

GLOBULAR CLUSTERS INDICATE ULTRA DIFFUSE GALAXIES ARE DWARFS

MICHAEL A. BEASLEY^{1,2} AND IGNACIO TRUJILLO^{1,2}
Draft version June 19, 2021

ABSTRACT

We present an analysis of archival *HST/ACS* imaging in the F475W (g_{475}), F606W (V_{606}) and F814W (I_{814}) bands of the globular cluster (GC) system of a large (3.4 kpc effective radius) ultra-diffuse galaxy (DF17) believed located in the Coma Cluster of galaxies. We detect 11 GCs down to the 5σ completeness limit of the imaging ($I_{814}=27$ mag). Correcting for background and our detection limits yields a total population of GCs in this galaxy of 27 ± 5 and a V -band specific frequency, $S_N = 28 \pm 5$. Based on comparisons to the GC systems of Local galaxies, we show that both the absolute number and the colors of the GC system of DF17 are consistent with the GC system of a dark-matter dominated dwarf galaxy with virial mass $\sim 9.0 \times 10^{10} M_\odot$ and a dark-to-stellar mass ratio, $M_{vir}/M_{star} \sim 1000$. Based on the stellar mass-growth of the Milky Way, we show that DF17 cannot be understood as a failed Milky Way-like system, but is more similar to quenched Large Magellanic Cloud-like systems. We find that the mean color of GC population, $g_{475}-I_{814} = 0.91 \pm 0.05$ mag, coincides with the peak of the color distribution of intracluster GCs and are also similar to those of the blue GCs in the outer regions of massive galaxies. We suggest that both the intracluster GC population in Coma and the blue-peak in the GC populations of massive galaxies may be fed - at least in part - by the disrupted equivalents of systems such as DF17.

Subject headings: galaxies: clusters: individual (Coma) — galaxies: evolution — galaxies: structure

1. INTRODUCTION

Ultra-diffuse galaxies (UDGs - a termed coined by van Dokkum et al. 2015) constitute a likely heterogeneous population of low-surface brightness systems (e.g. Impney et al. 1988; Bothun et al. 1991; Dalcanton et al. 1997; van Dokkum et al. 2015; Koda et al. 2015; Mihos et al. 2015; Muñoz et al. 2015; van der Burg et al. 2016; Martínez-Delgado et al. 2016). Their most outstanding characteristic is that while their stellar masses are of order $10^8 M_\odot$ or less, their effective radii are comparable to L_* galaxies (2 - 5 kpc). For this reason, the origin of the UDGs remains controversial. One possibility discussed by van Dokkum et al. (2015) is that UDGs are failed L_* galaxies whose early accretion to the cluster environment ($z \sim 2$) quenched their growth. Others, however, have suggested that UDGs are the high-spin tail of normal dwarf galaxies (Amorisco & Loeb 2016).

The two competing scenarios can be confronted with the observations using different approaches. A strong test is to measure the virial mass of UDGs and explore whether they inhabit dark matter (DM) haloes of dwarf-mass ($M_{vir} \sim 10^{10-11} M_\odot$) or Milky Way (MW)-mass haloes ($M_{vir} \sim 10^{12} M_\odot$). UDGs are generally too faint to measure dynamical masses directly through stellar velocity dispersions and rotation curves. Beasley et al. (2016) have shown that the dynamics of the globular cluster (GC) systems of UDGs in the Virgo cluster can be used to measure dynamical masses. These authors determined a total virial mass of $(8 \pm 4) \times 10^{10} M_\odot$ for the UDG VCC 1287, in agreement with the hypothesis that UDGs are dwarf-like systems. An alternative, fol-

lowed by Román & Trujillo (2016), is to explore the spatial distribution of UDGs versus dwarfs and L_* galaxies in clusters and outside these structures. These authors also find that the spatial distribution of UDGs are more similar to dwarfs than to L_* galaxies.

In this contribution we determine the total number of GCs in a large UDG (DF17; van Dokkum et al. 2015) in the Coma cluster based on archival *Hubble Space Telescope* imaging. This galaxy has a size (effective radius 3.4 kpc) large enough to be considered as a good candidate for a failed MW galaxy at high redshift, and is the fourth most luminous UDG in the van Dokkum et al. (2015) catalog. If this UDG were an early quenched L_* galaxy, a natural expectation would be that the number of GCs in DF17, and the GC mean colors, will be similar to the in-situ GCs of the MW. As we will show in this work, the total number of GCs in DF17, and the mean GC colors, imply that they are hosted by a dwarf rather than a giant galaxy.

During the refereeing process of this paper, Peng & Lim (2016) published a study based on the same dataset analysed here. These authors obtain very similar results for the total number of GCs in DF17 ($N_{GC} = 28 \pm 14$ GCs), but focus on slightly different aspects of the GC system, namely the GC luminosity function and density profile rather than color distributions.

