Research Article

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Morphological Distribution of Galaxies in Some Nearby Clusters

<https://doi.org/10.1515/astro-2019-0007>

Received Nov 03, 2018; accepted Feb 01, 2019

Abstract: We study the morphological distribution of galaxies in some nearby clusters, using the Sloan Digital Sky Survey – Data Release 9 (SDSS-DR9). The segregation between early-type galaxies and late-type ones is investigated in $g - r / u - g$ color space, using the color cut $u - r = 2.22$. The results are compared with those obtained using a color cut that changes with magnitude. They are found to be consistent, particularly for late-type galaxies. The results obtained by the fixed color-cut criterion are also found to be consistent with those obtained by the inverse concentration index parameter, especially for early-type galaxies. Comparable results are obtained for the stacked sample, whose morphologies, given by the fixed color-cut criterion are compared with the visual morphologies provided by the Galaxy Zoo project. A good degree of consistency is seen, which becomes more evident for late-type galaxies.

Keywords: galaxy clusters; galaxy morphology

1 Introduction

Galaxy morphology has received a considerable interest since a long time, due to its important role in the study of galaxy formation and evolution. De Vaucouleurs (1961) found that morphology of galaxies correlates with their colors. Since then, a number of studies have been conducted concerning the correlation of galaxy morphology with color (e.g. Fukugita *et al.* 1995; Ferreras *et al.* 1999; Fioc and Rocca-Volmerange 1999).

It has been known that Galaxies are divided on a color-magnitude diagram (CMD) into early-type galaxies, lying on a red sequence, and late-type galaxies, appearing within a blue cloud (Baldry *et al.* 2004). However, with the aid of the Sloan Digital Sky Survey (SDSS, York *et al.* 2000) and the Galaxy Zoo project (Lintott *et al.* 2008), it was found that a certain population of blue early-type galaxies do not reside on the red sequence (Schawinski *et al.* 2009). These blue early-type galaxies help us understand the physical processes underlying their evolution, and give evidence for star formation activity in various morphological types.

Furthermore, a certain population of red late-type galaxies was also found. These galaxies have different evolutionary paths from ordinary late-type galaxies, and show that late-type galaxies may stop star formation activity without changing their morphology (Masters *et al.* 2010).

The Sloan Digital Sky Survey has provided an accurate photometric data for a huge number of galaxies, extending the scope of study in the field of galaxy colors. This survey uses a dedicated 2.5 m telescope at the Apache Point Observatory in New Mexico to map about one third of the sky (14,555 square degrees) in five passbands, u (3543 Å), g (4770 Å), r (6231 Å), i (7625 Å), and z (9134 Å) (Fukugita *et al.* 1996). Since the advent of this survey, many works have been achieved about the morphological segregation of galaxies. Shimasaku *et al.* (2001), using SDSS, have shown that early-type galaxies can be segregated from late-type ones using a parameter called (inverse) concentration index (C_{in}), defined as the ratio of 50 to 90 percent Petrosian light radii. The value of (inverse) $C_{in} = 0.4$ is found to separate between the two populations. This parameter was used by many workers for the same purpose (e.g., Strateva *et al.* 2001; Goto *et al.* 2003; Zhang and Yang 2017). Strateva *et al.* (2001) studied the color distribution of a large uniform sample of galaxies from SDSS, and have shown that the distribution of the $u - r$ color is bimodal, with early-type galaxies being segregated from late-type ones by a fixed color cut $u - r = 2.22$. Zandivarez and Martínez (2011) proposed another criterion to separate between galaxy types. They used a color cut in the form of a second-degree poly-

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Table 1. The sample data

Cluster	Equ. J2000.0 ^(a)		Redshift ^(a)	v (km s ⁻¹) ^(a)	σ (km s ⁻¹) ^(b)	N_{gal}
	R.A.	Dec.				
A1656	12 59 48.7	+27 58 50	0.0231	6925	970	651
A2199	16 28 38.0	+39 32 55	0.0302	9039	733	305
A2634	23 38 25.7	+27 00 45	0.0314	9409	721	189
A2147	16 02 18.7	+16 01 12	0.0350	10493	859	367
A0085	00 41 50.1	-09 18 09	0.0551	16507	963	450
A2256	17 03 43.5	+78 43 03	0.0581	17418	1216	244
A2065	15 22 42.6	+27 43 21	0.0726	21765	1146	161
A2029	15 10 55.0	+05 43 12	0.0773	23168	1247	478
A2255	17 12 13.0	+64 05 33	0.0806	24163	998	375
A2142	15 58 20.6	+27 13 37	0.0909	27251	1008	601

^(a) These data have been taken from the NED database.

