

APPROXIMATELY A THOUSAND ULTRA-DIFFUSE GALAXIES IN THE COMA CLUSTER

JIN KODA¹, MASAFUMI YAGI^{2,3}, HITOMI YAMANOI², AND YUTAKA KOMIYAMA^{2,4}¹ Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA; jin.koda@stonybrook.edu² Optical and Infrared Astronomy Division, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan³ Department of Advanced Sciences, Hosei University, 3-7-2, Kajinocho, Koganei, Tokyo, 184-8584, Japan⁴ SOKENDAI (The Graduate University for Advanced Studies), Mitaka, Tokyo, 181-8588, Japan

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ABSTRACT

We report the discovery of 854 ultra-diffuse galaxies (UDGs) in the Coma cluster using deep R band images, with partial B , i , and $H\alpha$ band coverage, obtained with the Subaru telescope. Many of them (332) are Milky Way (MW) sized with very large effective radii of $r_e > 1.5$ kpc. This study was motivated by the recent discovery of 47 UDGs by Dokkum et al.; our discovery suggests > 1000 UDGs after accounting for the smaller Subaru field (4.1 deg^2 ; about one-half of Dragonfly). The new Subaru UDGs show a distribution concentrated around the cluster center, strongly suggesting that the great majority are (likely longtime) cluster members. They are a passively evolving population, lying along the red sequence in the color–magnitude diagram with no signature of $H\alpha$ emission. Star formation was, therefore, quenched in the past. They have exponential light profiles, effective radii $r_e \sim 800 \text{ pc} - 5 \text{ kpc}$, effective surface brightnesses $\mu_k(R) = 25 - 28 \text{ mag arcsec}^{-2}$, and stellar masses $\sim 1 \times 10^7 M_\odot - 5 \times 10^8 M_\odot$. There is also a population of nucleated UDGs. Some MW-sized UDGs appear closer to the cluster center than previously reported; their survival in the strong tidal field, despite their large sizes, possibly indicates a large dark matter fraction protecting the diffuse stellar component. The indicated baryon fraction $\lesssim 1\%$ is less than the cosmic average, and thus the gas must have been removed (from the possibly massive dark halo). The UDG population is elevated in the Coma cluster compared to the field, indicating that the gas removal mechanism is related primarily to the cluster environment.

Key words: galaxies: clusters: individual (Coma) – galaxies: evolution – galaxies: structure

1. INTRODUCTION

This study is motivated by the discovery of 47 ultra-diffuse galaxies (UDGs) in the Coma cluster by van Dokkum et al. (2015a) using the Dragonfly Telescope Array (Abraham & van Dokkum 2014, hereafter Dragonfly). This unexpected discovery revealed a new population of low surface brightness (SB) galaxies. Indeed, their central SBs are very low $24 - 26 \text{ mag arcsec}^{-2}$ in g -band and their median stellar mass is only $\sim 6 \times 10^7 M_\odot$, despite their effective radii $r_e = 1.5 - 4.6 \text{ kpc}$ being as large as those of L_* galaxies (e.g., $\sim 3.6 \text{ kpc}$ for the Milky Way (MW), calculated from Rix & Bovy 2013). van Dokkum et al. (2015a) speculated that the UDGs probably have very high dark matter fractions as they have survived in the strong tidal field of the cluster.

Dragonfly is optimized to efficiently discover faint structures over a large field of view, but has relatively poor spatial resolution with seeing and pixel scales of $\sim 6''$ and $2''8$, respectively. The above properties of the Dragonfly UDGs were derived after their discovery from archival Canada–France–Hawaii Telescope imaging. Follow-up studies are needed to understand their nature and origin, as well as their relationship to the cluster environment (Boselli & Gavazzi 2014 for review) and to other more studied galaxy populations, such as dwarfs and low SBs, in clusters (e.g., Binggeli & Cameron 1991; Bothun et al. 1991; Ulmer et al. 1996, 2011; Adami et al. 2006b, 2009; Ferrarese et al. 2012; Lieder et al. 2012).

Optical telescopes of larger aperture are advantageous for a resolved study of this population. Yamanoi et al. (2012) used the Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) on the Subaru telescope and derived a galaxy luminosity function down to $M_R \sim -10$ in Coma. Their three

$34' \times 27'$ fields include nine Dragonfly UDGs. All of the nine were easily found in their catalog, being resolved spatially in the images. Therefore, Subaru imaging can identify this new galaxy population efficiently and permits an investigation of their internal properties. Several archival Subaru images are available for the Coma cluster (Yagi et al. 2007, 2010; Yoshida et al. 2008; Okabe et al. 2010, 2014). In this Letter, we use the archival Subaru data and report the discovery of 854 UDGs, implying ~ 1000 UDGs after scaling for the Dragonfly field of view.

