The Subaru Survey of Ultra Diffuse Galaxies

Z~0!

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Collaborators
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Discovery of MW-sized, Ultra-Diffuse Galaxies (UDGs)

Large Low Surface Brightness Galaxies

van Dokkum et al. 2015a

47 in the direction of the Coma cluster

Dragonfly Telephoto Array

Commercially available
CANON 400mm lenses

Specially-built for LSB objects

Abraham & van Dokkum 2014

Coma cluster: $R_{\text{virial}} \sim 1.7$ deg $\sim 2.8$ Mpc
Members of the Coma cluster? - Probably

As large as MW in size, but only 1/100-1/1,000 of MW’s stellar mass

van Dokkum et al. 2015a

$r_e \sim 1.5-4.5$ kpc
$\mu_0(g) \sim 24-26$ mag/arcsec$^2$

$r_e = 1.5$ kpc
(resolution limit)
How do they survive in the strong tidal field of Coma? Ultra Dark Matter-rich Galaxies?

How do these puffy galaxies survive in the cluster’s tidal field?

→ Massive Dark Halos?

The Coma center: 0.89° x 0.70° (1.6Mpc x 1.2Mpc)

For survival in tidal force

\[ m_{total} > 3M_{\text{cluster}} \left( \frac{r_{tide}}{R_{\text{cluster}}} \right)^3 \]

\[ r_{tide} = 2r_e = 6\text{kpc} \]
\[ R_{\text{cluster}} = 300\text{kpc} \]

Cluster mass model from Newman et al. (2013)

UDGs avoiding the central 300 kpc

\[ m_{DM} / m_{total} > 98\% \]
Spectroscopic Confirmation of Membership
Keck LRIS spectroscopy of one Dragonfly UDG (mg=19.4)
Quick inspection of Subaru data in hand
Similar galaxies very abundant

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, \( r_e > 0.8 \) \( e_e N N \), 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 Dragon fly UDGs. Figure 2 shows a sample 66'x6' region, showing the Subaru (green circles) and Dragon fly 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 (9.5 kpc_97.5 Mpc). The greater number of detections, compared to Dragon fly, 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 Dragon fly UDGs within their field were also cataloged in Adami et al. (2006a), but none were classified as low SB (Adami et al. 2006b).
Dragonfly UDG vs Subaru UDG

that result from SExtractor and GALFIT were occasionally very inconsistent; we use SExtractor's results for identification and GALFIT's results 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, $r_e \approx 0.8 N N_e$, 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).

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Subaru Archival Data

Supreme-Cam (Subaru Prime Focus Camera)
FOV: 34x27 arcmin²

Reduced using a larger grid (51.7") for sky subtraction
Identification - Tuned parameters to find all Dragonfly UDGs

- **SExtractor**
  - Detection threshold of 27.3 mag arcsec\(^{-2}\)
- **Remove spurious detections** - astronomical objects should have
  - FLAGS < 4
  - PETRO_RADIUS > 0
  - 2,627,495 candidates (~30% overlap regions of adjacent frames)
- **Constraints on R-mag and size**
  - 18 < MAG_AUTO < 26
  - FWHM(Gaussian) > 4’’ (~1.9kpc)
  - 7362 candidates
- **UDGs should have**
  - Large: \(r_e > 1.5’’\) (~0.7kpc)
  - Low surface brightness: \(<\mu(r_e) > 24\)
  - Not centrally-concentrated: \(\mu(r_e) - <\mu(r_e) < 0.8\)
  - 1779 candidates
- **Eye-based removal**
  - Optical ghosts & image edges
  - Tidal tails & galaxy blending
  - 854 objects
Subaru UDGs
854 found (132 shown here)
Internal Structures

GALFIT → Round, smooth, exponential, not disturbed

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 $R_0$ 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 $R_{AB} - R_{Vega} = 0.21$). Dotted, diagonal lines show constant SBs ($n_s$) from 23 to 29 mag arcsec$^{-2}$ with a 1 mag arcsec$^{-2}$ interval for the case of an exponential profile (note $1.8^{20}e^{20n}$ 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).
Size-Luminosity

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Koda et al. 2015b

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UDGs along the Red-Sequence
Passively-evolving stellar population

Green
Subaru UDGs with B & R measurements

Red & Blue
Objects in the field of Coma, including background objects.

