A RICH GLOBULAR CLUSTER SYSTEM IN DRAGONFLY 17: ARE ULTRA-DIFFUSE GALAXIES PURE STELLAR HALOS?*

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ABSTRACT
Observations of nearby galaxy clusters at low surface brightness have identified galaxies with low luminosities, but sizes as large as $L^*$ galaxies, leading them to be dubbed “ultra-diffuse galaxies” (UDGs). The survival of UDGs in dense environments like the Coma cluster suggests that UDGs could reside in much more massive dark halos. We report the detection of a substantial population of globular clusters (GCs) around a Coma UDG, Dragonfly 17 (DF17). We find that DF17 has a high GC specific frequency of $S_N = 26 \pm 13$. The GC system is extended, with an effective radius of $12'' \pm 2''$, or $5.6 \pm 0.9$ kpc at Coma distance, 70% larger than the galaxy itself. We also estimate the mean of the GC luminosity function to infer a distance of $97^{+17}_{-14}$ Mpc, providing redshift-independent confirmation that one of these UDGs is in the Coma cluster. The presence of a rich GC system in DF17 indicates that, despite its low stellar density, star formation was intense enough to form many massive star clusters. If DF17’s ratio of total GC mass to total halo mass is similar to those in other galaxies, then DF17 has an inferred total mass of $\sim10^{11} M_{\odot}$, only ~10% the mass of the Milky Way, but extremely dominated by dark matter, with $M/L_N \approx 1000$. We suggest that UDGs like DF17 may be “pure stellar halos,” i.e., galaxies that formed their stellar halo components, but then suffered an early cessation in star formation that prevented the formation of any substantial central disk or bulge.

Key words: galaxies: evolution – galaxies: halos – galaxies: star clusters: general – galaxies: stellar content – globular clusters: general

1. INTRODUCTION

The realm of low surface brightness (LSB) is still one of the most unexplored in astronomy. Many of the visible counterparts to structures expected in a cold dark matter universe are expected to be at a surface brightness much fainter than that of the night sky. A recent study using a new telescope optimized for LSB imaging, the Dragonfly Telephoto Array, in conjunction with imaging from the Canada–France–Hawaii Telescope, reported the discovery of 47 ultra-diffuse galaxies (UDGs; $h_{(c,g)} = 24–26$ mag arcsec$^{-2}$) in the direction of the Coma cluster of galaxies (van Dokkum et al. 2015a). These galaxies have luminosities and appearances similar to early-type dwarf galaxies, but have much larger sizes, similar to $L^*$ galaxies ($1.5 < R_c < 4.5$ kpc). Their luminosities and sizes make them outliers in traditional scaling relation diagrams for galaxies. One UDG, DF44, has been confirmed to have a redshift consistent with membership in the Coma cluster (van Dokkum et al. 2015b). Subsequently, 854 new diffuse galaxies have been identified in Coma (Koda et al. 2015), and even lower surface brightness galaxies have been identified in the nearby Virgo cluster of galaxies (Mihos et al. 2015; Beasley et al. 2016) showing that these galaxies are far from uncommon, and that they may even be able to exist in the dense core of a galaxy cluster. Unfortunately, their low surface brightness and apparent lack of ongoing star formation makes it prohibitively difficult to study their stellar populations. Moreover, the distance of the Coma cluster ($\approx100$ Mpc; Carter et al. 2008) puts resolved studies of their red giant branch stars beyond the capabilities of current telescopes.

One probe of stellar populations that is within reach for these diffuse galaxies is globular clusters (GCs). GCs are old, compact star clusters whose presence in galaxies points to an early epoch of galaxy building where the intense star formation needed to form massive star clusters was commonplace. Observationally, they are useful tracers of old stellar populations because they can be observed at large distances. The number of GCs in a galaxy also correlates linearly with the total host halo mass (Blakeslee et al. 1997; Peng et al. 2008; Spitler & Forbes 2009; Harris et al. 2013), giving a way to estimate the total mass of a galaxy without other information. A recent study by Beasley et al. (2016) used kinematics of GCs in the Virgo cluster UDG VCC 1287 to show that the galaxy has an extremely high mass-to-light ratio, consistent with the premise that the number of GCs trace total mass, even in these extreme galaxies. The GC luminosity function peaks at a nearly universal luminosity, allowing an estimate of the distance to the galaxy. At the distance of the Coma cluster, GCs are readily visible in Hubble Space Telescope (HST) images.

We use archival HST Advanced Camera for Surveys/Wide Field Channel (ACS/WFC) imaging of one Coma UDG, Dragonfly 17 (DF17), to investigate whether UDGs in the dense Coma cluster can host a system of GCs, and what that implies for the mass and origin of UDGs.

