCLF turnover point at $M_V \simeq -7.3$, $M_{I,F} \simeq -8.4$ and thus to secure the largest possible GC sample sizes within the limits of the program.

Preprocessing consisted of CTE correction on the raw images (Anderson & Bedin 2010), and then use of the standard Multidrizzle package to generate a combined image in each filter that kept the native pixel scale of 0′′.05.

### 2.2. Photometric Reductions

Photometry was carried out with the standard tools in Source-Extractor (Bertin & Arnouts 1996) and DAOPHOT (Stetson 1987) in its IRAF implementation, including aperture photometry (phot) and then point-spread-function (PSF) fitting through allstar. All PSFs were empirically generated from stars on the target fields, with anywhere from 60 to 160 individual stars on each frame. Finding bright, isolated candidate PSF stars was easily done, since our targets are all moderately high-latitude fields that are completely uncrowded in any absolute sense.

Each target galaxy was found, as expected, to be surrounded by many thousands of clusters. Virtually all of the individual GCs appear starlike: since our target systems are in the distance range 125–205 Mpc, a typical GC effective radius of $\sim 3$ pc corresponds to an angular size in the range $0′′.003–0′′.005$, far below the $0′′.1$ resolution of the telescope and safely in the “unresolved” category according to the criteria in Harris (2009a).
Figure 1. Color–magnitude diagrams for the seven BCGs in our sample. The filter-based magnitudes ($F_{475W}, F_{814W}$) have been converted to ($B, I$) as described in the text, and intrinsic colors and absolute magnitudes are calculated from the distance moduli and reddenings in Table 1. For comparison, the horizontal lines in each panel show the values of $L_{\text{min}}$ and $L_{\text{max}}$ within which the Gaussian LF fitting was done. The “superluminous” objects discussed in Section 4 of the text are ones brighter than $L_{\text{max}}$.

(A color version of this figure is available in the online journal.)

Figure 2. Measurement uncertainties in magnitude $F_{814W}$ and color ($F_{475W} - F_{814W}$), plotted as a function of absolute $I$-band magnitude. Solid red line: NGC 6166. Dotted red line: NGC 7720. Dashed red line: UGC 9799. Solid black line: UGC 10143. Dotted black line: ESO 509. Dashed black line: ESO 383. Dot-dashed black line: ESO 444.

(A color version of this figure is available in the online journal.)

the uncertainties in the $F_{814W}$ magnitudes are $\lesssim 0.1$ mag for all levels brighter than the GCLF turnover, implying that the $\approx 1.3$ mag intrinsic width of the GCLF is negligibly broadened by photometric scatter.

Any field contamination of the GC samples is due to sparsely distributed foreground stars and a few very small, faint unresolved background galaxies. To gauge the level of contamination, we used the offset WFC3 fields, placed on relatively galaxy-free locations in the outskirts of the galaxy cluster. After the same photometric procedure, rejection of nonstellar objects, and rejection of objects with extreme colors (see below), we found that the residual contamination (and thus its effects on the measured GC LFs) was negligible at any level brighter than the limiting magnitudes of the survey.

The CMDs generally show evidence for broad bimodal or multimodal distributions in the GC colors. A more extensive discussion will be given in following papers that concentrate on the color–magnitude and spatial distributions.

3. THE LUMINOSITY FUNCTION

3.1. GCLF Fitting

To reduce the contamination of our sample, we select only objects within the dereddened color range $1.0 < (B - I)_0 < 2.3$. A cutoff at the blue end eliminates any objects bluer than the minimum metallicity known for GCs ([Fe/H] < $-2.5$) (see Harris 2009a). Translation from $(B - I)_0$ to metallicity [Fe/H] here assumes the linear relation $(B - I)_0 = 2.158 + 0.375 [\text{Fe/H}]$ (Harris et al. 2006). The red end cut is based on empirical increase of contaminants in the parallel background fields,
which are more frequent at colors redder than the GC sequences. In the case of ESO444, we have also cross-correlated our objects with the catalog of nucleated dwarf galaxies identified by John Blakeslee in program GO-10429. We found only four objects in common and eliminated those. The 0.02 arcmin angular resolution limit above which we could reliably identify nonstellar objects (see Harris 2009a) corresponds to a linear resolution of \( \sim 20 \) pc at the average distance of our BCG targets. This limit is not low enough to distinguish many or most UCDs from luminous GCs, so our sample is likely to include some UCDs at the high-L end (see the discussion in Section 4).