^(b) These data have been taken from Sereno and Ettori (2015).

nomial function: $P(x) = -0.02x^2 - 0.15x + 2.46$, in which $x = M_r - 5 \log(h) + 20$. Galaxies lying above this color cut are considered as early-type galaxies, while those lying below it are considered as late-type galaxies.

In this paper, we study the morphological distributions of galaxies belonging to some nearby clusters. In Section 2, we give a detailed description of our sample and data. Our results and discussion are presented in Section 3. In Section 4, we outline our conclusions. Λ CDM parameters ($\Omega_M = 0.27$, $\Omega_A = 0.73$, $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$) are used throughout this work.

2 The sample and data

We consider a sample of galaxy clusters selected from Abell catalog (Abell *et al.* 1989), having redshifts in the range ($0.0 \lesssim z \lesssim 0.1$). Their basic properties are given in Table 1. The photometric data are extracted from the Sloan Digital Sky Survey – Data Release 9 (SDSS-DR9, Ahn *et al.* 2012). We use model magnitudes for calculating colors, and Petrosian magnitudes for calculating absolute magnitudes. The model magnitudes give the optimal measure of the flux for a galaxy by fitting de Vaucouleurs and exponential models (convolved with a double Gaussian fit to the point-spread function, PSF) in the r-band as a matched aperture for calculating galaxy fluxes in all bands.

The searching process for each cluster is carried out in such a way that all possible member galaxies be taken into consideration. To confirm the membership of these galaxies, redshift data are obtained from SDSS-DR9 database (for A1656, A2199, A2147, and A2065), and NASA/IPAC Extragalactic Database (NED) (for A2634, A2255, and A2142). For the other clusters, redshift data were obtained from

the literature (Agulli *et al.* 2016, for A85, Berrington *et al.* 2002, for A2256, and Sohn *et al.* 2017, for A2029). A cross-matching is then achieved with the SDSS-DR9 database to extract the required photometric data for each cluster. In order to eliminate foreground and background galaxies, and maintain only members, we select those galaxies having radial velocities (v) within $\pm 3\sigma$ (velocity dispersion) from the mean radial velocity of each cluster. The reason is that all cluster members, due to gravitation, move at comparable velocities.

All the photometric data are corrected for galactic foreground extinction using values given by Schlafly and Finkbeiner (2011). They are also K-corrected, using a web-based service (Chilingarian *et al.* 2010; Chilingarian and Zolotukhin 2012), which approximates them as two dimensional polynomials of redshift with one observed color.

3 Results and discussion

3.1 Morphology Segregation in Color Space

Figure 1 shows the $g - r/u - g$ color-color diagrams for our clusters, with the dashed line being the $u - r = 2.22$ color separator. According to this fixed color cut, all galaxies with $u - r \geq 2.22$ are classified as early-type (E, S0, and Sa) galaxies, while those with $u - r < 2.22$ are classified as late-type (Sb, Sc, and Irr) galaxies (Strateva *et al.* 2001). Figure 2 displays the $u - r$ histograms for galaxies classified as early and late types according to the $u - r = 2.22$ criterion. The Gaussian fits have also been plotted to see the behaviors of these histograms more easily. Table 2 summarizes the percentage populations of both early-type and late-type galaxies, according to the fixed color cut $u - r = 2.22$. We see that early-type galaxies constitute the dominant popu-

Figure 1. The rest-frame $g-r$ / $u-g$ color-color diagrams for our sample. The dashed line is the fixed color cut $u-r = 2.22$ used to separate early-type galaxies (gray) from late-type ones (black)).

Figure 2. The $u-r$ histograms of early-type (gray) and late-type (black) galaxies for our sample clusters with their Gaussian fits, classified according to the $u-r = 2.22$ color cut.

Figure 3. The g histograms of early-type (gray) and late-type (black) galaxies for our sample clusters with their Gaussian fits, classified according to the $u-r = 2.22$ color cut.

Figure 4. The rest-frame $u-r/M_r$ color – magnitude diagrams of our sample. The dashed line is the fixed color cut $u-r = 2.22$, and the solid line is the color cut that changes with magnitude.

Figure 5. Inverse C_{in} histograms for our sample clusters with their Gaussian fits.

Figure 6. Inverse concentration index C_{in} versus color index $u - r$ for our clusters. Vertical dashed line denotes the $u - r = 2.22$ separator; horizontal dashed line denotes the $(\text{inverse}) C_{in} = 0.4$ separator.

lation in each cluster, as it is known from previous studies (see, for example, Dressler 1980). In Figure 3, we see the g histograms of the sample clusters for both types of galaxies (early & late), according to the fixed color cut, together with their Gaussian fits. These histograms, also, support the already known fact that early-type galaxies constitute the brightest population in any cluster.