2. DATA

2.1. Image preparation

van Dokkum et al. (2015) identified a sample of 47 UDGs projected against the Coma cluster with the Dragonfly telephoto array (Abraham & van Dokkum 2015). One of these UDGs, DF17, van Dokkum et al. re-identified in archival *HST/ACS* imaging.

We retrieved these data in order to analyse the GC population of this system. These data comprise of deep

beasley@iac.es

¹ Instituto de Astrofísica de Canarias, Calle Via Láctea, La Laguna, Tenerife, Spain

² University of La Laguna. Avda. Astrofísico Fco. Sánchez, La Laguna, Tenerife, Spain

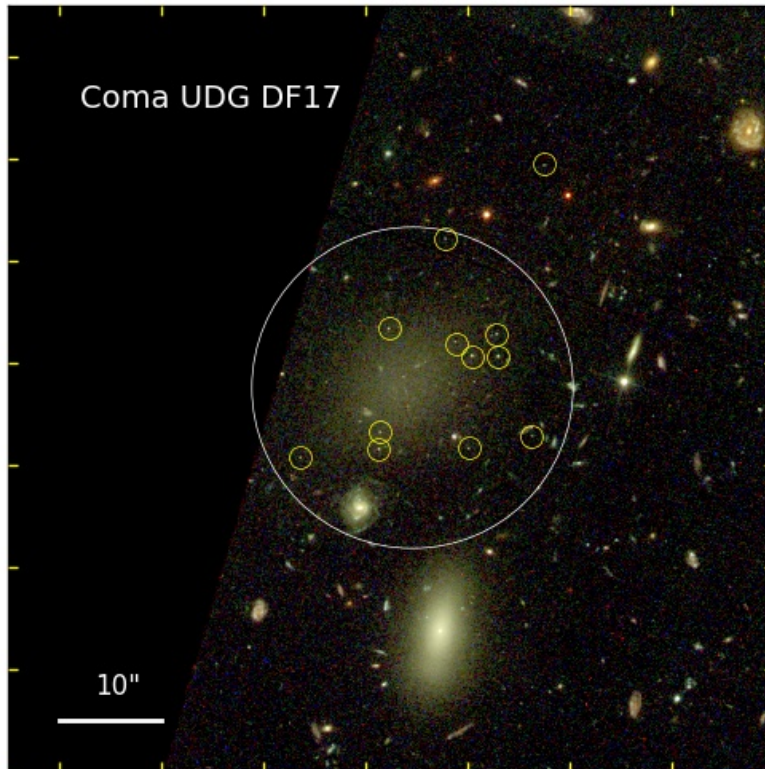


Figure 1. $g_{475}, V_{606}, I_{814}$ *HST/ACS* composite image centered on DF17. GC candidates are marked with small yellow circles. The large white circle represents a 300 pixel radius region ($15''$, or ~ 2 times the galaxy effective radius) within which we associate GC candidates as those belonging to DF17.

imaging in the F475W (g_{475}), F606W (V_{606}) and F814W (I_{814}) filters (GO-12476; PI: Cook; Macri et al. 2013). Exposure times totalled 5100s, 5820s and 5100s in each filter, respectively.

These data were retrieved from the archive on 18 March 2016 and after pipeline reduction, individual exposures were median combined with SWARP (Bertin et al. 2002) in order to place them on a common grid and remove a significant cosmic ray contribution. The combined 3-band color image zooming in the the region around DF17 is shown in Fig. 1.

2.2. Globular cluster photometry and selection

We performed aperture photometry on the imaging data using SExtractor (Bertin 1996) with a 5-pixel radial aperture. In order to maximize our object detection, we set both the detection and analysis thresholds to 0.9σ of the background level, and detected objects on 7-pixel unsharp masked images in the F814W filter. We required that objects were detected within all three filters to be considered a real source. We performed photometry on the original images. Magnitude zeropoints were obtained from the ACS webpages corresponding to the dates of the observations, and are $ZP(F475W) = 26.06$, $ZP(F606W) = 26.49$ and $ZP(F814W) = 25.94$. AB magnitudes were then obtained by correcting to infinite aperture using the

enclosed energy curves of Sirianni et al. (2005). For the above radial aperture, we determine that the *HST/ACS* imaging is 5σ complete down to $F475W = 27.20$, $F606W = 27.33$ and $F814W = 26.98$.

At the distance of the Coma cluster ($m - M = 35.0$; Carter et al. 2008), GCs are unresolved and appear as point-sources. However, the majority of background galaxies are resolved allowing for their effective removal. We selected point sources by running our photometry with two aperture sizes, one of 5 pixel radius and another of 10 pixels similar to the approach of Peng et al. (2011).

Our point source selection window is shown in Fig. 2. The locus of point sources lies at 0.25, and we selected objects ± 0.1 mag about this locus. In addition, we imposed a faint magnitude limit at $I_{814} = 26.98$, which corresponds to our 5σ completeness limit, and a bright limit at $I_{814} = 22.0$, which corresponds to $M_I = -13.0$ at our adopted Coma distance, and would include all known MW GCs. Objects brighter than $I_{814} = 22.0$ are assumed to be stars.