Figure 3 shows the resulting GCLFs for each of the seven BCGs. At the lowest plotted luminosity, \( L_I = 10^5 L_\odot \) (which is closely similar to the fiducial GCLF turnover luminosity), three systems are complete to at least 50% at that level and the others are essentially complete to \( \sim 100\% \).

We fit a log-normal (Gaussian in log \( L \)) distribution to the GCLF in the \( I \) band

\[
\frac{dN}{d\log L} = N_0 \exp \left[ -\frac{(\log L - \log L_0)^2}{2\sigma_L^2} \right],
\]

for clusters within a chosen range \( L_{\text{min}} < L_I < L_{\text{max}} \) described below. (NB: by log we denote logarithm base-10.) To convert \( M_I \) to \( L_I \), we adopt \( M_I(\odot) = 4.08 \). The free parameters are the turnover (peak) luminosity \( L_0 \) and the Gaussian dispersion \( \sigma_L \), while \( N_0 \) is constrained by the total number of clusters.

We bin the data evenly spaced in log \( L \) and, for consistency, we use the same bin size for all seven systems in the survey. We have experimented with varying the bin size from 0.01 dex to 0.1 dex and calculated the average \( \chi^2 \) per number of degrees of freedom (\( n_{\text{dof}} \)) of individual galaxy fits. It is defined as

\[
\chi^2 = \sum_i \frac{(N_{i,\text{obs}} - N_{\text{exp}}(L_i|L_0, \sigma_L, N_0))^2}{(\Delta N_{i,\text{obs}})^2},
\]

where \( N_{i,\text{obs}} \) is the observed and completeness-corrected number of clusters in bin \( i \), \( N_{\text{exp}} \) is the expected number from the fitting function above, and \( \Delta N_{i,\text{obs}} = N_{i,\text{tot}}^{1/2} \) is the Poisson counting uncertainty. The number of degrees of freedom is the number of bins minus 3, accounting for \( L_0 \), \( \sigma_L \), and \( N_0 \). The minimum \( \chi^2/n_{\text{dof}} \) occurs at \( \delta \log L = 0.02 \) dex, which we adopt for our analysis. This choice also results in a statistically optimum number of bins \( \approx N_{i,\text{tot}}^{1/2} \).

Limiting the range of luminosity for constraining the fit parameters is necessary because at low \( L \) the cluster counts are incomplete in both \( B \) and \( I \), and at high \( L \) the log-normal function does not account for any superluminous clusters that form an extended tail to the LF (see Section 4 below). We have varied \( \log L_{\text{min}} \) (in Solar units) from 5.0 to 5.3 in steps of 0.1, and calculated \( \chi^2/n_{\text{dof}} \) for each system. Values of 5.1 and 5.2 gave similar fits for most galaxies, and therefore we adopt \( \log L_{\text{min}} = 5.1 \) to include more clusters in our analysis. This limit is also conservatively brighter (by about 1 mag) than the \( I \)-band completeness limit of the photometry, but is near the \( B \)-band limit for the reddest GCs. For one system (ESO509) we found that lowering \( \log L_{\text{min}} \) to 4.7 gave the most robust fit.

The upper \( L_{\text{max}} \) to the fitted range is determined by an iterative procedure. First, we set \( L_{\text{max}} \to \infty \) and find the best-fitting log-normal function for all clusters above \( L_{\text{min}} \). Given this fit, we define \( L_{\text{max}} \) as the limit above which the integrated GCLF...
predicts only 10 clusters:

\[
\int_{L_{\text{max}}}^{\infty} \frac{dN_{\text{exp}}}{dL} \, dL = 10. \tag{3}
\]

The number 10 was chosen based on empirical comparison with the high-\(L\) tail of the observed GCLF so that small number statistics in the uppermost \(L\) bins would not unduly influence the fit. Integrating Equation (1) gives an explicit non-linear relation for \(L_{\text{max}}:\)

\[
N_0 \sigma_L \sqrt{\frac{\pi}{2}} \, \text{erf} \left( \frac{\log L_{\text{max}} - \log L_0}{\sqrt{2} \sigma_L} \right) = 10. \tag{4}
\]

For a given combination \((L_0, \sigma_L, N_0)\), we solve this equation numerically and use the new value of \(L_{\text{max}}\) to repeat the GCLF fit. This process is iterated until \(L_{\text{max}}\) varies by less than 1%. The values of \(L_{\text{max}}\) are determined for each system individually. Clearly, \(L_{\text{max}}\) is not a fixed boundary because it will be higher for galaxies with larger total populations \(N_0\). However, defining it this way ensures that we will be fitting the fiducial Gaussian function over the luminosity range where the number of clusters per bin is satisfactorily large. In Figure 1, we show the adopted \(L_{\text{min}}\) and \(L_{\text{max}}\) levels for each galaxy.