2. OBSERVATIONS AND GC CANDIDATE SELECTION

We used images taken with the HST ACS/WFC (GO-12476, PI: Cook; Macri et al. 2013). These data were described in van Dokkum et al. (2015a) and are comprised of parallel observations in three filters ($g_{475}$, $V_{606}$, and $I_{814}$). We made...
3. RESULTS

3.1. The GC System of DF17

Figure 1 shows an image of DF17 with GC candidates from the “optimal” sample circled. The spatial distribution of GC candidates is highly concentrated toward DF17. The GC candidates roughly follow the stellar light of the galaxy, with a steep drop in numbers just beyond DF17’s optical radius. This strongly suggests that the GC candidates are physically associated with DF17. Within 20″ of the center of DF17 (a radius which contains all of the GC candidates clustered around the galaxy), we expect only 1.4 of the 15 selected objects to be background contaminants. This indicates that nearly all of the GC candidates around DF17 are, in fact, real GCs associated with the galaxy.

The GCs appear to be asymmetrically distributed about the galaxy, with nearly three times as many on the NW side along the major axis (which runs roughly NW–SE). Because DF17 is on the edge of the field of view, it is difficult to say whether this imbalance is mitigated at larger radii to the SE. We also note that there is no obvious nuclear star cluster above our detection limit.

Figure 2 shows the GC surface density profile. We characterize the profile using a Sersic function and constant background, with best-fit parameters estimated using maximum likelihood and bootstrap resampling. We find that the GC system has a profile consistent with a low Sersic index, n = 0.85 ± 0.22, with a flat core and a steep outer drop off. The size of the GC system is characterized by the effective radius, $R_e$ = 12″ ± 2″. For comparison, the effective radius measured for the stars from the same imaging is $R_e$ = 7″0 (van Dokkum et al. 2015a), so the GCs have an extent 70% larger than the already diffusely distributed stars, something which is also seen in more massive galaxies (e.g., McLaughlin 1999; Kartha et al. 2014).

3.2. The GC Luminosity Function and the Distance to DF17

The luminosity of the GCLF peak is a well-known distance indicator (e.g., Harris 2001), and measuring its apparent magnitude provides perhaps the only way to obtain a redshift-independent distance for such a distant UDG. At the distance of the Coma cluster ($m − M ≈ 35$), a GC system with a standard Gaussian luminosity function for a low-mass early-type galaxy (with mean $M_V = −7.3$ mag; Miller & Lotz 2007) has a peak whose measurement is within the reach of these observations ($V_0 ≈ 27.7$ mag). Lee & Jing (2016) showed that GCLF distances to the Coma cluster can be obtained with HST imaging. For this analysis, we used our “deep” sample, which extends to $V = 29$ mag.

We used artificial star tests to quantify the detection efficiency across our images. We used DAOPHOT II (Stetson 1987) to construct an empirical PSF using bright stars. We added artificial stars to images in all three filters, giving them a typical GC color, then ran the same detection and selection procedures as were used to generate the “deep” sample. The 90% completeness level is $V_{0.66} = 28.1$ mag, and the 50% completeness level is $V_{0.66} = 28.8$ mag. This latter limit is fainter by ~1 mag than the expected GCLF peak at the distance of Coma (see the dashed line in Figure 3).

We used a Gaussian form for the GC luminosity function, a power law for the number counts of background sources (distant, unresolved galaxies), and multiplied both by the derived detection efficiency function. Using maximum likelihood estimation, we fit the normalization and power-law slope of the background counts using the GC candidates outside a radius of 36″ ($3R_e$) from DF17, assuming that all of these objects are background objects. We fixed the power-law model for the background to then estimate the Gaussian GCLF parameters for GC candidates within 12″, the effective radius of the GC system. Figure 3 shows the number counts of GC candidates within the central 12″ of DF17, as well as the background-subtracted GC counts. HST resolution eliminates much of the background contamination at these magnitudes, and the small area in which the GCs reside also helps suppress contamination.

We find the best-fit parameters for the Gaussian GCLF to be $\mu_{V_{0.66}} = 27.53 ± 0.34$ mag and $\sigma_{V_{0.66}} = 0.76 ± 0.23$ mag. Figure 3 shows the best-fit Gaussian model, as well as the region that encompasses 68% of the models fit using 1000 bootstrap resamples.

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1. http://www.stsci.edu/hst/HST_overview/drizzlepac
Because the $V_{606}$ magnitude is not a standard $V$, we use transformations from DeGraaff et al. (2007, Equation (3)) to convert the best-fit $\mu_{V_{606}}$ to $\mu_V$. Using the color of a typical GC, we find that $V - V_{606} = 0.13$ mag and $A_V = 0.025$ (Schlafly & Finkbeiner 2011), which results in the GCLF mean being $\mu_V = 27.63 \pm 0.35$. Assuming that the form of DF17’s GCLF is similar to those of nearby low-mass galaxies, this value of $\mu_V$ places DF17 at a distance of $97^{+14}_{-12}$ Mpc, putting it exactly in the Coma cluster.

### 3.3. Total Number of GCs and Specific Frequency

With our assumption of the form of the GCLF and the GC spatial density profile in DF17, we can estimate the total number of GCs. Counting seven GCs within $R_e$ and brighter than the estimated GCLF mean, we find that $N_{GC} = 28 \pm 14$ (where we include the uncertainty in the GCLF mean). DF17 has a luminosity of $M_V = -15.1$ mag (using our distance and transforming from $V_{606}$ reported in van Dokkum et al. 2015a), which gives a GC specific frequency of $S_N = 26 \pm 13$.