Koda et al. 2015b
Spatial Distribution in the Coma cluster

Centrally-concentrated and relaxed
→ Majority - very likely long-time Coma cluster members

Koda et al. 2015
Radial Distribution in the Coma cluster

Follows the distribution of normal galaxies in Coma

Normal galaxies from SDSS
- \( r < 16 \text{mag} \) (\( M_r < -19 \))
- \( 0.015 < z < 0.030 \)

Yagi et al. 2016
Survival in the Tidal Field of the Coma cluster
Ultra Dark matter-rich Galaxies?

For survival in tidal force

$$m_{\text{total}} > 3 M_{\text{cluster}} \left( \frac{r_{\text{tide}}}{R_{\text{cluster}}} \right)^3$$

$$r_{\text{tide}} = 2r_e = 6\text{kpc}$$
$$R_{\text{cluster}} = 300\text{kpc}$$
Cluster mass model from Newman et al. (2013)

$$m_{\text{DM}} / m_{\text{total}} > 98\%$$
van Dokkum et al. 2015a

We found
11 Subaru UDGs within $R_{\text{cluster}}=5'$ (140kpc)
→ Ultra Dark Galaxies?

How do they form?
Baryon fraction much less than the Cosmic average (~15%)
→ Gas removed
• galactic wind?
• ram-pressure?
• tidal-interaction?
• starvation?
UDGs in Previous Catalogs?
Their Cores - YES; Whole extents - NO

They were cataloged as small galaxies

- Adami et al. (2006a,b)’s study
  - 248 out of 309 Subaru UDGs in their field
    - Only 11 out of the 248 classified as LSB galaxies
  - 11 out of 12 Dragonfly UDGs in their field

- Yamanoi et al. (2012)’s study
  - 232 out of 240 Subaru UDGs in their field
UDGs in Other Environments

- **Clusters**
  - Virgo - Mihos et al. 2015
  - Fornax - Munoz et al. 2015
  - 8 Abell clusters - van der Burg et al. 2016
  - Pisces-Perseus - Martinez-Delgado et al. 2016

- **Groups**
  - NGC253 - Toloba et al. 2016
  - NGC3413, NGC5371 - Makarov et al. 2015
  - NGC5485 - Merritt et al. 2016

- **Large scale structures**
  - Roman & Trujillo 2016
### UDGs in Clusters & Field from previous LSB studies

Compilation by Yagi - see Yagi et al. (2016) for details and notes

<table>
<thead>
<tr>
<th>Publication</th>
<th>Environment</th>
<th>#</th>
<th>Criterion (r_e &gt; 1.5kpc)</th>
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</thead>
<tbody>
<tr>
<td>Impey et al. (1988)</td>
<td>Virgo Cluster</td>
<td>11</td>
<td>μ0 &gt; 24 V(Vega)</td>
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<td>Binggeli &amp; Jerjen (1998)</td>
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<td>Abell 1367</td>
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<td>McConnachie (2012)</td>
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<td>Buzzoni et al. (2012)</td>
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<td>van Dokkum et al. (2015a)</td>
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<td>μ0 &gt; 24 g</td>
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<td><strong>Our study</strong></td>
<td><strong>Coma Cluster</strong></td>
<td><strong>271</strong></td>
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<td><strong>More in recent astro-ph</strong></td>
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<td>Bothun et al. (1987)</td>
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<td>Hunter &amp; Elmegreen (2006)</td>
<td>Field</td>
<td>6</td>
<td>μ0 &gt; 24 V</td>
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</table>
How did they form? — two possible origin suggested.

**Failed M$_*$ Galaxies** - Little baryon in MW-mass halo (van Dokkum et al. 2015)
- Ram-pressure stripping (Yozin & Bekki 2015)
- Galaxy collisions (Baushev 2016)

**Extreme Dwarf Galaxies**
- High spin tail of galaxies in $\Lambda$CDM (Amorisco & Loeb 2016)
- Extremely prolonged stellar feedback (di Ciento et al. 2016)

Environmental dependence? NO/LITTLE

Mixture of the two or more populations? (Merritt et al. 2016)
Measurements of Kinematics

7 globular clusters around VCC 1287 in Virgo (Beasley et al. 2016)

\[ \sigma = 33^{+16}_{-10} \text{ km/s within 8.1 kpc} \]
\[ M_{\text{dyn}}(<8.1 \text{kpc}) = 4.5 \pm 2.8 \times 10^9 M_\odot \]
\[ M_{200} \sim 8 \times 10^{10} M_\odot \]

\[ \sigma = 47^{+8}_{-6} \text{ km/s} \]
\[ M_{\text{dyn}}(<r_{1/2}) = 0.7^{+0.3}_{-0.2} \times 10^{10} M_\odot \]
\[ r_{1/2} = 4.6 \pm 0.2 \text{kpc} \]
\[ M_{\text{tot}} \sim 10^{12} M_\odot \text{ (like MW halo)} \]

