Revisiting the Size–Luminosity Relation in the Era of Ultra Diffuse Galaxies

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Abstract

Galaxies are generally found to follow a relation between their size and luminosity, such that luminous galaxies typically have large sizes. The recent identification of a significant population of galaxies with large sizes but low luminosities (“ultra diffuse galaxies,” or UDGs) raises the question of whether the inverse is also true—that is, whether large galaxies typically have high luminosities. Here we address this question by studying a size-limited sample of galaxies in the Coma cluster. We select red cluster galaxies with sizes of \( r_{\text{eff}} > 2 \) kpc down to \( M_g \approx -13 \) mag in an area of \( 9 \) deg\(^2\), using carefully filtered Canada–France–Hawaii Telescope images. The sample is complete to a central surface brightness of \( \mu_{g,0} \approx 25.0 \) mag arcsec\(^{-2}\) and includes 90% of Dragonfly-discovered UDGs brighter than this limit. Unexpectedly, we find that red, large galaxies have a fairly uniform distribution in the size–luminosity plane: there is no peak at the absolute magnitude implied by the canonical size–luminosity relation. The number of galaxies within \( \pm 0.5 \) mag of the canonical peak (\( M_g = -19.69 \) for \( 2 < r_{\text{eff}} < 3 \) kpc) is a factor of \( \sim 9 \) smaller than the number of fainter galaxies with \( -19 < M_g < -13 \). Large, faint galaxies, such as UDGs, are far more common than large galaxies that are on the size–luminosity relation. An implication is that, for large galaxies, size is not an indicator of the halo mass. Finally, we show that the structure of faint large galaxies is different from that of bright large galaxies: at a fixed large size, the Sérsic index decreases with the magnitude following the relation \( \log_{10} n \approx -0.067 M_g - 0.989 \).

Key words: galaxies: clusters: individual (Coma) – galaxies: halos – galaxies: luminosity function, mass function – galaxies: structure

1. Introduction

Early-type and late-type galaxies exhibit scaling relations, involving their structural, photometric, and physical parameters (Faber & Jackson 1976; Tully & Fisher 1977; Djorgovski & Davis 1987). These relations are used as distance indicators (e.g., Freedman et al. 2001) and provide insights into the formation and evolution of galaxies (e.g., Governato et al. 2007), as well as constraints on the nature of dark matter (e.g., Sanders & McGaugh 2002). One of the most straightforward relations is that between the sizes of galaxies (parameterized by the half-light or half-mass–radius, \( r_{\text{eff}} \)) and their luminosities or masses (Kormendy 1977). The slope and normalization of this relation presents distinct trends depending on environment and cosmic time. Previous studies have derived the size–luminosity relation from large data sets complete down to faint limits, carefully measuring the photometric parameters of galaxies using the advanced galaxy modeling and fitting (Shen et al. 2003; Bernardi et al. 2014). The fairly tight log-linear relation between the size and the integrated magnitude of galaxies that is found in these studies suggests that the majority of large galaxies are bright. It is well known, however, that these results suffer from surface brightness selection effects (e.g., McGaugh 1996). Recent low surface brightness imaging efforts resulted in the discovery of a significant population of galaxies with large effective radii (\( r_{\text{eff}} > 1.5 \) kpc) and low central surface brightness (\( \mu_0 > 24 \) mag arcsec\(^{-2}\)), mostly in cluster environments (e.g., Koda et al. 2015; Miho et al. 2015; van Dokkum et al. 2015a). Some isolated examples of these large, low surface brightness galaxies, dubbed “ultra diffuse galaxies” (UDGs), were detected earlier (e.g., Dalcanton et al. 1997; Caldwell 2006) but it is their large abundances, particularly in cluster environments, that are new to us. In light of this discovery, it is interesting to examine how UDGs modify the derived galaxy size–luminosity relation. Specifically, the key questions are whether most large galaxies are, in fact, luminous, and whether there is a continuum in luminosity between large “normal” galaxies and UDGs.