We adopted $m - M = 35.05$ (Kavalaars et al. 2000) as the distance modulus of the Coma cluster, which corresponds to an angular diameter distance of 97.5 Mpc ($1'' = 0.47 \text{ kpc}$).⁵ The full catalog of the Subaru UDGs will be published in M. Yagi et al. (2015, in preparation). We use the AB-magnitude system in this work.

2. DATA

The raw R band images from the Suprime-Cam were obtained from the Subaru data archive (Baba et al. 2002). Suprime-Cam has a mosaic of ten 2048×4096 CCDs and covers a wide field of $34' \times 27'$ with a pixel scale of $0''.202$. An 18-pointing mosaic with Suprime-Cam was taken by Okabe et al. (2014) and covered about 4.1 deg^2 (Figure 1). The seeing was $0''.6 - 0''.8$, typically $0''.7$. Integration times for the 18 fields were not the same, resulting in variations in background noise, i.e., $28.3 - 28.7 \text{ mag arcsec}^{-2}$ (1σ) in a $2''$ aperture (equivalent to $30.0 - 30.4 \text{ mag arcsec}^{-2}$ in a $10''$ aperture, $\sim 1 \text{ mag}$ deeper than van Dokkum et al. 2015a).

⁵ We adopted the Cosmological parameters of $(h_0, \Omega_M, \Omega_\Lambda) = (0.71, 0.27, 0.73)$ from Larson et al. (2011).