### 4. DISCUSSION

#### 4.1. The Mass of DF17

DF17 has a substantial population of GCs, with a specific frequency ($S_N = 26 \pm 13$) that is among the highest measured for any galaxy, and is the highest for its luminosity range. Figure 4 shows a compilation of high-quality, HST-derived $S_N$ values for early-type galaxies (ETGs) across a range of luminosities. DF17 is a clear outlier at its luminosity, having a value of $S_N$ only seen in galaxies two magnitudes fainter. Two extreme cases are VCC 1287 (Beasley et al. 2016), which has $S_N \sim 80$, and VLSB-B, and another UDG in Virgo (Mihos et al. 2015) that has $S_N \sim 40$, but there are also low-mass galaxies with high $S_N$ from Georgiev et al. (2010).

Work over the past couple decades has shown that the number of GCs in ETGs appears to be a reasonable estimator of the total mass of a galaxy or cluster (Blakeslee et al. 1997; McLaughlin 1999). As a result, the relationship between GC specific frequency (or GC stellar mass fraction) and galaxy stellar mass traces reasonably well the total mass–stellar mass relation for galaxies, both with a minimum around $L^*$ (Peng et al. 2008; Spitzer & Forbes 2009; Harris et al. 2013; Hudson et al. 2014). Provided that this relation holds across all galaxies, we can use the number of GCs in DF17 to estimate its total mass. We use the Harris et al. (2013) relation between the GC system mass and the total galaxy mass ($M_{GC}/M_{halo} = 6 \times 10^{-5}$) to determine a total mass for DF17 of $(9.3 \pm 4.7) \times 10^{10} M_\odot$ and a mass-to-light ratio of $M/L_V \approx 1000$. This total mass is roughly $\sim 10\%$ that of the Milky Way.

The survival of UDGs in dense environments like Coma and other massive clusters (van der Burg et al. 2016; Roman & Trujillo 2016) provides independent evidence that UDGs must...
be dark matter dominated. Moreover, Beasley et al. (2016) used GC kinematics to find that the Virgo UDG, VCC 1287, has $M/L \approx 3000$, which was in line with what they inferred from their total number of GCs. These high mass-to-light ratios, and optical colors consistent with old stellar populations, suggest that tremendous gas loss (or lack of accretion) could have occurred early in the evolution of UDGs.

4.2. Ultra-diffuse Galaxies as “Pure Stellar Halos”

The diffuseness of DF17’s stellar population seems to be at odds with the presence of GCs. Star clusters massive enough to be GC progenitors require intense star formation episodes, like those seen in gas-rich galaxy mergers. The existence of GCs require this kind of starburst in DF17, but a high star formation rate density should also produce a high surface brightness stellar component. Amorisco & Loeb (2016) suggested that UDGs could be the high angular momentum tail of the normal dwarf galaxy population. While their model produces the proper number of UDGs in clusters, it is unclear how such extended, LSB galaxies can produce massive star clusters. Present-day LSB disks, also thought to result from high angular momentum (Dalcanton et al. 1997), typically have little molecular gas and low star formation efficiencies (Bothun et al. 1997).

One way to explain a high $S_N$ in a UDG is to posit that massive star clusters preferentially form earlier in a given star formation episode (e.g., Peng et al. 2008), and then the subsequent formation of field stars is rapidly quenched. This
behavior is supported by measurements of [$\alpha$/Fe] in Virgo dwarf galaxies (Liu et al. 2016), in which dwarfs with higher $S_N$ tend to have higher [$\alpha$/Fe], suggesting a more rapid (and truncated) star formation history. In this scenario, DF17 should also have chemical abundance patterns typical of rapid star formation.

The constituents of DF17—an extended, spheroidal stellar population and a rich system of GCs—make it most similar to the stellar halos of normal galaxies. In effect, UDGs like DF17 are analogous to the stellar halos of more luminous, high surface brightness galaxies, and that UDGs are part of the surviving population of proto-galaxies that built up the high-$S_N$, high-$M/L$ stellar populations in the outskirts of today’s massive galaxies.

While the inferred mass of DF17 makes it unlikely that it is a “failed” Milky Way–like galaxy, DF17 could be the stellar halo of something less massive. A bright, relatively compact central stellar component in DF17 might look similar to a “normal,” sub-L* galaxy with a rather extended GC system. We speculate that UDGs like DF17 are analogous to the stellar halos of more luminous, high surface brightness galaxies, and that UDGs are part of the surviving population of proto-galaxies that built up the high-$S_N$, high-$M/L$ stellar populations in the outskirts of today’s massive galaxies.

Our ability to detect GCs in UDGs out to the distance of the Coma cluster with HST gives us a relatively inexpensive way to estimate their total masses and distances, and to study their star formation histories. Combined with the measurements of the extent of these GC systems, which can be compared to those of nearby galaxies, GCs will be a valuable resource to investigate the origins of UDGs.

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