To narrow our selection further we applied a color cut $0.5 < (g_{475} - I_{814}) < 1.5$ which is consistent with the expected color ranges for old GCs (e.g., Beasley et al. 2016; Peng et al. 2011). From our selection criteria, we detect 68 GC candidates. The color-magnitude diagram

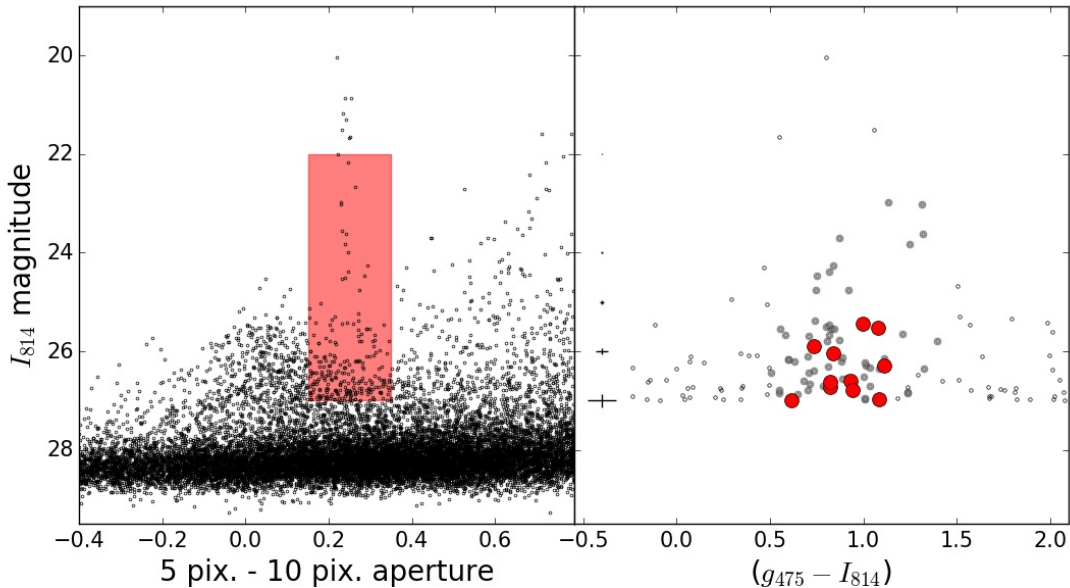


Figure 2. Left panel : Selection of point sources in the I_{814} imaging. The locus for point sources is located at 0.25. Our point source selection box is shown as the shaded region, corresponding to ± 0.1 mag about this locus. Right panel: Color-magnitude diagram of all points sources brighter than $I_{814} = 27.0$ (small circles). GC candidates within our color selection are shown as filled circles, with GC candidates within $15''$ radius (two galaxy effective radii) from the center of DF17 shown as large red circles. There are 11 GC candidates within this radius. Mean photometric uncertainties are indicated to left of the plot.

of point sources is shown in Fig. 2. Inspection of these sources across the field showed a fairly uniform distribution, with a clustering of candidates around DF17. To select potential GC candidates associated with DF17, we placed a 300-pixel radius aperture about the center of DF17 (RA(J2000) = $13^{\text{h}} 01^{\text{m}} 58.13^{\text{s}}$, Dec. (J2000) = $+27^{\circ} 50^{\text{m}} 11.6^{\text{s}}$) and selected all sources within this radius (Fig. 1). A 300 pixel radius corresponds to $15''$, or ~ 2 times the effective radius of DF17 ($7''$; van Dokkum et al. 2015). This radius is smaller than the extent of the GC system of the Virgo UDG VCC 1287 (Beasley et al. 2016). We deliberately defined a smaller region in order to minimize the background contribution in our GC selection. There are 11 candidates within this radius and their locations are shown in Figs. 1 and 2.

We also measured total magnitudes for DF17 itself by integrating the surface brightness profile fits. To $10''$ semimajor axis we obtain $g_{475} = 20.17$, $V_{606} = 19.88$, $I_{814} = 19.33$. For Coma, this corresponds to $M_{V_{606}} = -15.12$, or $M_{V,0} = -14.98$ by comparing the ACS V_{606} and Johnson V filter responses using an old, metal-poor stellar population model (Vazdekis et al. 2010) and using the reddening corrections of Schlafly & Finkbeiner (2011).

To determine the total GC population in DF17, it is necessary to correct for the contribution from background sources (intracluster GCs and interlopers) and the limited depth of the *HST/ACS* imaging. We determine the background contribution by randomly placing 1,000 300 pixel radius apertures across the field and counting the number of GC candidates within the aperture. We masked out the region of DF17 itself, and accounted for regions where the selection region fell outside the detector. Since no other bright galaxies are present in the ACS field, we masked out no other regions. We

find a mean background of 0.93 ± 1.1 objects within the 300 pixel radius, or 4.7 ± 5.6 objects per arcmin 2 .