Here we present the size–luminosity relation of galaxies in the Coma Cluster, using imaging from the Canada–France–Hawaii Telescope (CFHT) covering an area of 9 deg\(^2\), down to low surface brightness levels. To ensure size completeness, we focus on galaxies with large effective radii (\( r_{\text{eff}} > 2 \) kpc). We show that large galaxies do not follow the canonical size–luminosity relation and that the apparently tight size–luminosity relation might be a result of selection effects, due to poor sensitivity to large, low surface brightness galaxies. Throughout this paper, we assume a distance of 100 Mpc to the Coma cluster and a flat \( \Lambda \)CDM model with parameters of \( \Omega_m = 1 - \Omega_\Lambda = 0.27, \quad \Omega_\Lambda = 0.0469, \quad h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7, \quad \sigma_8 = 0.82, \) and \( n_s = 0.95 \) that is compatible with combined constraints from the Wilkinson Microwave Anisotropy Probe, Baryonic Acoustic Oscillations, supernovae, and cluster abundance (Komatsu et al. 2011).

2. Analysis

2.1. Data and Catalog Selection

Our size-limited sample of Coma galaxies is constructed from imaging data obtained with the CFHT, as they cover a large region of the Coma cluster in a homogeneous way, and it was shown in van Dokkum et al. (2015a) that they reach the require depth. We obtained the data from the Canadian Astronomy Data Centre. A 3° × 3° field was imaged with a
nine-pointing mosaic, in the g and i bands (Head et al. 2014). Exposure times were short, at 300 s per pointing per filter. The image quality is FWHM \( \approx 0\'08 \) and the sampling is 0\'186 pixel \(^{-1}\). We also obtained images in a 3\' \( \times \) 3\' area in the CFHT Legacy Survey wide fields (W1, CFHTLS; Erben et al. 2013). These data are used to correct the Coma counts for contamination, as detailed below. Similarly to the Coma data, nine-pointing mosaic images were obtained in the g and i bands. Exposure times were much longer, at 3000 and 4300 s per pointing for the g and i filters, respectively. For each of the nine images, we measured the noise, using the distribution of flux values measured in 25 \( \times \) 25 pixel boxes placed in empty areas. For each Coma field, we assigned a control field whose variation in 25 \( \times \) 25 pixel boxes was matched to that in Coma. This matching was done by adding Poisson-distributed noise to the control field.

To create a size-limited sample, we need to include both luminous galaxies and very faint low surface brightness objects. We created this “high dynamic range” catalog in the following way. The same procedure was applied to both the Coma images and the blank field data. First, the g and i images were summed to increase the signal-to-noise ratio (S/N). Then, SExtractor (Bertin & Arnouts 1996) was used to create a catalog of bright objects, by setting the detection threshold to \( > 5\sigma \) per pixel. Objects with high measured flux (FLUX\_AUTO > 10\(^4\), corresponding to \( gi < 20.7 \) mag) were included in the catalog and then masked in the images, in preparation for the next steps. Objects with a FWHM smaller than 1.5 arcsec were not included in the catalog but masked outright. Next, the masked image was rebinned by 3 \( \times \) 3 to a lower resolution to increase the S/N per pixel for a better detection of low surface brightness objects. SExtractor was run a second time on this masked and rebinned image, now using a lower detection threshold of 3\( \sigma \) per pixel. Objects with a FWHM smaller than 3.5 arcsec and objects that are likely to be stars (CLASS\_STAR > 0.9) were masked. SExtractor was run a third time after this masking step, with a low detection threshold of 2\( \sigma \) per pixel and a large minimal number of detected pixels (DETECT\_MINAREA = 30). Objects with a FWHM \( \geq 4 \) arcsec were kept. Finally, a manual rejection was applied to all images to exclude non-galaxies objects (e.g., a part of a previously masked galaxy, blended compact objects, etc.) and artifacts (e.g., ghosts of optics, edge effects, etc.). The final catalog contains 6258 galaxies in the 3\' \( \times \) 3\' Coma field and 3152 galaxies in the 3\' \( \times \) 3\' control field.

