Searching for shadows in the dark:
Discovering Low Surface Brightness Galaxies in the DES data

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LIneA webinar

(arXiv:2006.04294)

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Low Surface Brightness Galaxies (LSBGs)

**Definition**: Diffuse galaxy with a surface brightness at least one magnitude fainter than the ambient sky.

Dark Sky: \( \mu \sim 22 \text{ mag arcsec}^{-2} \)

We are interested in objects > 5x fainter: \( \mu > 24 \text{ mag arcsec}^{-2} \)

- LSBGs are difficult to detect.
- Difficult to study over a wide sky area and in different environments (clusters vs field).
- Test models of galaxy formation and the galaxy—halo connection.
- Renewed interest in Ultra Diffuse Galaxies (UDGs) defined as LSBGs with large physical sizes.
Part I: The “Past”

Malin 1, from HST
Visibility of galaxies

It is well known that our counts of galaxies could be seriously biased by selection effects, largely determined by the brightness of the night sky. To illustrate this, suppose the Earth were situated near the centre of a giant elliptical galaxy, then the mean surface brightness of the sky would appear some 8–9 mag brighter than is observed from our position in the Galaxy (~ 23 V mag (arc s)^{-1} looking toward the galactic pole, discounting atmospheric and zodiacal contributions^{1,2}). Optical astronomers would then find extragalactic space an empty void; spiral and irregular galaxies would be quite invisible and all they would easily detect of galaxies would be the core regions of ellipticals very similar to their own. They would be blinded to much of the Universe by the surface brightness of their parent

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**Origins**

Mike Disney 1976

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**Malin 1 1986**

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**DISCOVERY OF A HUGE LOW-SURFACE-BRIGHTNESS GALAXY: A PROTODISK GALAXY AT LOW REDSHIFT?**

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**ABSTRACT**

We report on the accidental discovery of an extremely large, extremely H i-rich low-surface-brightness galaxy located at a redshift of z = 0.083. Its nuclear spectrum exhibits broad, low-level emission lines. Surface photometry at V indicates the presence of a bulge component and a very extended disk, with scale length of \( \sim 45' \) (55 kpc for \( H_0 = 100 \)) and with central surface brightness of \( V(0) \sim 25.5 \) mag arc sec\(^{-2} \). The total amount of H i is at least \( 1.0 \times 10^{11} \, M_\odot \). This amount of H i is at least 5 times more H i than any spiral galaxy previously observed. If disk formation is a quiescent process, then it is likely that we have caught a disk in the process of formation. We also point out that the properties of this disk are

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**Fig. 1** Central surface brightnesses \( S_\nu \) of exponential disks of spiral and irregular galaxies taken from Freeman^{4} plotted against galactic type. Filled circles show most reliable data, open circles less reliable. Some of the original points, subsequently shown to be incorrect (K. C. Freeman, personal communication) have been removed. (--- --- ---) is at 21.65 B mag (arc s)^{-1}.
However, LSB regime largely unexplored

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Expected to be dominated by LSBGs

Dalcanton+ 1997, arXiv: 0705088

Galaxy-Halo connection

Dalcanton+ 1997, arXiv: 0705088

Wechsler & Tinker 2018
Renewed interest in UDGs: A special class of LSBGs

Ultra Diffuse Galaxies (UDGs): LSB + extended (physical radius)

Surf. brightness: \( \mu \gtrsim 24 \text{ mag arcsec}^{-2} \)

Effective radius: \( R_{\text{eff}} > 1.5 \text{ kpc} \)