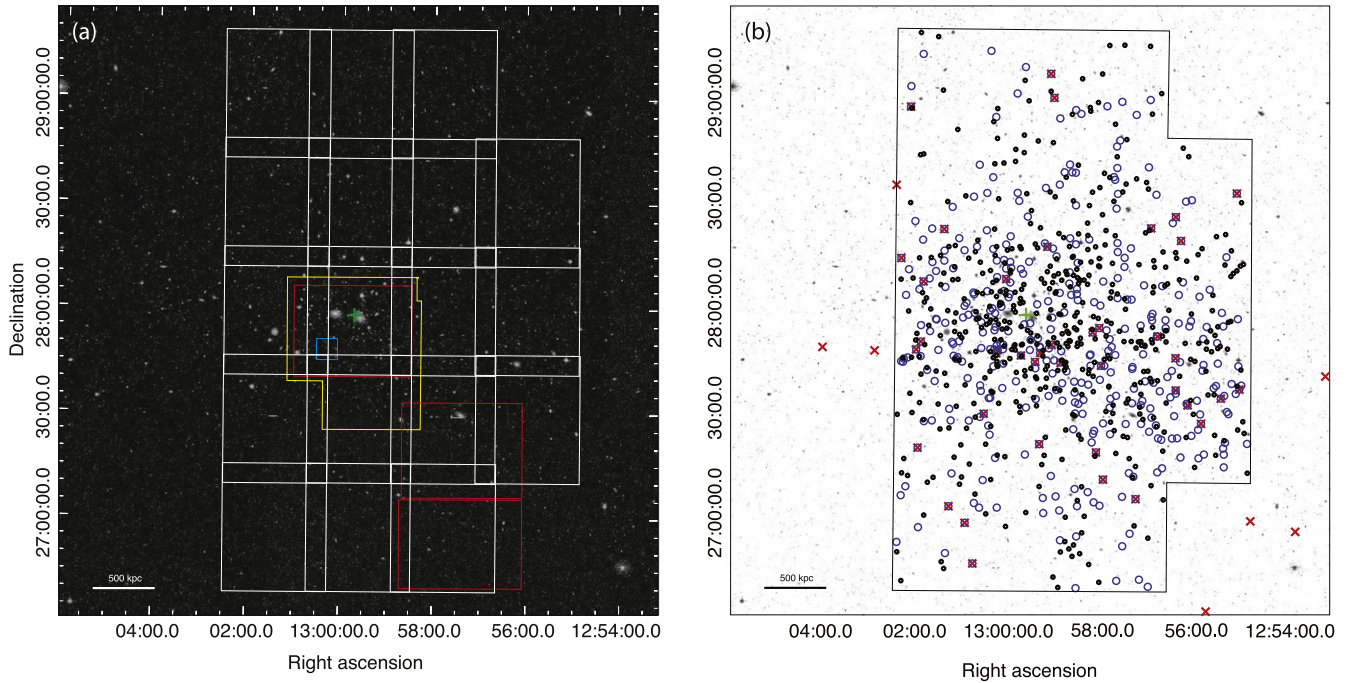


Figure 1. The $2^{\circ}86 \times 2^{\circ}90$ ($\sim 4.87 \times 4.94$ Mpc 2) area centered on the Coma cluster, the same area as in Figure 1 of van Dokkum et al. (2015a). (a) Image from the Digitized Sky Survey. The white borders show the 18 fields covered in the Subaru R band (Okabe et al. 2014), which have the total area of 4.1 degree 2 , about one-half of the Dragonfly coverage. Red indicates the area analyzed by Yamanoi et al. (2012). Yellow outlines the area analyzed by Yagi et al. (2010) using the Subaru B , R , $H\alpha$, i bands. Cyan indicates the area in Figure 2. The center of the cluster ($\alpha_{J2000}, \delta_{J2000}$) = (12:59:42.8, +27:58:14) is marked with a green cross (White et al. 1993). (b) The same area as in (a), showing the distribution of the 854 Subaru UDGs (circles). The MW-sized UDGs, with large effective radii (>1.5 kpc), are shown in blue. The Subaru field coverage in R is enclosed with the solid line. The 47 Dragonfly UDGs are indicated with red crosses.

The very central field has a higher variation of 27.8 mag arcsec $^{-2}$ since the field is contaminated by the outer envelope of bright galaxies.

The data were reduced in a standard way (Yagi et al. 2002, 2010). We used self-sky flat images, subtracted sky background locally in each small grid (256×256 pixel 2 ; $51''7 \times 51''7$), used the WCSTools (Mink et al. 2002) for astrometry, and applied a photometric calibration (Yagi et al. 2013) using the Sloan Digital Sky Survey (SDSS)-III DR9 catalog (Ahn et al. 2012). The grid size for the background subtraction was larger than the expected size of UDGs ($<30'' \sim 15$ kpc). The Galactic extinction in the R band varies from 0.016 to 0.031 mag across the 18-field mosaic (Schlafly & Finkbeiner 2011). We adopted the Galactic extinction value at the center of each field and neglected variation within each field. The final photometric error is $\lesssim 0.1$ mag. More details of the data reduction procedure will be presented in M. Yagi et al. (2015, in preparation). In addition, we used the Suprime-Cam B , i , and $H\alpha$ reduced images (see Figure 1) by Yagi et al. (2010) and Yamanoi et al. (2012).

We also analyzed a control field for comparison. The R band data of one Suprime-Cam pointing, 1/18 of the Coma field, were taken from the Subaru Deep Field (SDF) project (Kashikawa et al. 2004). We used only a part of the raw SDF exposures taken in 2008 June to make the background noise comparable to that in the Coma fields. The 1σ background noise in a $2''$ aperture is 28.6 mag arcsec $^{-2}$. For consistency we started from the raw data and matched data reduction parameters.

3. IDENTIFICATION

Our goal is to find UDGs in the Subaru images. Forty of the 47 UDGs discovered by Dragonfly are within the Subaru R band coverage based on their coordinates (van Dokkum et al. 2015a). All were detected significantly (with the faintest one, DF27, off by $12''5$ from the published coordinate) and their structures were resolved in the Subaru images. The detection threshold was approximately 27.3 mag arcsec $^{-2}$ in the R band. We describe our selection procedure for the final catalog of 854 UDGs in the Coma cluster. We found no counterparts in the control field.

We ran SExtractor (version 2.19.5; Bertin & Arnouts 1996) on individual mosaic frames with a fixed detection threshold of 27.3 mag arcsec $^{-2}$ in R . We removed a first set of spurious detections using SExtractor’s “FLAGS < 4” and “PETRO_RADIUS > 0.” This initial catalog had 2,627,495 objects, including duplicates in the overlap regions of adjacent mosaic frames ($\sim 30\%$). We used the Dragonfly UDGs as the fiducial set in adjusting parameters for selection of UDG candidates, but could not use exactly the same selection criteria as van Dokkum et al. (2015a) due to the difference in image quality. We applied constraints on R magnitude and size, “ $18 < \text{MAG_AUTO} < 26$ ” and “FWHM(Gaussian) > $4''$ ” (i.e., all Dragonfly UDGs satisfy this condition), which left 7362 objects.