The procedure is illustrated in the top panels of Figure 1, where we show a 3\' \( \times \) 3\' section from an image after applying the key steps of the detection pipeline. The bottom panels show examples of five galaxies from our sample. The galaxies have similar sizes (\( r_{\text{eff}} \sim 3.5 \) kpc) but span a wide range of luminosities. The faintest one with \( m_i = 19.82 \) mag is easily detected in the CFHT data.

### 2.2. Structural and Photometric Parameters

We use SExtractor only to obtain a catalog that includes all large galaxies down to a faint detection limit. Structural and photometric parameters of the galaxies were determined from parametric fits of the two-dimensional surface brightness distribution, using GALFIT (Peng et al. 2002) in two steps. First, fits were performed on the summed \( g + i \) images, with neighboring objects masked, to determine structural parameters of the galaxies. A single-component Sérsic profile was assumed, and the values of the \( r_{\text{eff}}, n, m_{g + i}, b/a, \) position angle (PA), and the sky were fitted by GALFIT. The galaxies were then fitted again in each band separately to determine (total) magnitudes and colors. In this second fit, all previously free parameters were fixed except the integrated \( m_i \) and \( m_j \) magnitudes. A total of 6045 out of 6132 were successfully fit, with an average and a median \( \chi^2 \) of 1.39 and 1.1, respectively. A small fraction of fits (1.4\%) did not converge.

### 2.3. Red Sequence and Cluster Member Selection

The color–magnitude diagrams (CMDs) for galaxies in the Coma field and the control field are shown in Figure 2. Only large galaxies with \( r_{\text{eff}} > 4\'' \) are shown, as we are complete above this limit (see above). The red sequence (Gladders & Yee 2000) is very clear in the Coma field, as expected. A visual comparison of the two fields suggests that most of the bluest and reddest objects in the Coma field are background galaxies, and we begin by selecting objects close to the red sequence. We fit the red sequence in the Coma field CMD, using the least squares method, and we obtain \( (g - i) = -0.045M_i + 0.113 \). This relation is similar to that obtained by Head et al. (2014). In the following, we only consider galaxies that are within \( \pm 0.2 \) mag of the red sequence line in the analysis. As is evident in the right panel of Figure 2, the contamination by unrelated objects is small but nonzero within these limits.

### 3. Results

#### 3.1. The Size–Luminosity Plane

The distribution of red galaxies in the size–magnitude plane, color coded by their number, is shown in Figure 3. Galaxies are placed into bins of size and magnitude in the \( g \) band. The top left panel shows galaxies in the Coma field, the top right panel shows galaxies in the control field, and the bottom panel shows the subtracted histogram where control galaxies are subtracted from the Coma histogram for each bin of size and magnitude. In the top panels, we show galaxies with their apparent sizes and magnitudes (measured in arcseconds and magnitudes, respectively), and in the bottom panel, we compute their physical sizes and absolute magnitudes under the assumption that they are all at the distance of the Coma cluster (100 Mpc).

Galaxies span a wide range of sizes and magnitudes, from dwarf galaxies to UDGs and giant ellipticals. The sample is not complete for dwarf galaxies, due to our cut on FWHM \( \geq 4\'' \) which roughly corresponds to an effective radius of \( \sim 1 \) kpc at a distance of 100 Mpc. The red symbols denote a population of early-type objects, adapted from Brodie et al. (2011). This is not a complete sample, but thought to be representative for different classes of dynamically hot, early-type objects. Galaxies in our Coma sample show a markedly different distribution: the bright end follows the Brodie et al. data points, which roughly corresponds to an effective radius of 1 kpc at a distance of 100 Mpc. The red symbols denote a population of early-type objects, adapted from Brodie et al. (2011). This is not a complete sample, but thought to be representative for different classes of dynamically hot, early-type objects. Galaxies in our Coma sample show a markedly different distribution: the bright end follows the Brodie et al. data points, which roughly corresponds to an effective radius of 1 kpc at a distance of 100 Mpc. The red symbols denote a population of early-type objects, adapted from Brodie et al. (2011). This is not a complete sample, but thought to be representative for different classes of dynamically hot, early-type objects.
discovered UDGs that have $\mu_{g,0} < 25$ mag arcsec$^{-2}$ in the van Dokkum et al. (2015a) sample.