Size \sim \text{Milky Way}

Stellar content \sim 1000 \text{ times less}

ABSTRACT

We report the discovery of 47 low surface brightness objects in deep images of a \( 3^\circ \times 3^\circ \) field centered on the Coma cluster, obtained with the Dragonfly Telephoto Array. The objects have central surface brightness \( \mu(g, 0) \) ranging from 24 – 26 mag arcsec\(^{-2}\) and effective radii \( r_{\text{eff}} = 3'' - 10'' \), as measured from archival Canada France Hawaii Telescope images. From their spatial distribution we infer that most or all of the objects are galaxies in the Coma cluster. This relatively large distance is surprising as it implies that the galaxies are very large: with \( r_{\text{eff}} = 1.5\text{kpc} - 4.6\text{kpc} \) their sizes are similar to those of \( L^* \) galaxies even though their median stellar mass is only \( \sim 6 \times 10^7 M_\odot \). The galaxies are relatively red and round, with \( (g - i) = 0.8 \) and \( (b/a) = 0.74 \). One of the 47 galaxies is fortuitously covered by a deep Hubble Space Telescope ACS observation. The ACS imaging shows a large spheroidal object with a central surface brightness \( \mu_{275} = 25.8 \text{ mag arcsec}^{-2} \), a Sersic index \( n = 0.6 \), and an effective radius of \( 7'' \), corresponding to 3.4 kpc at the distance of Coma. The galaxy is not resolved into stars, consistent with expectations for a Coma cluster object. We speculate that these “ultra-diffuse galaxies” (UDGs) may have lost their gas supply at early times, possibly resulting in very high dark matter fractions.

Van Dokkum+15, arXiv: 1410.8141

Dragonfly Telephoto Array

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Most UDGs discovered in clusters

No signs of tidal effects

Using stellar kinematics: \( M_h \sim 10^{12} M_\odot \)

Are UDGs failed L* galaxies?
In such host masses, galaxy formation \( \rightarrow \) effective

Dragonfly 44, Coma Cluster, Van Dokkum+16, arXiv: 1606.06291

Other observations: \( M_h \sim 10^{10} M_\odot \)

UDGs “normal” UDG dwarfs?
Can be explained if:
• Formed late
• High spin

(Amorisco & Loeb, 2016
Rong et. al. 2017,
Conselice 2018)

Rong+17, arXiv: 1703.06147

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State of the Art in Wide-Field Surveys searches for LSBGs: Hyper-Supreme-Cam (HSC)

(Greco+18, arXiv 1709.04474)

Analysis of the first \(\sim 200 \text{ deg}^2\) LSBGs

Depth, \(i \sim 26\) (point source)

781 LSBGs

Signs of spatial clustering for red LSBGs

Dwarf spheroidals and UDGs to gas-rich irregulars and giant LSB spirals
Part II: The Present

LSBGs in DES
The Dark Energy Survey (DES)

- Optical - Near IR survey

- 4m Blanco Telescope, CTIO, Chile

- \( \sim 5000 \text{ deg}^2 \) footprint

- Five photometric bands: \( g, r, i, z, Y \)

  (Median limiting magnitudes 
  \( g = 23.52, r = 23.10, i = 22.51, z = 21.81, \)
  \( Y = 20.61 \))

- 758 observing nights, \( \sim 6 \) years, last observations: Jan 9th, 2019

- \( > 300M \) objects (closer to \( \sim 400M \) objects)
A Catalog of LSBGs in 4 steps

From the first three years (Y3) of DES data
**Step 1:** Catalog cuts on the SExtractor-derived parameters

- Mean surface brightness: \( 24.3 < \bar{\mu}_{\text{eff}}(g) < 28.8 \) mag arcsec\(^{-2}\)

- Flux radius: \( r_{1/2}(g) > 2.5'' \)

- + star/galaxy separation cuts, ellipticity, color cuts

(Cuts motivated by a similar analysis on HSC Greco et. al. 2018, arXiv: 1709.04474)

413,608 candidates

413,608 LSBGs?
~ 90% false detections

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Step 2: Machine Learning Classification

Problem: Training set?

Solution: Create a set of objects with labels determined by visual inspection:

- 7 4 x 4 degree regions
- 7760 objects in total
- 640 true LSBGs
**SVM classifier**

Select classifier with minimum False Negative Rate
- completeness over purity

Completion: \(~90.1\%\)

Purity: \(~56.1\%\)

**False Negatives**

40,820 candidates

**Feature importance (RF classifier)**
Step 3: Visual Inspection

Reject remaining false positives

21,286 Galaxies
Step 4: Galfit modeling and extinction correction

- Recalculate photometric (magnitudes) and structural (eff. radius, Sérsic index) parameters using Galfit

- Correct for Galactic extinction based on the position of each object and the E(B-V) map (Schlegel et. al. 1998)

- Perform cuts based on the updated parameters

Final Catalog: 20,977 radially extended LSBGs
How efficient are we? Comparison with external dwarf catalogs