We determined the total number of GCs in DF17 by assuming that the GC luminosity function (GCLF) is described by a gaussian function. Our photometry is 5σ complete to $I_{814} = 26.98$, corresponding to $M_I = -8.02$ for $m - M = 35.0$. By comparison, Peng et al. (2011) quote a turn-over in the GCLF of $M_{I,AB} = -8.12$ for the Virgo galaxy M87. However, studies of cluster dwarfs suggest that the turn-over of the GCLF in less massive systems tends to fainter magnitudes, with $M_{I,AB} = -7.67$ (Miller & Lotz 2007; Villegas et al. 2010; Peng et al. 2011).

In the case of an “M87-like” GCLF, and by integrating a gaussian function, we would detect 54 percent of the GC population in DF17, implying a total of 19 GCs (including the background correction). In the “dwarf-like” case, we would detect the brightest ~ 37.5 per cent of the GC population, since the GCLF is both fainter and narrower in these systems, implying a total of 27 GCs. Since our range of estimates is consistent with that expected for dwarfs, rather than giant galaxies (e.g., Peng et al. 2008), we assume a dwarf-like GCLF and adopt the latter estimate for the total GC population of DF17, i.e., $N_{\text{GC}} = 27 \pm 5$ GCs. Uncertainties come from the quadrature sum of the poisson and background uncertainties, including a ± 3 Mpc (± 0.07 mag) uncertainty in the location of the peak of the GCLF. From this we calculate a V -band specific frequency, $S_N = 28 \pm 5$.

3. ANALYSIS

3.1. Comparing total globular cluster populations

We show in Fig. 3 the total GC populations as a function of M_{star} for DF17, UDG VCC 1287 in the Virgo cluster (Beasley et al. 2016) and for local galax-

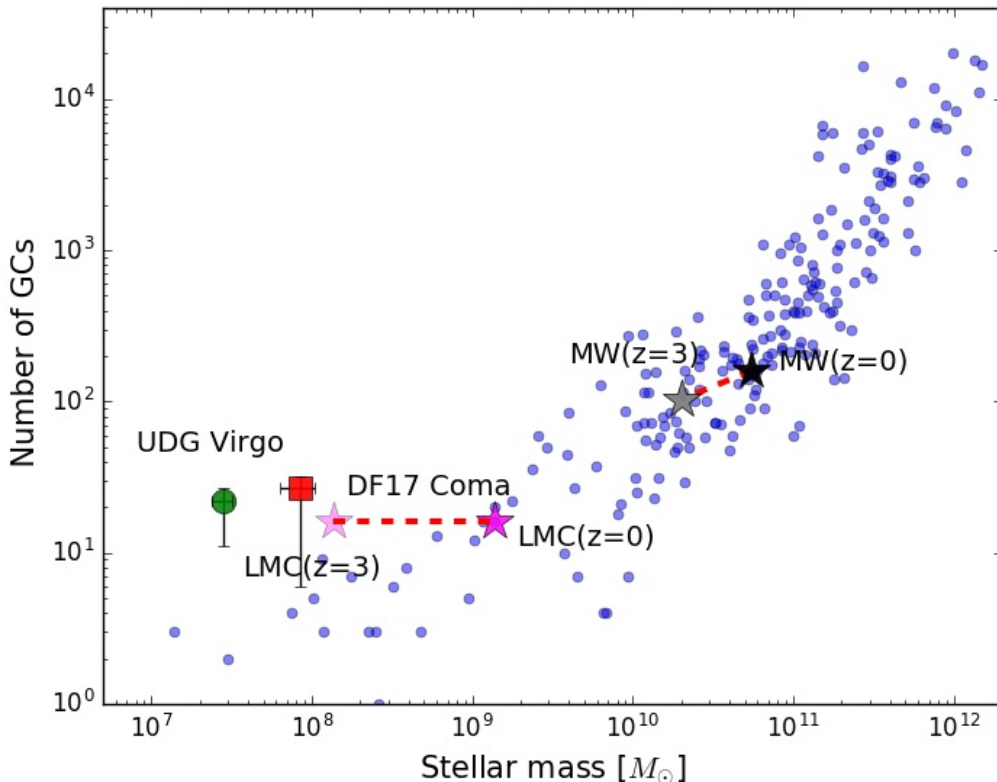


Figure 3. Number of GCs versus stellar mass for DF17, VCC 1287 UDG in Virgo (Beasley et al. 2016) and nearby galaxies from the Harris et al. (2013) catalog. Also shown are the locations of the present-day MW and LMC, and the expected locations of these galaxies at redshift 3 assuming a stellar mass evolution for the MW from Snaith et al. (2014) and a GC accreted fraction of 30 percent (Forbes & Bridges 2010), and a stellar mass evolution for the LMC from Leaman et al. (2016; in preparation)

ies from the catalog of Harris et al. (2013). Stellar masses are calculated from the V -band luminosities of the systems and stellar mass-to-light ratios from Zibetti et al. (2009). The lower-limit errorbars for DF17 and VCC 1287 indicate the position of the number of detected GCs prior to correction for incomplete sampling of the GCLF. For DF17 we calculate a stellar mass, $M_{\text{star}} = (8.4 \pm 2.1) \times 10^7 M_{\odot}$, based on the relation of Taylor et al. (2011) and a conversion from $g_{475} - I_{814}$ to Sloan g and i using the Vazdekis et al. (2010) models.