Table 2. Galaxy populations, based on the $u - r = 2.22$ criterion.

Cluster	Early-type Galaxies (%)	Late-type Galaxies (%)
A1656	56.7	43.3
A2199	61.6	38.4
A2634	66.1	33.9
A2147	53.4	46.6
A0085	58.4	41.6
A2256	75.0	25.0
A2065	78.3	21.7
A2029	62.6	37.4
A2255	68.3	31.7
A2142	69.9	30.1

Morphological segregation of galaxies can be done using a color cut that changes with absolute magnitude (Zandivarez and Martínez 2011), as mentioned in Section 1. Table 3 displays the percentage populations of early-type and late-type galaxies according to this color cut, together with a comparison with the results of fixed color cut $u - r = 2.22$. A high degree of overall consistency is seen between the results of the two color-cut criteria, which becomes more evident for late-type galaxies.

The bimodality of galaxies in color space can be examined through plotting color-magnitude diagrams (CMDs). Figure 4 displays the rest-frame CMDs of our sample clusters. The dashed line is the fixed color cut $u - r = 2.22$, and the solid line is the color cut that changes with magnitude. The majority of red-sequence members are found to lie above the dashed line. This gives evidence for the consistency of the color cut $u - r = 2.22$ in separating early-type galaxies from late-type ones.

3.2 The (Inverse) Concentration Index

Morphological classification of galaxies can be achieved with a parameter called (inverse) concentration index, C_{in} (Shimasaku *et al.* 2001; Strateva *et al.* 2001). It is defined as the ratio of the radii containing 50% and 90% of the r-band Petrosian light. This parameter exhibits a strong correlation with visual morphology, and so, may be considered as the best one for achieving morphological classifications

of galaxies (Shimasaku *et al.* 2001). According to this parameter, galaxies with (inverse) $C_{in} \geq 0.4$ are considered as late-type galaxies and those with (inverse) $C_{in} < 0.4$ as early-type ones (Goto *et al.* 2003). Figure 5 shows the (inverse) C_{in} distribution in each cluster. The correlation between $u - r$ colors and inverse concentration index for each cluster is illustrated in Figure 6. The vertical dashed line is the $u - r = 2.22$ color cut, and the horizontal dashed line is the (inverse) $C_{in} = 0.4$ separator. Table 4 outlines the percentage populations of both early-type and late-type galaxies, based on the (inverse) $C_{in} = 0.4$ separator, with a comparison with the data given by the fixed color cut criterion. It is seen from this table that early-type galaxies form the dominant population in each cluster, in agreement with the results obtained from the fixed color cut criterion. Also, a high degree of overall consistency is noticed between the results of the two criteria, and it becomes very obvious for early-type galaxies. This is illustrated well in Figure 6.

3.3 The Stacked Sample

In a similar way, we carry out the analyses for the stacked sample. Figure 7 displays the $g - r/u - g$ color-color diagram, with the dashed line being the $u - r = 2.22$ color cut. In Figures 8 & 9, the $u - r$ and g histograms, with Gaussian fits, are shown for early-type and late-type galaxies, classified according to the fixed color cut criterion.

Figure 7. The rest-frame $g - r / u - g$ color-color diagram for the stacked sample, with the dashed line separating between early-type (gray) and late-type (black) galaxies.

Figure 8. The $u - r$ histograms of early-type (gray) and late-type (black) galaxies for the stacked sample, with their Gaussian fits.

Table 3. Galaxy populations, based on the color cut changing with magnitude, with comparison with the $u - r = 2.22$ results.

Cluster	Population based on color cut changing with magnitude (%)		Comparison with the $u - r = 2.22$ results		Overall consistency (%)
	Early	Late	Early	Late	
A1656	44.4	55.6	55.6	70.2	61.9
A2199	50.2	49.8	75.5	90.6	81.3
A2634	23.3	76.7	32.0	93.8	52.9
A2147	22.1	77.9	38.3	96.5	65.4
A0085	58.7	41.3	76.0	65.8	71.8
A2256	28.7	71.3	38.3	100	53.7
A2065	32.9	67.1	42.1	100	54.7
A2029	46.0	54.0	69.2	92.7	78.0
A2255	42.4	57.6	60.5	96.6	72.0
A2142	51.7	48.3	71.4	93.9	78.2

Table 4. Galaxy populations, based on (inverse) $C_{in} = 0.4$ criterion, with comparison with the $u - r = 2.22$ results.