The reported effective radius of the Dragonfly UDGs is $r_e \gtrsim 3''2$ (using r_e from GALFIT; Peng et al. 2002). However, in the resolved Subaru images we found that an alternative constraint, SExtractor’s $r_e \gtrsim 1''5$, captures all the Dragonfly UDGs. We therefore used $r_e > 1''5$ and a mean SB of $\langle \mu(r_e) \rangle > 24$ to choose UDG candidates. (Note that we found

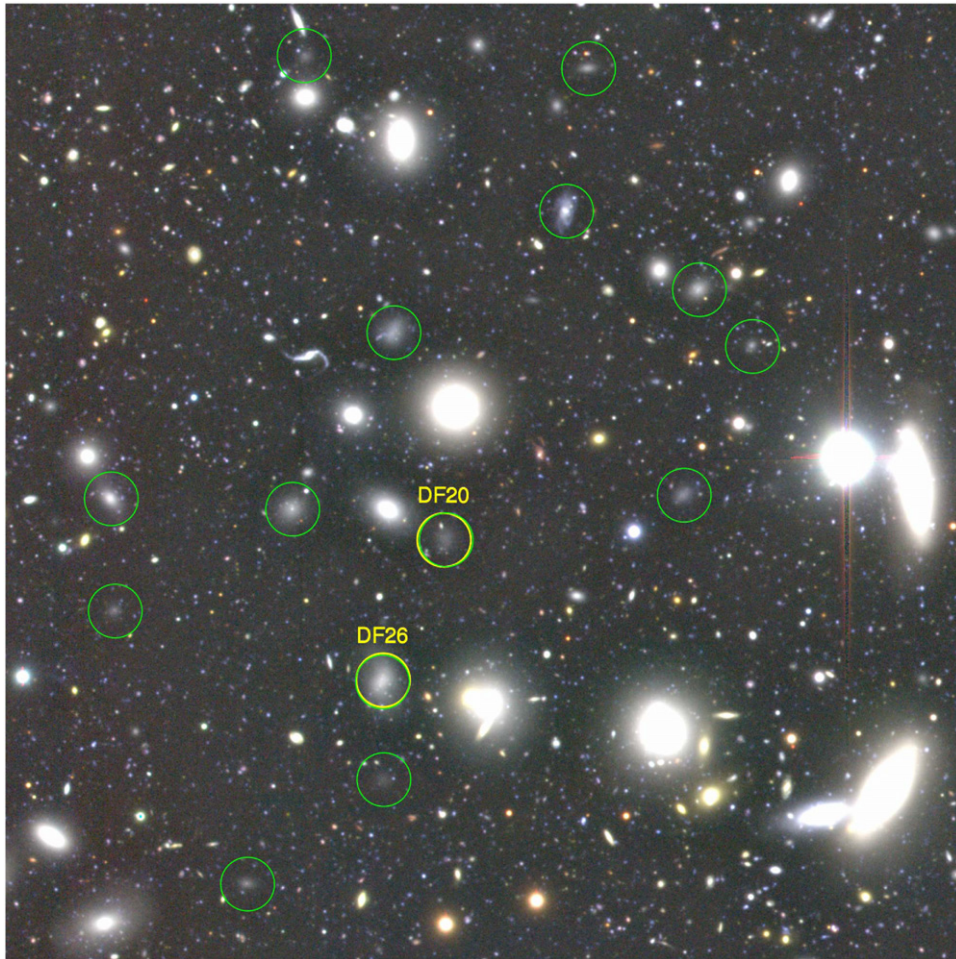


Figure 2. Subaru *BRi* color image of the $\sim 6' \times 6'$ region ($\sim 170 \times 170 \text{ kpc}^2$ region at $d = 97.7 \text{ Mpc}$), shown in cyan in Figure 1(a). The Dragonfly and Subaru UDGs are marked respectively with yellow and green circles with a diameter of $20''$ ($\sim 9.5 \text{ kpc}$).

that r_e from SExtractor and GALFIT were occasionally very inconsistent; we use SExtractor's r_e for identification and GALFIT's r_e for studies of structural properties.) We excluded objects with high central concentrations (mostly high- z galaxies) by removing those whose mean SB within r_e deviates largely from the SB at r_e . This constraint, $\mu_e - \langle \mu(r_e) \rangle < 0.8$, left 1779 candidates.

The final step was removal of spurious objects by visual inspection. Most spurious detections were due to the crowding in the cluster, such as faint tidal tails and galaxy blending, as well as distant edge-on disk galaxies, artifacts at image edges, and optical ghosts. To minimize human error, the four authors separately went through all postage stamp images. After this step and removal of duplications based on their coordinates, 854 UDG candidates were left on which at least three of us agreed. The full catalog will be published by M. Yagi et al. (2015, in preparation).

4. ULTRA-DIFFUSE GALAXY CANDIDATES

The 854 UDGs candidates from Subaru are visually comparable to the Dragonfly UDGs. Figure 2 shows a sample $6' \times 6'$ field, showing the Subaru (green circles) and Dragonfly (yellow) UDGs. Their low SBs are evident compared to the surrounding galaxies, including major galaxies in the cluster and distant background ones. Their large sizes are also clear

when compared to the $20''$ diameter of the circles ($\sim 9.5 \text{ kpc}$ at $d = 97.5 \text{ Mpc}$). The greater number of detections, compared to Dragonfly, may be due to the superior seeing (less blending) and higher signal-to-noise ratio.