The locations of the two UDGs indicate that they have significantly poorer GC systems than the present-day MW ($N_{\text{GC}} = 160$; $M_{\text{star}} \sim 5 \times 10^{10} M_{\odot}$). Also, the UDGs have significantly lower stellar mass than the LMC, but have comparable GC populations (LMC; $N_{\text{GC}} = 16$; Mackey & Gilmore 2004).

This is significant because one hypothesis put forward by van Dokkum et al. (2015) as the origin of Coma UDGs is that they may be quenched L_* systems. GCs are generally thought to have formed at high redshifts, as suggested by the ages of MW GCs (≥ 12 Gyr, or $z > 3$; e.g., VandenBergh et al. 2013) and the old ages of extragalactic GC systems (Puzia et al. 2005; Strader et al. 2005). Presumably any quenching of star formation in UDGs took place *after* the bulk of the GCs formed, thereby making the absolute number of GCs an indicator of the nature of UDGs.

In Fig. 3 we plot the expected location of the MW at

$z = 3$, assuming a stellar mass evolution from Snaith et al. (2015), or a factor of ~ 2.5 change in stellar mass over this period. We assume that the *in situ* population of MW GCs formed at high redshift constitutes ~ 70 per cent of the present-day GC population, with the remaining ~ 30 per cent later accreted (Forbes & Bridges 2010). The direction of evolution of the MW is indicated by the dashed line in Fig. 3. We find that, assuming a Milky-Way like star formation history, quenching occurring at $z = 3$ does not reproduce the stellar mass or, perhaps more importantly, the total GC population observed in DF17 (or VCC 1287). Even assuming quenching at $z = 5$ (a factor of ~ 5 change in stellar mass) does not place the MW near the stellar mass of DF17.

Performing a similar exercise with the LMC is illustrative. Assuming quenching at $z = 3$ implies a mass evolution of a factor of ~ 10 to the present day (Leaman et al. 2016; in preparation), placing the LMC (and its GC system) at a stellar mass similar to DF17.

Further, we also obtain an estimate of the virial mass of DF17 by using N_{GC} as a proxy for total halo mass (Beasley et al. 2016; Harris et al. 2013). For $N_{\text{GC}} = 27 \pm 5$ GCs, we obtain $M_{\text{vir}} = (9 \pm 2) \times 10^{10} M_{\odot}$, using the relation of Harris et al. (2013). The uncertainty on this mass estimate comes purely from the uncertainty in N_{GC} , the scatter in mass in the $N_{\text{GC}} - M_{\text{vir}}$ relation is at least a factor of two in the dwarf galaxy regime (Harris et al. 2013). This yields $M_{\text{vir}} / M_{\text{star}} \sim 1000$.