H\(\alpha\) absorption in Dragonfly 44 with Keck (van Dokkum et al. 2016)

Caveat (Intrinsic FWHM)
F-star: \(~500\text{km/s}\)
A-star: \(~1,000\text{km/s}\)
Globular Cluster Counts
Using the $M_{\text{halo}}$-$M_{\text{GCs}}$ ($N_{\text{GC}}$) relation

- **Massive halos**
  - V1287 in Virgo (Beasley et al. 2016a)
  - Dragonfly 44 (van Dokkum et al. 2016)

- **Dwarf-mass halos**
  - Dragonfly 17 (Peng & Lim 2016; Beasley et al. 2016b)
  - Subaru UDGs (Amorisco, Monachesi & White 2016)
Intrinsic Shape from Statistical Analysis ➔ Prolate

Axis ratio
Intrinsic: $\beta = c/a$
Random projections
Apparent: $q$

Model

Model vs Obs

Oblate model overpredicts round UDGs
Observations

Oblate

Prolate model explains obs.
Observations

Prolate model

➡ Anisotropic vel dispersion
➡ Interactions?

Prolate
Preferentially Oriented toward Cluster Center

\[ b/a < 0.85 \rightarrow 564 \text{ UDGs} \]

\[ \varphi = \text{angle w.r.t the direction toward the cluster center} \]

Environmental Dependence

Entire cluster

Outer >1.3 Mpc - random orientation

Middle: 1.3 > R > 0.7 Mpc

Inner <0.7 Mpc - toward center

Two-bin test: \( \varphi < 45 \) vs \( \varphi \geq 45 \)

\( \rightarrow \) p-value \approx 0.04\% for random orientations

No alignment detected for normal galaxies in our analysis of SDSS DR7.

Yagi et al. 2016
(\# of UDGs) \propto \text{(Cluster mass)}

Consistent analysis of 8 Abell clusters (van der Burg et al. 2016)
+ Several other measurements (caveat: heterogeneous selection criteria)

SB \sim 1-2 \text{ mag brighter than Subaru UDGs}

Need larger sample, variety of environments, consistent analysis
Environmental Dependence
Subaru/HSC Imaging of clusters

Hyper Suprime-Cam
FoV~1.5degree
Environmental Dependence
Subaru/HSC Imaging of clusters

8 clusters observed in r-band

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>$R$ [$m_3, m_3+2$]</th>
<th>$N_{gal}$</th>
<th>$d_A$ (Mpc)</th>
<th>$M_{200}$ [$10^{14} M_\odot$]</th>
<th>$R_{200}$ (Mpc)</th>
<th>$D_{200}$ (deg)</th>
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<td>0</td>
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<td>A1060 (Hydra)</td>
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<td>r, (g)</td>
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<td>A1656 (Coma)</td>
<td>0.023</td>
<td>1008</td>
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<td>96</td>
<td>11.54</td>
<td>2.14</td>
<td>2.55</td>
<td>r, g</td>
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</tbody>
</table>
The Coma Cluster

Virial diameter ~ 2.6deg (4.2Mpc)
• Census of UDGs including the faintest, most fragile UDGs
• Environmental dependence
  • between clusters
  • centers to beyond viral radii
• Detections of surrounding GCs
• Connections to normal & dwarf galaxies in param. space
Virial diameter ~ 2.3 deg (3.7 Mpc)

~ 0.9 deg (1.7 Mpc)

+ 4 more clusters observed
Summary: UDGs

- **Internal properties**
  - As large as MW, but 1/100-1/1,000 of MW’s stellar mass
  - Round, smooth, exponential, not disturbed
  - Red-sequence, passively-evolving stellar population

- **Distribution in the Coma cluster**
  - Symmetric around the cluster center, similar to normal galaxies

- **Failed M$_*$ galaxies? or Extreme dwarfs?**
  - Velocity dispersion measurements — Failed M$_*$?
  - Globular cluster counts — Failed M$_*$? or Extreme dwarfs?
  - Prolate shapes — External perturbations?
  - Preferentially oriented toward the cluster center — External perturbations?

- **New Subaru HSC survey of local clusters of galaxies**
  - Census including faintest, most fragile UDGs
  - Larger sample, variety of environments, and consistent analysis