The majority of the 854 candidates are most likely UDGs in the Coma cluster. One of them has been spectroscopically confirmed as a cluster member (van Dokkum et al. 2015b). The control SDF field has virtually no counterparts—only 13 were left after the SExtractor-based selection, twelve of which were obvious image artifacts or tails of bright galaxies. The last one appeared to be a blend of multiple objects. Hence, contamination by non-cluster members is rare and negligible. Note, however, that some negligible number of contaminations might still exist. For example, the third object from the top in Figure 2 may be a background spiral galaxy. Despite this significantly increased sample, the UDGs are still a minor population in the Coma cluster (Yamanoi et al. 2012).

In the literature, we found that many of the Subaru UDGs had been cataloged, albeit as more compact objects; Adami et al. (2006a) found 248 of 309 that lay within their coverage, and Yamanoi et al. (2012) 232 of 240. Among them, only 17 were classified as low SB galaxies (Adami et al. 2006b). Their large extents and low SBs were revealed for the first time in this study. We note that 11 out of the 12 Dragonfly UDGs within their field were also cataloged in Adami et al. (2006a), but none were classified as low SB (Adami et al. 2006b).

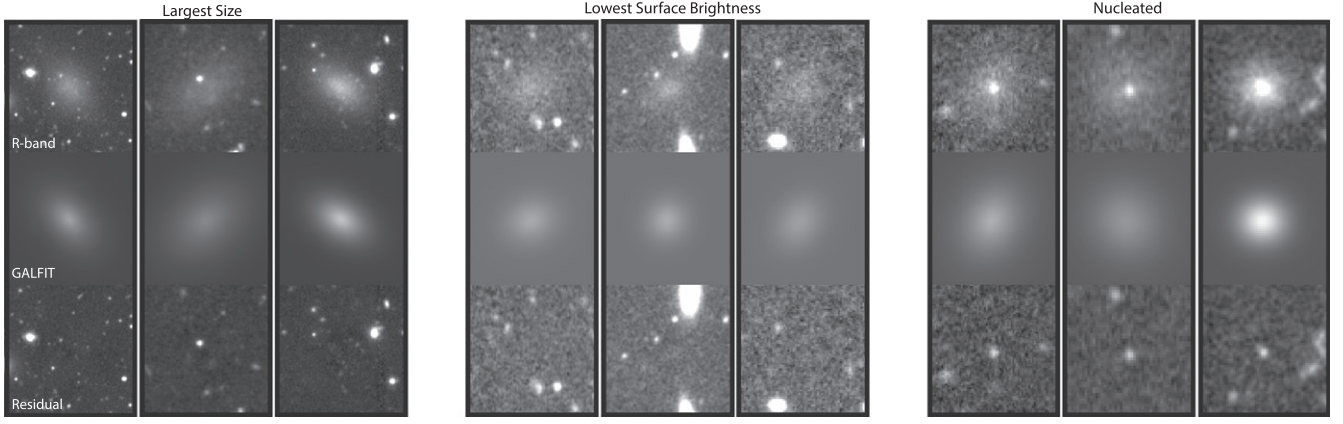


Figure 3. Examples of GALFIT results drawn from the groups of largest-size UDGs, lowest surface-brightness UDGs, and nucleated UDGs.