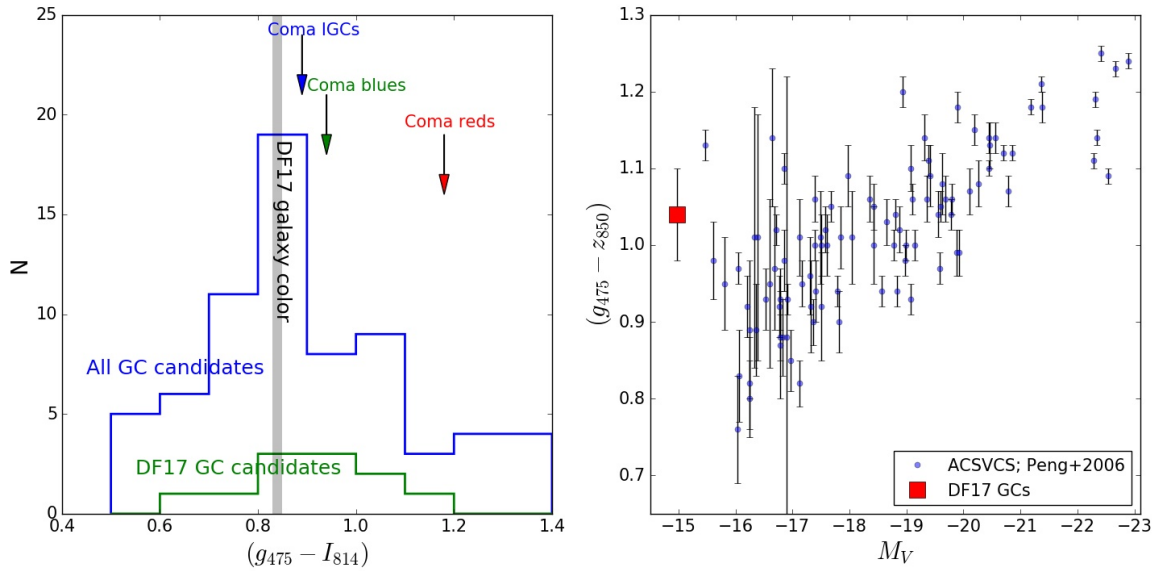


Figure 4. Left: Colors of all GC candidates in ACS field compared to that of GC candidates we associate with DF17. Also indicated are the locations of the mean colors of intracluster GCs (Coma IGCs), and the blue and galaxy subpopulations identified by Peng et al. (2011). The vertical shaded region shows the mean color of the galaxy with uncertainties ($g_{475}-I_{814}=0.84\pm 0.1$) within 1 effective radius. Right: $g_{475}-z_{850}$ colors of the DF17 GCs compared to the mean colors from ACSVCS (Peng et al. 2006). Our colors have been converted as described in the text. The location of the DF17 GCs is consistent with a “normal” galaxy with $M_V \sim -19.0$.

This virial mass is very similar to that of VCC 1287 (8.0 ± 4.0) $\times 10^{10} M_{\odot}$; Beasley et al. 2016). Interestingly, it is also similar to mass estimates for the LMC ($\sim 1 \times 10^{11} M_{\odot}$; Gómez et al. 2015) - i.e., a relatively massive dwarf galaxy.

3.2. Colors of the globular clusters

The color distribution of DF17 GCs is shown in the left panel of Fig. 4, where we compare with GCs in the field which we regard as intracluster GCs (IGCs). For the IGCs, we measure a mean $(g_{475}-I_{814}) = 0.89 \pm 0.03$, $\sigma(g_{475}-I_{814})=0.21$. This color is identical to that measured by Peng et al. (2011) for IGCs in the Coma cluster. For the DF17 GCs, we measure a mean $(g_{475}-I_{814}) = 0.91 \pm 0.05$, $\sigma(g_{475}-I_{814})=0.15$, identical to the IGCs, and only slightly bluer than the $(g_{475}-I_{814}) = 0.94$ obtained by Peng et al. (2011) for the blue GCs these authors associate with massive galaxies. By contrast, the red peak of the Coma cluster galaxies are substantially redder, with $(g_{475}-I_{814}) = 1.18$ (Peng et al. 2011). Thus, based on their colors, both the IGC populations in Coma and also the outer regions of the massive Coma galaxies may comprise, at least in part, of GCs from systems similar to DF17.

To compare the colors of the DF17 GCs with a larger sample of galaxies we turned to the results for the color distributions of GCs from the ACS Virgo Cluster Survey (ACSVCS; Peng et al. 2006). The ACSVCS observed 100 galaxies in the g_{475} and z_{850} bands, whereas our observations include g_{475} and I_{814} . We searched the literature for a conversion between $g_{475}-I_{814}$ and $g_{475}-z_{850}$ but found none, therefore we made our own. We convolved the ACS filter throughput curves for g_{475} , I_{814} and z_{850} from the ACS webpage with the empirically-based model spectra of MIUSCAT (Vazdekis et al. 2012) selecting 12 Gyr ages for a range of metallicities. The

resulting relation between the predicted $g_{475}-I_{814}$ and $g_{475}-z_{850}$ colors is linear, and from linear regression we obtain:

$$g_{475} - z_{850} = (g_{475} - I_{814}) \times 1.023 + 0.128 \quad (1)$$

and, for completeness,

$$g_{475} - I_{814} = (g_{475} - z_{850}) \times 0.975 - 0.122 \quad (2)$$

Applying Eq. 1 to the mean $g_{475}-I_{814}$ colors of the DF17 GCs we obtain $g_{475}-z_{850} = 1.04 \pm 0.06$. These are shown in the right panel of Fig. 4. The mean colors of GC systems of the ACSVCS galaxies define a color-magnitude sequence; more luminous galaxies have, on average, redder GC systems. In this context the GCs of DF17 appear anomalous since they appear too red for the luminosity of their host galaxy. To lie on the ACSVCS relation, DF17 would be expected to have $M_V \sim -19.0$, ~ 4 magnitudes more luminous than its present location. Typical stellar masses of $M_V \sim -19.0$ galaxies in the ACSVCS are $\sim 5 \times 10^9 M_{\odot}$. Both abundance-matching and simulations suggest characteristic virial masses of these systems to be $\sim 1 \times 10^{11} M_{\odot}$ (e.g., Behroozi et al. 2010; Brook & Di Cintio 2015; Schaller et al. 2015). This virial mass estimate from the GC colors is in excellent agreement with the mass obtained from the GC numbers.