The best-fit parameters \((L_0, \sigma_L, N_0)\) for individual fits to each GC system are listed in Table 3. The 68% confidence error bars, \(\Delta \log L_0\) and \(\Delta \sigma_L\), are calculated at \(\Delta \chi^2 = 1\). The table also lists the de-reddened 50% completeness limits \(L_{\text{lim}}\), which are fainter than our adopted lower cut for all systems. The fraction of missing (undetected) clusters between \(L_{\text{min}}\) and the peak of the GCLF, \(L_0\), relative to that expected from the fit, ranges between 18% and 29%. We conclude that our samples are complete enough in the chosen luminosity range for accurate fitting to be carried out.

The observed number of clusters above the peak (shown in the second column in the table) can be roughly doubled to estimate the total expected population of the GC system, assuming the log-normal GCLF is symmetric. The total number of clusters per galaxy therefore ranges from about 6000 to over 14,000. The currently detected number of GCs above the 50% completeness limit for all seven systems is 47,910 and the number of clusters above \(L_f = 10^5 L_\odot\) is 43,783. This sample represents the largest single data set of GCs in the literature, an order of magnitude larger, for example, than the total number of GCs brighter than the turnover in the Virgo survey (Jordán et al. 2007).

Table 3 also lists the \(\chi^2\) of the Gaussian fit and the number of degrees of freedom, \(n_{\text{dof}}\). For each system, the ratio of the two

![Figure 4](image)

*Figure 4. Confidence intervals of best-fit parameters \(L_0\) and \(\sigma_L\) of a log-normal fit for the global GCLF; with all galaxies combined (Equation (1)). (A color version of this figure is available in the online journal.)*
large statistical size of our database allows us to determine the parameters fairly precisely. In the second last column of Table 3, we quantify how well this global GCLF matches each individual system by evaluating the goodness of fit \( \chi^2 \) (without solving for the parameters separately, but simply adopting \( \log L_0 = 5.24 \) and \( \sigma = 0.52 \)). The fit is calculated in the range of luminosity between \( L_{0,g} \) and each galaxy’s \( L_{\text{max}} \). We find that the quality of the global fit is scarcely worse than the fits optimized to each individual galaxy. Last, we also perform a Kolmogorov–Smirnov (KS) test and calculate the probability \( P_{\text{KS}} \) (calculated over the same range as \( \chi^2 \) and listed in the last column) that the observed cluster samples were drawn from the same global distribution. Table 3 shows that at least six systems have \( P_{\text{KS}} > 1\% \), which means they are not inconsistent with the universal GCLF. We note, of course, that these \( P_{\text{KS}} \) values cannot be as large as similar ones calculated one-by-one (where we would be testing only the hypothesis that each individual LF adequately matches the log-normal model). The KS probability is low for one galaxy (NGC 6166), primarily because of the somewhat steeper downturn of the LF at high luminosities.

In summary, we find that our data for these seven galaxies are consistent with a “universal” lognormal GCLF shape for BCG-type systems. Visually the global fit is indistinguishable from the individual fits. The red lines in Figure 3 overplot the global fit on the histograms of observed cluster numbers, adjusting only the normalization to the actual size of the GC system.

### 3.2. Comparisons with Other Galaxies

Several comparisons can be made for GCLF fits in other giant ellipticals. Peng et al. (2009), using the same F814W bandpass for extremely deep HST data around M87, find \( \log L_0 = 5.06 \pm 0.02 \) and \( \sigma = 0.55 \pm 0.02 \) dex with an excellent fit to a log-normal model (see their Figure 8). Harris et al. (2009) studied the GCLFs of the Coma cluster galaxies and for a composite LF of five gE’s found \( \sigma_L = 0.59 \) dex, \( \log L_0 \approx 5.0 \) (transformed from the V band), and again a good match to the log-normal model. These Coma data do not have as large a total GC sample and do not reach quite as faint in absolute magnitude as our present BCG sample, so the correlation noted above between the turnover point and dispersion may partly explain why the fitted \( L_0 \) is a bit fainter and \( \sigma_L \) a bit broader than we find.