Cluster	Population based on (inverse) $C_{in} = 0.4$ criterion (%)		Comparison with the $u - r = 2.22$ criterion.		Overall consistency (%)
	Early	Late	Early	Late	
A1656	75.7	24.3	83.2	34.0	69.9
A2199	66.2	33.8	82.4	59.8	73.8
A2634	72.5	27.5	87.2	56.3	76.7
A2147	65.9	34.1	85.2	56.1	71.7
A0085	41.8	58.2	55.9	78.1	65.1
A2256	63.5	36.5	76.5	75.4	76.2
A2065	70.8	29.2	84.9	80.0	83.9
A2029	51.7	48.3	61.9	65.4	63.2
A2255	57.9	42.1	70.7	69.7	70.4
A2142	56.6	43.4	66.4	66.3	66.4

Figure 9. The g histograms of early-type (gray) and late-type (black) galaxies for the stacked sample clusters, with their Gaussian fits. **Figure 10.** The rest-frame CMD of the stacked sample. The dashed line is the fixed color cut $u - r = 2.22$, and the solid line is the color cut that changes with magnitude.

The rest-frame color-magnitude diagram for the stacked sample is illustrated in Figure 10. The dashed line is the fixed color cut and the solid line the color cut that changes with magnitude. A comparison between these two color-cut criteria is made, and the results are given in Table 5. As we see, the results of this comparison are very close to those obtained for the individual clusters. The fixed color-cut criterion is also compared with the (inverse) $C_{in} = 0.4$ criterion for the stacked sample, and the results are given in Table 5. It is also found that these results are comparable with those belonging to the individual clusters. Figure 11

shows the (inverse) C_{in} distribution for the stacked sample, with its Gaussian fit. In Figure 12, the inverse concentration index, C_{in} , is plotted against the color index ($u - r$) for the stacked sample.

Finally, the morphological classification of galaxies within the stacked sample, based on the $u - r = 2.22$ color cut, is compared with the data given by the Galaxy Zoo project (Lintott *et al.* 2011). This project aims at providing visual morphologies for about one million galaxies from SDSS. A position-matching between our stacked sample

Figure 11. Inverse C_{in} histogram for the stacked sample, with its Gaussian fit.

Figure 12. (Inverse) C_{in} versus $u - r$ for the stacked sample. Vertical dashed line denotes the $u - r = 2.22$ separator; horizontal dashed line denotes the (inverse) $C_{in} = 0.4$ separator.

Table 5. Comparison of the $u - r = 2.22$ criterion with color cut changing with magnitude, (inverse) $C_{in} = 0.4$, and the Galaxy Zoo morphology for the stacked sample.

	Consistency (%)		Overall consistency (%)
	Early-type	Late-type	
With color cut changing with magnitude	59.6	85.9	69.0
With (inverse) $C_{in} = 0.4$ separator	73.3	60.0	68.4
With Galaxy Zoo morphology	64.5	78.9	68.5

and the Galaxy Zoo database reveals that about 600 members of the stacked sample have visual morphologies in this database. A comparison, made between these morphologies and those obtained from the $u - r = 2.22$ color-cut criterion reveals a good degree of consistency between them. This becomes more evident in late-type galaxies (see Table 5).

4 Conclusions

In this work, photometric data from SDSS-DR9 are used to investigate the morphological distribution of galaxies in some nearby clusters ($0.0 \lesssim z \lesssim 0.1$). Rest-frame ($g -$

r)/($u - g$) color – color diagrams are plotted to separate early-type galaxies from late-type ones, using the fixed color cut $u - r = 2.22$. These results are compared with those obtained using a color cut that changes with magnitude. A good degree of consistency is found between these two color-cut criteria, which becomes more evident for late-type galaxies. The results of fixed color-cut criterion are also found to be consistent with those obtained, using (inverse) $C_{in} = 0.4$ separator, particularly for early-type galaxies. The results obtained for the stacked sample are found to be comparable with those obtained for the individual clusters. The morphologies given by the $u - r = 2.22$ color-cut criterion for the stacked sample, are also compared with the visual morphologies provided by the Galaxy Zoo project. They are found to be consistent with each other, and this consistency becomes obvious in late-type galaxies.

Acknowledgment: Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III web site is <http://www.sdss3.org/>.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This research has also made use of the TOPCAT software (Taylor 2005), and the “Aladin Sky Atlas” developed at CDS, Strasbourg Observatory, France (Bonnarel *et al.* 2000; Boch and Fernique 2014).

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