For comparison, stellar and halo mass estimates for the LMC, M33 and the MW are, (LMC: $M_{\text{star}} = 3 \times 10^9 M_{\odot}$, $M_{\text{vir}} = 1 \times 10^{11} M_{\odot}$; van der Marel et al. 2014, Gómez et al 2015; M33: $M_{\text{star}} = 6 \times 10^9 M_{\odot}$, $M_{\text{vir}} = 2 \times 10^{11} M_{\odot}$; Corbelli 2003, Seigar 2011; MW: $M_{\text{star}} = 5 \times 10^{10} M_{\odot}$, $M_{\text{vir}} = 1 \times 10^{12} M_{\odot}$; McMillan 2011; Watkins et al. 2010).

Therefore, both the total numbers and colors of the GCs in DF17 suggest that they are hosted in a halo more massive than otherwise suggested by the stellar mass of

DF17. Furthermore, the inferred total mass of the system is characteristic of massive dwarf systems such as the LMC, rather than the MW.

4. DISCUSSION AND CONCLUSIONS

At least three independent observational tests (Beasley et al. 2016, Román & Trujillo 2016 and the one presented here) support the idea that UDGs are not failed MW galaxies but instead dwarf galaxies. However, while the stellar masses of UDGs are close to $10^8 M_{\odot}$, many of their properties are like those of galaxies a factor of 10 more massive in stellar mass. For instance, the total number of GCs in DF17 (and in VCC 1287) is similar to that found in the LMC. Also, the inferred virial masses of DF17 and VCC 1287 ($M_{vir} \sim 10^{11} M_{\odot}$) locate these objects closer to the expectations of a galaxy such as the LMC rather than the MW. Moreover, the sizes of UDGs ($1.5 < r_e < 5$ kpc) are not actually uncommon among $10^9 M_{\odot}$ dwarfs (e.g. Amorisco & Loeb 2016; Román & Trujillo 2016; Shen et al. 2003). All these studies support the idea that UDGs are dwarf-like systems, and relatively massive dwarfs (in terms of virial mass) - again, perhaps similar to the LMC.

However, what does seem to make UDGs unusual is their low stellar masses when compared to their inferred virial masses (e.g., as shown here and in Beasley et al. 2016). Low stellar masses, but relatively rich GC systems suggests that UDGs are quenched systems, but whose quenching occurred *after* the bulk of GC formation occurred. Based on the old ages of MW GCs, and present-day stellar masses of UDGs, this possibly places their quenching somewhere in the region of $z = 3$ (c.f., Fig. 3). This quenching redshift is consistent with those seen in simulations (Yozin & Bekki 2015). We view as unlikely the possibility that the low stellar masses but rich GC systems of these systems is a result of stripping due to the tidal field of the Coma cluster, since simulations suggest that GCs are expected to be lost preferentially over the stars in these systems (Smith et al. 2013, 2015).

If UDGs are quenched LMC-type galaxies, we should expect that that UDG colors would be compatible with the old stellar populations in the LMC. Measuring ages from broad-band colors is fraught with uncertainty, but the global colors measured for DF17 ($g_{475} - I_{814} = 0.84$) are consistent with larger samples (Román & Trujillo 2016), and with a metallicity of $[Fe/H] \sim -1.0$ at old ages (using the Vazdekis 2010, 2015 models). This metallicity is in agreement with the old (> 10 Gyr; $z > 2$) stars in the disk of the LMC (Carrera et al. 2008).

Therefore, we conclude that UDGs constitute a class of quenched dwarfs - perhaps quenched LMC-like galaxies, whose quenching took place at $z \sim 3$. Further mass measurements of UDGs are important, since it is not presently clear whether the DM fraction of UDGs (Beasley et al. 2016) are compatible with both proposed models for their formation (e.g., Amorisco & Loeb 2016) and also the predicted scatter in simulations (e.g., Garrison-Kimmel et al. 2016). In addition, detailed stellar population analyses will help elucidate the precise time and mechanism of quenching in these systems.

We thank Javier Román for many interesting discussions, Alejandro Vazdekis for computing models for our

color conversions and Ryan Leaman for use of his mass evolution calculations. We also thank the referee for their review which improved the paper. The authors of this paper acknowledge support from grant AYA2013-48226-C3-1-P from the Spanish Ministry of Economy and Competitiveness (MINECO).