The seven BCGs studied here can be added to the trends of GCLF turnover and dispersion with host galaxy luminosity, as defined from the many lower-luminosity galaxies in Virgo and Fornax (Villegas et al. 2010). The results are shown in Figure 5. In the top panel, \( M^\ast_{\text{F814W}} \) is the GC mass corresponding to the GCLF turnover luminosity, calculated with a stellar mass-to-light ratio from the Into & Portinari (2013) relations. For the Virgo and Fornax galaxies imaged with HST/ACS, the \((g-z)\) color index was used, whereas for the seven BCGs the color index is \((B-I)\). The error bars in \( M^\ast_{\text{F814W}} \) for the BCGs (for which only the bright half of the GCLF is measured) are inevitably larger than for the much nearer Virgo and Fornax members (for which almost the entire run of the GCLF was measured and the turnover is more precise). The trend derived by Villegas et al. (2010) is \( \Delta \sigma / \Delta M^\ast = -0.10 \pm 0.01 \); it is clear that the BCGs continue this trend smoothly upward.

The lower panel of Figure 5 shows the same trend for the GCLF dispersion. Both parameters are plotted against galaxy stellar mass \( M^\ast_{\text{gal}} \), again derived from the Into & Portinari (2013) color–\((M/L)\) relations. Again, the BCGs continue upward along very much the same trend defined by the smaller galaxies. In both panels, weighted best-fit lines are shown for an assumed linear relation (solid line) and a quadratic relation (dashed line); these are scarcely different, and in either case indicate that the BCGs belong to the same family as other smaller galaxies.

The GCLF dispersion \( \sigma \) has also been measured for various giant galaxies at distances \( \sim 100 \) Mpc and beyond from surface brightness fluctuation analysis. Though this method is not strictly comparable to fully resolved photometry of GCs, the results are consistent with the data listed above. Blakeslee et al. (1997), from a ground-based imaging survey of BCGs, determined \( \langle \sigma_L \rangle = 0.57 \) dex (1.42 \( \pm 0.02 \) mag) for 14 such galaxies with low internal uncertainties on \( \sigma \). Overall, an empirical picture emerges in which the intrinsic width of the GCLF (for large galaxies) is consistently in the range \( \sigma_L = 0.52-0.55 \) dex.

### 3.3. Internal Gradients with Galactocentric Distance

We have also briefly investigated how the GCLF might change with projected galactocentric distance \( R \). In Figure 6, the best-fit solutions for turnover luminosity \( L_0 \) and dispersion \( \sigma_L \) are plotted against \( R \) in kiloparsecs. For each galaxy the \( R \) range was broken into eight to nine rather narrow zones, a subdivision that was permitted by the very large statistical sample sizes (the relative numbers of clusters in each zone are indicated by the error bar sizes in the upper panel of the figure). We note that although formal solutions were carried out for the regions \( R \leq 20 \) kpc, these should be given little weight: in these inner zones the numbers of clusters per bin are \( \leq 100 \) with few faint GCs, and the gradually increasing background light from the central galaxy begins to affect the limiting magnitude of the photometry particularly in the F814W band.
The number of superluminous clusters expected from the log-normal fit is 10, by definition of Equation (3). This will be the case if the LF shape continues to be strictly log-normal to arbitrarily large luminosity. However, in practice, we find that only one system (UGC 6166) contains the expected number, while the other six contain “too many” superluminous clusters (and if this argument is correct, a steeper metallicity gradient in the GC system should go along with a steeper gradient in the GC system). Other simple forms have been tried, the most notable of which is the “evolved Schechter function” introduced by Jordán et al. (2007) to fit the GCLFs in the Virgo galaxies. Harris et al. (2009) applied it to the Coma giants as well. This function is asymmetric and thus is preferable as a match for the entire luminosity range of GCLF because the GCLF is observed to decline more steeply on the faint side of the turnover $L_0$ than on the much more easily observable bright side. It also makes a logical link to the dynamical evolution of the GCS where an assumed initial power-law LF changes into the present-day form by preferential destruction of the lower-mass clusters (e.g., see the discussions of Vesperini 2001 and Jordán et al. 2007). However, for the great majority of cases in the literature (see Harris et al. 2013 for a catalog), the range $L > L_0$ is the only part covered by the observations, and over this high-luminosity range both functions do well at matching the empirical data (see Harris et al. 2009 for a specific comparison in the Coma cluster galaxies). More importantly, for the present discussion, either functional form leads to our major conclusion that the present-day GCLFs in BCG systems have a near-universal shape.
These numbers are listed as the Gaussian-like model. The highest number is 29, in ESO383-
Figure 7.
(A color version of this figure is available in the online journal.)