3.2. Size-limited Sample

Bernardi et al. (2014) study the size–luminosity relations for a large sample of $z \leq 0.1$ early-type galaxies by fitting $\sim 5 \times 10^5$ galaxies the from Sloan Digital Sky Survey DR7 Main Galaxy Sample with an apparent magnitude limit of $m_r < 17.75$ mag. In order to examine how the recently identified large population of UDGs affect the large size end of the size–luminosity relation, we analyze the luminosity distribution of Coma galaxies in three size bins: $r_{eff} = 2–3$ kpc, $r_{eff} = 2.5–3.5$ kpc, and $r_{eff} = 3–4$ kpc. The right panel of Figure 4 shows the luminosity function of red cluster galaxies, after subtracting the control field galaxies, in the different size bins.

The distribution of galaxies in all three size bins is broad with sharp cutoffs on both ends. The sharp decrease in the number of galaxies for magnitudes fainter than $M_g = -14$ is due to photometric incompleteness, and there is no evidence for a “preferred” magnitude of large galaxies. The best-fitting logarithmic slopes of the luminosity functions in the three size bins are

$$
\begin{align*}
\log_{10}N &= \begin{cases} 
(0.0569 \pm 0.0102)m_g + 0.901 & 2 < r_{eff} < 3 \text{ kpc} \\
(-0.008 \pm 0.0147)m_g + 1.756 & 2.5 < r_{eff} < 3.5 \text{ kpc} \\
(-0.0259 \pm 0.0218)m_g + 1.753 & 3 < r_{eff} < 4 \text{ kpc}
\end{cases}
\end{align*}
$$

in the magnitude range of $-21 < M_g < -14$. A large fraction of the galaxies have a central surface brightness fainter than 24 mag arcsec$^{-2}$ in $g$ band, which associates them with the UDGs population.

This result appears to be in contention with previous studies that reported a low measured scatter ($\sigma_{\text{rms}}(\log_{10} r_{eff}) < 0.15$) around the mean size–luminosity relation (Bernardi et al. 2014). Bernardi et al. derive a size–luminosity relation for early-type galaxies of the form

$$
\log_{10} R = 12.814 + 1.379M_r + 0.038M_r^2
$$

and so, for effective radii of 2.5, 3, and 3.5 kpc, we get absolute magnitudes of $M_r = -20.40$, $-20.97$, and $-21.28$ mag, respectively. The three dashed lines in the right panel of

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4 The two that are missing have $\mu_{g,0} = 24.8$ mag arcsec$^{-2}$ in van Dokkum et al. (2015a).
UDGs have morphologies similar to dwarf spheroidals in the Local Group (McConnachie 2012; van Dokkum et al. 2015a; Mowla et al. 2017). We note that other studies have shown that large faint galaxies are not only different from large bright galaxies but also from small faint galaxies. In particular, the specific frequency of globular clusters in Coma UDGs is a factor of $\sim 7$ higher than that of other galaxies of the same luminosity (Beasley et al. 2016; van Dokkum et al. 2017; Lim et al. 2018).

The flat, wide nature of the luminosity function in fixed size bins appears to be in contention with the canonical relation between the galaxy size and luminosity across the entire magnitude range. The previously derived tight size–luminosity relation is partly a result of selection effects, as typically only high surface brightness galaxies were considered (e.g., Bernardi et al. 2014). This builds on previous work by Disney (1976) and McGaugh (1996) who showed the effect of a selection bias on scaling relations, such as the “Freeman law.” Our study elaborates on earlier work by Conselice (2002), who studied the size–luminosity relation for a smaller sample of galaxies in the Perseus cluster. However, we emphasize that the fraction of faint galaxies that are large is small—that is, UDGs are in the tail of the size distribution at a fixed low luminosity. As our data are highly incomplete for galaxies smaller than 2 kpc, we cannot rederive the size–luminosity relation. We also note that there may be an environmental dependence, such that the luminosity function of large galaxies could be different in the general field. Van der Burg et al. (2017) find that the ratio of the number of UDGs to the number of luminous galaxies has a slight dependence on the halo mass, such that UDGs are relatively more common in clusters than in groups.