Next Generation Fornax Survey

DECam, ~ 30 deg² around Fornax, ~2 mag deeper than DES

643 dwarf galaxies:
- 181 nucleated
- 462 non-nucleated

(Eigenthaler et al. 2018; Ordenes-Briceño et al. 2018)

R. Munoz et. al., 1510.02475

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Use the full DES catalog around Fornax

Apply the different cuts, match with the NGFS catalog

**matching radius: 3”**

~ 8 objects within NGFS footprint, detected by us but not by them

### Table 1. Detection efficiency around the Fornax Cluster

<table>
<thead>
<tr>
<th>Cuts applied</th>
<th>All galaxies</th>
<th>Nucleated</th>
<th>Non-nucleated</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cuts</td>
<td>76.6%</td>
<td>89.5%</td>
<td>71.6%</td>
</tr>
<tr>
<td>Surface brightness cut only</td>
<td>61.7%</td>
<td>54.7%</td>
<td>64.4%</td>
</tr>
<tr>
<td>Angular size cut only</td>
<td>56.4%</td>
<td>81.8%</td>
<td>46.4%</td>
</tr>
<tr>
<td>Both cuts</td>
<td>42.4%</td>
<td>48.6%</td>
<td>39.9%</td>
</tr>
<tr>
<td>Final result (After ML/Vis. inspection)</td>
<td>36.8%</td>
<td>43.6%</td>
<td>34.1%</td>
</tr>
</tbody>
</table>
Exploring the Sample

Colors
(stellar populations)

Bimodality in $g-i$ - $g-r$ color-color space

Split into blue and red LSBGs

Separation: GMM in $g-i$

$$g - i = 0.59$$

13,829 LSBGs

7,148 LSBGs
Morphological differences

Blue LSBGs

Red LSBGs
Distribution of structural/photometric parameters

Blue galaxies brighter

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Spatial distribution: blue LSBGs
Spatial distribution: red LSBGs

7,148 LSBGs
Spatial distribution: Clustering properties quantified

Overdensities as a function of (angular) scale quantified through the 2pt function:

$$w(\theta) = \langle \delta_g(\hat{n})\delta_g(\hat{n} + \theta) \rangle$$
Spatial distribution: Comparison with HSB catalogs

Two samples:

- A HSB sample from DES data, with:
  \[ 20.0 < \bar{\mu}_\text{eff}(g) < 22.0 \text{ mag arcsec}^2 \]
  and the same magnitude distribution

- A sample from the 2MPZ catalog
  \[ 19.0 < \bar{\mu}_\text{eff}(g) < 23.0 \text{ mag arcsec}^2 \]

2MPZ catalog (Bilicki+14)
Local (peak z~ 0.07) accurate photo-z sample (\(\sigma \sim 0.015\))
Spatial distribution: Comparison with HSB catalogs

Auto-correlation 2pt functions

Cross-correlation 2pt functions

Apply redshift cuts

extended LSBGs -> low redshifts
Associating peaks with clusters

KDE map of the LSBG distribution with a 0.3 deg kernel width

88 peaks $5\sigma > \text{mean}$

Associating with clusters, groups and large galaxies provides: distance information!
# Associating peaks with clusters

## 88 peaks $5\sigma > \text{mean}$

- Abell: 32
- NGC: 18
- RXC: 10
- 2Mass: 12
- No assoc: 16

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### Table 2. Characteristics of the ten most prominent density peaks and their associations