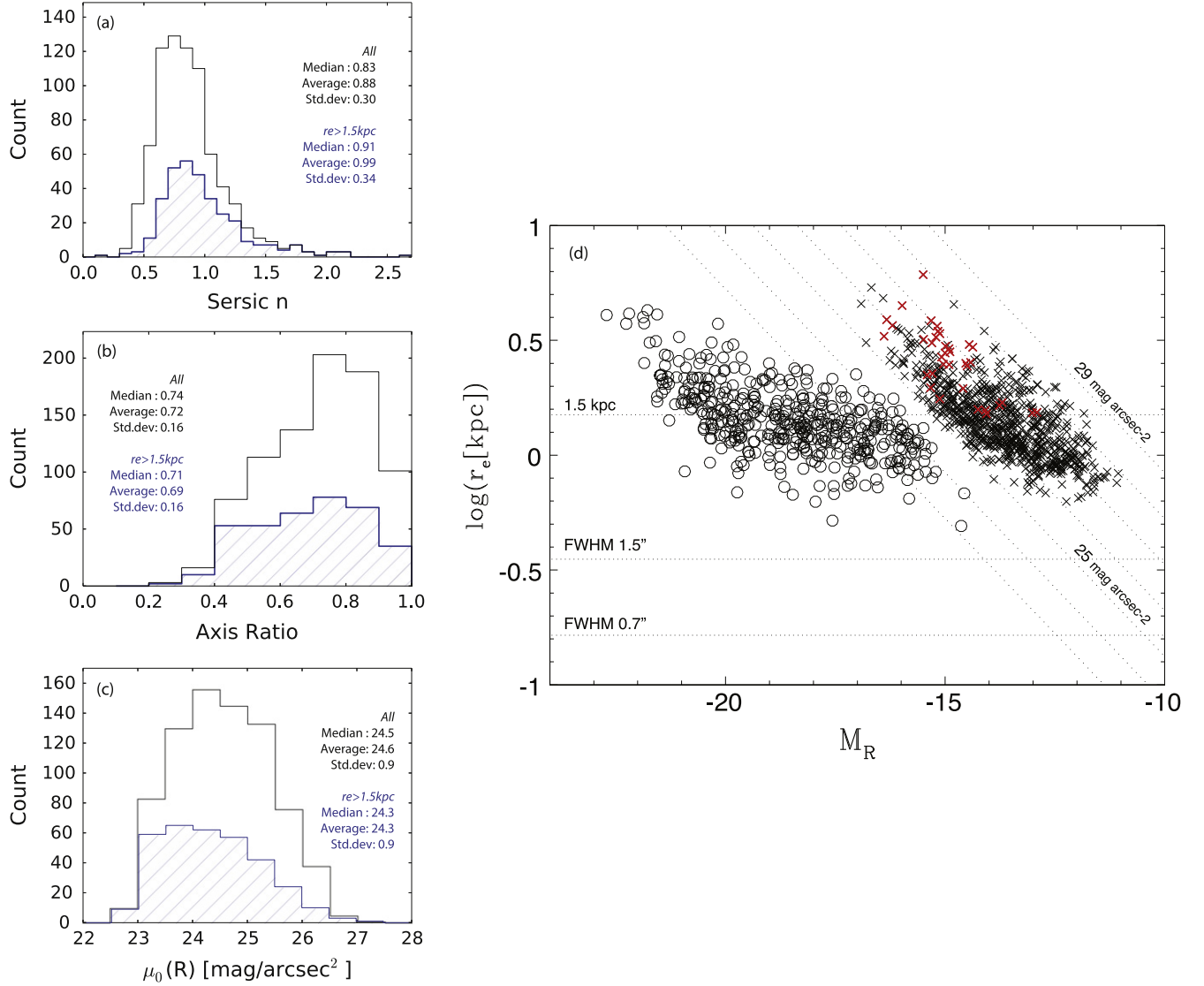


Figure 4. Structural properties of UDGs. (a) Histograms of Sérsic index n , (b) axis ratio b/a , and (c) central SB $\mu_0(R)$ with their medians, averages, and standard deviations. Black lines are for all 854 UDGs, while blue are for 332 MW-sized UDGs alone. (d) Effective radius vs. R magnitude. The parameters of the UDGs (crosses; red for the Dragonfly UDGs) are derived with GALFIT. Normal galaxies (circles)—spectroscopically confirmed Coma members (Mobasher et al. 2001)—are also plotted for comparison (from Komiyama et al. 2002, with the conversion $R(\text{AB}) - R(\text{Vega}) = 0.21$). Dotted, diagonal lines show constant SBs (μ_k s) from 23 to 29 mag arcsec⁻² with a 1 mag arcsec⁻² interval for the case of an exponential profile (note $\mu_0 = \mu_k - 1.82$ for $n = 1$). The gap between the normal galaxies and UDGs is due to selection effects. Horizontal lines show r_e of PSF with an FWHM of 1.5 arcsec (Komiyama et al. 2002) and an FWHM of 0.7 arcsec (this study).

5. STRUCTURAL PARAMETERS

The GALFIT package was used to measure the structural parameters of the Subaru UDGs. The fits were made with a single Sérsic profile (Sérsic 1968) with sky background fixed. We used SExtractor’s segmentation images to mask surrounding objects. Seventy-nine of the 854 required additional manual masks to exclude a bright compact object(s) within their boundaries—interestingly, 67 of these appear to have compact nuclei at their centers. We judged the fits acceptable based on the goodness-of-fit ($\chi^2_\nu < 1$; 75 objects were thus excluded) and consistency between GALFIT and SExtractor measurements (r_e from GALFIT and SExtractor consistent within a factor of 3; 11 removed). In this section, we use the sample of 768 objects with good GALFIT results, out of which 332 have GALFIT’s $r_e > 1.5$ kpc (i.e., MW-sized UDGs as defined in van Dokkum et al. 2015a). We refer to the former full set of galaxies as UDGs, and the latter as MW-sized UDGs. Figure 3 shows some examples of GALFIT results for the UDGs of lowest SB, of largest-size, and with a compact nucleus.