Kravtsov (2013) used the abundance matching ansatz to obtain estimates of the virial radius, $R_{200}$, over a wide range of stellar masses and showed that galaxies follow an approximately linear relation between their half-stellar mass–radius, $r_{1/2}$ and their virial radius. Since $R_{200}$ scales with the host dark matter halo, $M_{200}$, it implies that the effective radius scales with the halo mass. For $r_{	ext{eff}}$ of $\sim 3$ kpc, we obtain a halo mass of $M_h \sim 3 \times 10^{12} M_\odot$ from the Kravtsov relations. However, we

4. Discussion

In this paper, we revisited the luminosity function of galaxies in the Coma cluster using size-limited samples, down to the low surface brightness regime, accounting for the recently discovered population of UDGs. We find that the luminosity function for intrinsically large galaxies is nearly flat across eight orders of magnitudes ($-22 < M_g < -14$), with a slope that is close to zero for all three samples (Figure 4). We also find that the Sérsic index decreases systematically for fainter galaxies, and we infer that the structure of large bright galaxies is very different from large faint galaxies. This is consistent with many other studies, which have shown that large bright galaxies have high Sérsic indices (Kormendy et al. 2009) and...
find that, at fixed size of $\sim 3$ kpc, galaxies span at least a factor of $\sim 600$ in luminosity. Taken together, these results suggest that at a fixed halo mass, there is a factor of $\sim 600$ in the stellar mass, which is inconsistent with previous estimates of the scatter in the stellar mass–halo mass relation (e.g., Behroozi et al. 2013; Moster et al. 2013) and also with halo occupation statistics (e.g., Berlind & Weinberg 2002; Bullock et al. 2002; Amorisco 2018). The most straightforward interpretation is that UDGs do not follow the $r_{1/2} \approx 0.015 R_{200}$ relation derived in Kravtsov (2013). An interesting implication is that the baryons in UDGs “fill” a larger fraction of the volume of their halos than other galaxies of the same luminosity; this likely explains their high $M/L$ ratios within their half-light radii (e.g., Beasley et al. 2016; van Dokkum et al. 2016; Toloba et al. 2018).

We note that this does not rule the possibility of a relation between size and halo mass within the sample of UDGs; as an example, Dragonfly 44 is claimed to have a high halo mass (van Dokkum et al. 2016) compared to other UDGs (Sifón et al. 2018) and it is one of the largest-known UDGs. We also note that using the half-light radius is a somewhat arbitrary choice.
and different size definitions change the distribution of galaxies in size and thus the size–luminosity relation. In particular, recent studies (Miller et al. 2019; Mowla et al. 2019) have shown that $r_{80}$, the radius that contains 80% of a galaxy’s stellar light, may be more closely related to halo mass than the half-light radius. With this radius definition, UDGs are smaller in size than more luminous galaxies with the same half-light radius and, therefore, have a lower predicted halo mass.

In conclusion, UDGs are an important population in galaxy clusters and are far more common than large galaxies on the canonical size–luminosity relation. Specifically, the number of galaxies with $2 \text{kpc} < r_{\text{eff}} < 3 \text{kpc}$ that fall within $\pm0.5 \text{ mag}$ of the size–luminosity relation is a factor of nine smaller than those with $-19 < M_g < -13$. Deeper imaging is needed to determine whether the luminosity function remains flat at even fainter magnitudes. Furthermore, extending the study to smaller galaxies would enable a complete study of the size–luminosity plane. Finally, we confirm that UDGs are not a distinct population in the size–luminosity plane. Previous studies have shown that there is no bimodality in the sizes of galaxies at fixed luminosities (e.g., Conselice 2018); here we make the supplementary point that there is no bimodality in luminosity at a fixed size.

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