As seen directly from the color–magnitude diagrams and the LFs in the previous figures, these objects extend up to \( \sim 10^5 L_\odot \).

They may be the analogs of UCD galaxies, discovered in the nearby Virgo, Fornax, Hydra, Coma, and Centaurus galaxy clusters (e.g., Misgeld et al. 2011; Mieske et al. 2012). Such objects are defined as having \( L \gtrsim 10^6 L_\odot \), but otherwise are compact enough and metal-poor enough to bear some resemblances to GCs. As noted above, the only limits we can place on their scale sizes are that they have effective radii \( \lesssim 20 \) pc, a level that would rule out only the largest UCDs.

UCDs are typically located outside of the stellar effective radius of the host galaxy. We have examined the spatial distribution of superluminous clusters and found them to be consistent with the overall location of the regular \( (L < L_{\text{max}}) \) clusters. The projected median distance from the host galaxy center is on the average only 20% larger for the superluminous clusters, and ranges between 2 and 4 kpc, solidly within the locus of the regular GC population.

We have also compared the color distributions of the regular and superluminous clusters for the combined sample of all seven systems. For this purpose, we adopt the lowest common luminosity threshold of \( \log L_{\text{max}} = 6.7 \) to define the superluminous clusters, and to account for the vast difference in relative numbers of the two sets, we consider the cumulative fractional distributions. Figure 7 shows that the superluminous clusters are skewed systematically redder than the regular clusters; a KS test indicates that the difference between the two curves is significant well above the 99% level. In other words, the superluminous clusters tend to populate the region above the GC red sequence, though with noticeable scatter in color. Notably, the same sort of red-sequence extension was also seen in the Hydra I BCG, NGC 3311 (Wehner et al. 2008), and in the Coma BCG NGC 4874, but, interestingly, not in the other Coma supergiant NGC 4889 (Harris et al. 2009). The brighter UCDs are also typically redder than GCs (Misgeld et al. 2011), arguing that at least part of this superluminous GC population may be identifiable as UCDs.

It is only in these very large BCGs, with enormous numbers of GCs to draw from, that we can begin seeing these small numbers of superluminous objects as forming a rough “sequence” extending upward from the bulk of the GC population (Misgeld et al. 2011). Unfortunately, gaining more information about the physical properties of the superluminous objects will be difficult, at least for the galaxies studied here. Their numbers even with this data set are inevitably small, they are too faint \( (I \sim 23, B \sim 25) \) for easy spectroscopy, and spatial resolutions of 0′03 or less will be needed to resolve their structures with any confidence. Thus at present our case for identification of superluminous GCs with UCDs is tentative.

5. SUMMARY

We have presented the first results from a new HST imaging survey of the extremely rich GC systems around BCG galaxies. The strongest conclusion from our study is that these central supergiant galaxies have GC populations that follow a remarkably similar luminosity distribution that is virtually indistinguishable from the standard log-normal shape, at least for luminosities higher than the GCLF turnover.

If we adopt a mass-to-light ratio \( M/L_I \approx 2 \) for the old stellar populations of GCs at an average color \( (B - I)_0 \approx 1.7 \), according to the empirical relations of Bell et al. (2003), then the GCLF that we observe translates into a GCMF (MF) with the peak at \( M \approx 3 \times 10^6 M_\odot \). The GCLF shape is strongly inconsistent with a single power law from \( 10^5 M_\odot \) to \( 10^7 M_\odot \), contrary to what might be expected from the massive young star clusters seen in present-day merger or starburst environments. We suggest that if these massive clusters were little affected by dynamical disruption, then (at least at the high-mass end) the most massive GCs must have formed with an initial mass distribution that was not a single power law but rather more nearly resembling a log-normal shape from the start.

In six of our seven target galaxies we also find evidence for an excess of “superluminous” clusters particularly in the color range of the redder, more metal-rich GCs. Their luminosities and colors (though not their spatial distribution) provide some evidence that they may be identified as UCDs, though the case cannot yet be considered to be conclusive.

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