Figures 4(a)–(c) show histograms of Sérsic index (n), axis ratio (b/a), and central SB ($\mu_0(R)$). For both UDGs and MW-sized UDGs, their average Sérsic indices $\langle n \rangle = 0.9$ – 1.0 indicate an exponential profile. The distributions of axis ratio, as well as its average $\langle b/a \rangle = 0.7$ – 0.8 , are skewed toward a large value; therefore, this UDG sample does not consist of randomly oriented thin-disk galaxies in a statistical sense (which would skew their distribution toward a low b/a). The $\mu_0(R)$ ranges around 23–26 mag arcsec $^{-2}$. These results are consistent with van Dokkum et al. (2015a) when the difference in the adopted bands, SDSS g and Subaru R , is taken into account (roughly $g - R \sim 0.8$ mag for the red-sequence in Coma).

The Subaru UDGs are likely an extension of normal and dwarf galaxy populations and are not, on their own, a distinct population. Figure 4(d) shows the properties of the UDGs (crosses) with respect to normal galaxies in Coma (circles; from Komiyama et al. 2002). The apparent R magnitude of the UDGs is 18–24 mag, indicating an absolute magnitude of about -12 to -16 mag at the Coma distance. The smallest and faintest UDGs (e.g., $r_e < 1$ kpc and $M_R < -12$ in Figure 4(c)) overlap with the largest and brightest dwarf galaxies and share some properties in common with them (e.g., the exponential profile, nucleated population; see Tolstoy et al. 2009; McConnachie 2012; Boselli & Gavazzi 2014). Dotted lines represent constant SBs (μ_k s) from 23 to 29 mag arcsec $^{-2}$ with a 1 mag arcsec $^{-2}$ interval, assuming an exponential profile. The average SB of the Subaru UDGs is distributed from about 25 mag arcsec $^{-2}$ (i.e., a cutoff due to the selection) to 28 mag arcsec $^{-2}$ (due to the detection limit; this lower boundary is lower than the pix-to-pix detection limit, because the UDGs are extended).

The absolute magnitudes correspond to stellar masses of $1 \times 10^7 M_\odot$ – $5 \times 10^8 M_\odot$ if we adopt a mass-to-light ratio of $M/L_R \sim 3$. Note the M/L_R varies by a factor of ~ 2 for ages of 4–12 Gyr and metallicities between 0.2–1.0 solar based on calculations using Starburst99 (Leitherer et al. 1999), a single starburst, and a Kroupa initial mass function.

6. A PASSIVELY EVOLVING POPULATION

The UDGs are distributed widely over the entire area of the cluster with a concentration toward its center (Figure 1(b)).

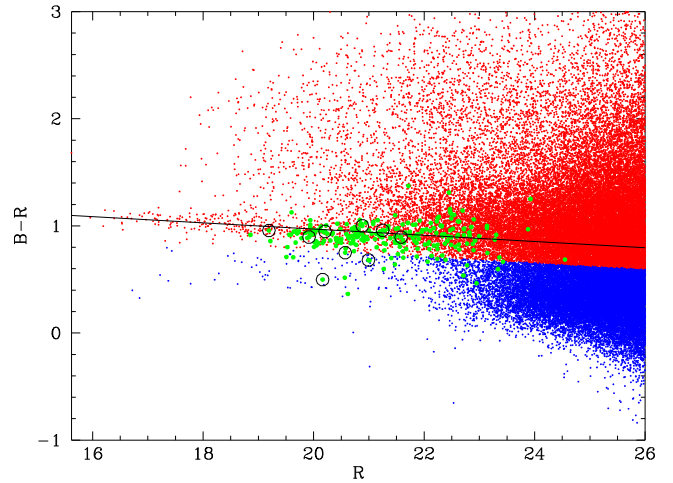


Figure 5. Color-magnitude diagram using B and R band photometry. The green points are 232 UDGs observed both in B and R with Subaru (the Dragonfly UDGs are circled), and the red and blue are red and blue galaxies taken from the Coma field of Yamanai et al. (2012) which includes cluster members as well as background galaxies. Due to saturation, most giant galaxies are not included, but the red-sequence is evident. The UDGs clearly follow the red-sequence population of the Coma cluster.