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>Peak Coordinates (deg, deg)</th>
<th>Best Association</th>
<th>Association Coordinates (deg, deg)</th>
<th>Redshift</th>
<th>Distance (Mpc)</th>
<th>Number of Clusters ($N(&lt;0.5')$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(21.5012, -1.4286)</td>
<td>Abell 194</td>
<td>(21.4200, -1.4072)</td>
<td>0.018</td>
<td>75.07 ± 5.26</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>(54.9388, -18.4712)</td>
<td>RXC J0340.1-1835</td>
<td>(55.0475, -18.5875)</td>
<td>0.0057</td>
<td>23.41 ± 1.64</td>
<td>45</td>
</tr>
<tr>
<td>3</td>
<td>(18.4983, -31.7043)</td>
<td>Abell S141</td>
<td>(18.4758, -31.7519)</td>
<td>0.020</td>
<td>84.80 ± 5.94</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>(9.8887, 3.1829)</td>
<td>NGC 199</td>
<td>(9.8882, 3.1385)</td>
<td>0.0153</td>
<td>62.81 ± 4.41</td>
<td>39</td>
</tr>
<tr>
<td>5</td>
<td>(17.4972, -45.9398)</td>
<td>Abell 2877</td>
<td>(17.6017, -45.9228)</td>
<td>0.0247</td>
<td>106.61 ± 7.45</td>
<td>39</td>
</tr>
<tr>
<td>6</td>
<td>(53.9377, -35.3133)</td>
<td>Fornax (Abell S373)</td>
<td>(54.6162, -35.4483)</td>
<td>0.0046</td>
<td>18.97 ± 1.33</td>
<td>32</td>
</tr>
<tr>
<td>7</td>
<td>(21.5017, 1.7794)</td>
<td>RXC J0125.5+0145</td>
<td>(21.3746, 1.7627)</td>
<td>0.01739</td>
<td>72.32 ± 5.10</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>(55.3393, -35.5138)</td>
<td>Fornax (Abell S373)</td>
<td>(54.6162, -35.4483)</td>
<td>0.0046</td>
<td>18.97 ± 1.33</td>
<td>27</td>
</tr>
<tr>
<td>9</td>
<td>(16.8965, -46.7418)</td>
<td>Abell 2870</td>
<td>(16.9299, -46.9165)</td>
<td>0.0237</td>
<td>102.03 ± 3.89</td>
<td>30</td>
</tr>
<tr>
<td>10</td>
<td>(46.1290, -12.0551)</td>
<td>NGC 1200</td>
<td>(45.9770, -11.9918)</td>
<td>0.01305</td>
<td>57.03 ± 4.01</td>
<td>30</td>
</tr>
</tbody>
</table>
Abell 194

NGC 199

???

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Application I: Radial Profiles

Distribution of LSB and HSB galaxies: similar in most cases
Application II: Size-Luminosity Relation

Distance information $\rightarrow$ physical size of the LSBGs

Comparison with the NGFS dwarfs

Natural continuation of the dwarf population

UDG limit

According to the physical size definition

108 UDGs
Part III: The Future

Vera C. Rubin observatory

Euclid survey
Legacy Survey for Space and Time (LSST) on the Vera C. Rubin Observatory

Area ~ 2000 deg$^2$

$u,g,r,i,z,Y$ optical survey

5-σ point source depth:
$g \sim 27.4$, $i \sim 26.8$

Data: 20TB/night

20 Billion galaxies after 10 years!

BIG data

Visual inspection??

Source: https://www.lsst.org/scientists/keynumbers
Convolutional Neural Networks

(LeCun+ 98)

Automatic Classification at the image level

Applications in astronomy:

- Star-galaxy separation
- Strong lensing identification
- Merging galaxies
- ...

Requires a large number of labeled training instances (examples)
CNNs require a large number of labeled training instances (examples)

20000 positive + 20000 negative examples (manually classified/annotated)
Preliminary results

Train for 100 epochs

Training set: 30000
Validation set: 5000
Test set: 5000

Accuracy ~ 92.3%
Purity ~ 89.5%
Transfer learning

Train on DES, classify HSC examples

Accuracy ~ **83.7%**
Purity ~ **83.2%**

Misclassified (?)

Examples of misclassified objects

Improvement: domain adaption
Other future directions

- Photometric redshift (distance) estimation for LSBGs
- Mass estimation through weak lensing
- LSBG clusters?
- Comparison with theory / galaxy formation models
- Spectroscopy for dynamical mass estimates
- Distances from cross correlations

The future is FAINT!
A great collaboration!

Alex Drlica-Wagner (FNAL/UChicago)
Kuang Wei (UChicago)
Ting S. Li (Carnegie/Princeton)

J. Sanchez Lopez (FNAL)
A. Peter (OSU)
A. Feldmeier-Krause (UChicago)
A. Ćiprijanović (FNAL)

+ DES IC reviewers + DES builders + the broader DES collaboration

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Thank you!!!