REFERENCES

- Abraham, R. G., & van Dokkum, P. G. 2014, *PASP*, 126, 55
 Amorisco, N. C., & Loeb, A. 2016, *MNRAS*, 459, L51
 Beasley, M. A., Romanowsky, A. J., Pota, V., et al. 2016, *ApJL*, 819, L20
 Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, 770, 57
 Bertin, E., Mellier, Y., Radovich, M., et al. 2002, *Astronomical Data Analysis Software and Systems XI*, 281, 228
 Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
 Bothun, G. D., Impey, C. D., & Malin, D. F. 1991, *ApJ*, 376, 404
 Brook, C. B., & Di Cintio, A. 2015, *MNRAS*, 450, 3920
 Carrera, R., Gallart, C., Hardy, E., Aparicio, A., & Zinn, R. 2008, *AJ*, 135, 836
 Carter, D., Goudfrooij, P., Mobasher, B., et al. 2008, *ApJS*, 176, 424-437
 Corbelli, E. 2003, *MNRAS*, 342, 199
 Dalcanton, J. J., Spergel, D. N., Gunn, J. E., Schmidt, M., & Schneider, D. P. 1997, *AJ*, 114, 635
 Forbes, D. A., & Bridges, T. 2010, *MNRAS*, 404, 1203
 Garrison-Kimmel, S., Bullock, J. S., Boylan-Kolchin, M., & Bardwell, E. 2016, arXiv:1603.04855
 Gómez, F. A., Besla, G., Carpintero, D. D., et al. 2015, *ApJ*, 802, 128
 Harris, W. E., Harris, G. L. H., & Alessi, M. 2013, *ApJ*, 772, 82
 Impey, C., Bothun, G., & Malin, D. 1988, *ApJ*, 330, 634
 Koda, J., Yagi, M., Yamanoi, H., & Komiyama, Y. 2015, *ApJL*, 807, L2
 Leaman, R., VandenBerg, D. A., & Mendel, J. T. 2013, *MNRAS*, 436, 122
 Mackey, A. D., & Gilmore, G. F. 2004, *MNRAS*, 355, 504
 Macri, L. M., Hoffmann, S. L., Cook, K. H., et al. 2013, *American Astronomical Society Meeting Abstracts #221*, 221, 152.06
 Martínez-Delgado, D., Läsker, R., Sharina, M., et al. 2016, *AJ*, 151, 96
 McMillan, P. J. 2011, *MNRAS*, 414, 2446
 Mihos, J. C., Durrell, P. R., Ferrarese, L., et al. 2015, *ApJL*, 809, L21
 Miller, B. W., & Lotz, J. M. 2007, *ApJ*, 670, 1074
 Muñoz, R. P., Eigenthaler, P., Puzia, T. H., et al. 2015, *ApJL*, 813, L15
 Peng, E. W., & Lim, S. 2016, *ApJL*, 822, L31
 Peng, E. W., Ferguson, H. C., Goudfrooij, P., et al. 2011, *ApJ*, 730, 23
 Peng, E. W., Jordán, A., Côté, P., et al. 2008, *ApJ*, 681, 197-224
 Peng, E. W., Jordán, A., Côté, P., et al. 2006, *ApJ*, 639, 95
 Puzia, T. H., Kissler-Patig, M., Thomas, D., et al. 2005, *A&A*, 439, 997
 Román, J., & Trujillo, I. 2016, arXiv:1603.03494
 Schaller, M., Frenk, C. S., Bower, R. G., et al. 2015, *MNRAS*, 451, 1247
 Schlafly, E. F., & Finkbeiner, D. P. 2011, *ApJ*, 737, 103
 Seigar, M. S. 2011, *ISRN Astronomy and Astrophysics*, 2011, 725697
 Shen, S., Mo, H. J., White, S. D. M., et al. 2003, *MNRAS*, 343, 978
 Sirianni, M., Jee, M. J., Benítez, N., et al. 2005, *PASP*, 117, 1049
 Smith, R., Sánchez-Janssen, R., Beasley, M. A., et al. 2015, *MNRAS*, 454, 2502
 Smith, R., Sánchez-Janssen, R., Fellhauer, M., et al. 2013, *MNRAS*, 429, 1066
 Snaith, O. N., Haywood, M., Di Matteo, P., et al. 2014, *ApJL*, 781, L31
 Strader, J., Brodie, J. P., Cenarro, A. J., Beasley, M. A., & Forbes, D. A. 2005, *AJ*, 130, 1315
 Taylor, E. N., Hopkins, A. M., Baldry, I. K., et al. 2011, *MNRAS*, 418, 1587
 van der Burg, R. F. J., Muzzin, A., & Hoekstra, H. 2016, *A&A*, 590, A20
 VandenBerg, D. A., Brogaard, K., Leaman, R., & Casagrande, L. 2013, *ApJ*, 775, 134
 van der Marel, R. P., & Kallivayalil, N. 2014, *ApJ*, 781, 121
 van Dokkum, P. G., Abraham, R., Merritt, A., et al. 2015a, *ApJL*, 798, L45
 Vazdekis, A., Coelho, P., Cassisi, S., et al. 2015, *MNRAS*, 449, 1177

- Vazdekis, A., Ricciardelli, E., Cenarro, A. J., et al. 2012, MNRAS, 424, 157
- Vazdekis, A., Sánchez-Blázquez, P., Falcón-Barroso, J., et al. 2010, MNRAS, 404, 1639
- Villegas, D., Jordán, A., Peng, E. W., et al. 2010, ApJ, 717, 603
- Watkins, L. L., Evans, N. W., & An, J. H. 2010, MNRAS, 406, 264
- Yozin, C., & Bekki, K. 2015, MNRAS, 452, 937
- Zibetti, S., Charlot, S., & Rix, H.-W. 2009, MNRAS, 400, 1181