This spatial correlation also supports the assumption that the great majority are cluster members. Figure 1 nearly covers the virial radius of the cluster (~ 2.8 Mpc; $\sim 1^\circ 7$; Kubo et al. 2007), and reveals their relatively symmetric distribution around the center with a potential elongation toward the south west (roughly toward NGC 4839). This symmetric, wide-spread distribution may indicate their long history within the cluster.

The UDGs closely follow the red-sequence of a passively evolving galaxy population on the color-magnitude diagram. 232 UDGs are in the catalog of Yamanai et al. (2012) with both B and R photometry. Figure 5 shows their distribution (green). The comparison data (red and blue) show other cluster member galaxies, as well as background galaxies, and are also from Yamanai et al. (2012). The red-sequence is evident, and the solid line is a fit by Yamanai et al. (2012). Clearly, the UDGs lie along this red-sequence, and their $B-R$ colors are around 0.8–1.0 mag. This is similar to the trends found among dwarfs and low SB galaxies in clusters (Adami et al. 2009; Ulmer et al. 2011; Lieder et al. 2012).

No significant $H\alpha$ excess was found in UDGs. 217 UDGs are within the Subaru $H\alpha$ coverage (yellow in Figure 1(a)), which was designed to detect faint $H\alpha$ emission around Coma member galaxies (Yagi et al. 2010). Therefore, the UDGs are not forming stars at the current epoch, as expected for passively evolving galaxies.

7. DISCUSSIONS

We report the discovery of ~ 1000 UDGs in the Coma cluster, about 40% of which are MW-sized. The new UDG sample is by no means complete, but already contains 10–20 times more than previously known (van Dokkum et al. 2015a). None of the UDGs show a signature of tidal distortions; this is our selection criteria, but indicates that this sample of UDGs are not likely recently disrupted tidal debris.

The UDG population, compared to brighter galaxies, is elevated in the Coma cluster, although a small number of large, low-SB galaxies are known in the field (Dalcanton et al. 1997; Burkholder et al. 2001; Impey et al. 2001). If the UDG-to-

brighter galaxy number ratio in Coma were common in the field, the expected UDG population would be implausibly large, $\gtrsim 10^5$ within 100 Mpc of the MW. To obtain this rough estimate, we used, as a reference, galaxies in the SDSS (Ahn et al. 2012) within $16 < r < 17$ mag ($-19 < M_r < -18$ in absolute magnitude) at the cluster's redshift of 0.013–0.033 (Mobasher et al. 2001). The number of reference galaxies in the field was estimated from the luminosity function of Blanton et al. (2001). The estimated number in the field, $\gtrsim 10^5$, is crude, but seems too large compared to the small number discovered so far. The cluster environment must play a role in their formation and evolution.

van Dokkum et al. (2015a) speculated that the MW-sized UDGs might be a dark matter (DM) dominated population in order for them to survive in the strong tidal field around the cluster core. In fact, the Dragonfly UDGs spatially avoided the central $r \sim 300$ pc region as if the ones there had been tidally disrupted; this apparent disruption was used to constrain the DM fraction (as large as $\gtrsim 98\%$; van Dokkum et al. 2015a). Surprisingly, we found UDGs even closer to the core (Figure 1(b)), and the closest one is MW-sized only about $3'$ (~ 85 kpc) away on the sky. Eleven UDGs were found within a radius of $5'$ (~ 141 kpc). These detections were, of course, not complete due to the high background emission there, and their apparent proximity may result from a chance coincidence along a line of sight. If any of them are within ~ 100 – 150 kpc from the core, an even larger DM mass than the estimate by van Dokkum et al. (2015a) is necessary, and the baryon fraction within a tidal radius should be $\lesssim 1\%$. This is below the cosmic average, and therefore, the baryons must have been removed from the possibly very deep DM potential.

The possible removal of the gas, and quenching of star formation (SF), are consistent with their red color and clustering in Coma (indicating their longevity within the cluster). The red-sequence can be produced by a metallicity-sequence if galaxies have been evolving passively since SF was quenched (Kodama & Arimoto 1997). Physical processes often suggested for the quench include (see Boselli & Gavazzi 2014 for review): (a) blow out of gas due to galactic winds from supernovae or AGN activities (Dekel & Silk 1986; Arimoto & Yoshii 1987), (b) ram-pressure stripping (Gunn & Gott 1972), (c) tidal-interaction and harassment (Moore et al. 1996), and (d) starvation due to the cessation of gas infall (Larson et al. 1980). The elevated population in the cluster indicates that environmentally driven mechanisms, such as (a), (b), and (c) are the most likely solutions ((a) may occur if SF is induced by (b) or (c)).

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