Research Article

Mariwan A. Rasheed and Khalid K. Mohammad*

Morphological Distribution of Galaxies in Some Nearby Clusters

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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 | R.A. | Dec. | Redshift(a) | v (km s\(^{-1}\))(a) | σ (km s\(^{-1}\))(b) | N\(_{\text{gal}}\) |
|---------|------|------|-------------|----------------|-----------------|---------|
| 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 |
| 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).

dnomial 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 (\( \Omega_M = 0.27 \), \( \Omega_A = 0.73 \), \( H_0 = 73 \) km s\(^{-1}\) 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 \( (0.0 \leq z \leq 0.1) \). 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 (inverse) $C_{in} = 0.4$ separator.
...ation 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 Martinez 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 |
|---------|----------------------------------------------------------|------------------------------------------|
|         | Early | Late          | Consistency (%) | Overall consistency (%) |
| 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. |
|---------|----------------------------------------------------------|------------------------------------------|
|         | Early | Late          | Consistency (%) | Overall consistency (%) |
| 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
Conclusions

In this work, photometric data from SDSS-DR9 are used to investigate the morphological distribution of galaxies in some nearby clusters (0.0 ≤ z ≤ 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-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.

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References

Abell, G.O., Corwin, H.G., Jr., and Olowin, R.P. 1989, ApJS, 70, 1-138.
Agulli, I., Aguerri, J.A.L., Sánchez-Janssen, R., Dalla Vecchia, C., Di Fabio, A. Barrena, R. et al. 2016, MNRAS, 458(2), 1590-1603.
Ahn, C.P., Alexandroff, R., Prieto, C.A., Anderson, S.F., Anderton, T., Andrews, B.H. et al. 2012, ApJS, 203(2), 21.
Baldry, I.K., Glazebrook, K., Brinkmann, J., Ivezić, Ž., Lupton, R.H., Nichol, R.C., and Szalay, A.S. 2004, ApJ, 600(2), 681-694.
Berrington, R.C., Lugger, P.M., and Cohn, H.N. 2002, AJ, 123, 2261-2279.
Boch, T. and Fernique, P. 2014, ASP Conference Series, 485, 277-280.
Bonarel, F., Fernique, P., Bienaymé, O., Egret, D., Genova, F., Louys, M. et al. 2000, A&AS, 143, 33-40.
Chilingarian, I.V., Melchoir, A., and Zolotukin, I.Y. 2010, MNRAS, 405(3), 1409-1420.
Chilingarian, I.V. and Zolotukin, I.Y. 2012, MNRAS, 419(2), 1727-1739.
De Vaucouleurs, G. 1961, ApJS, 5, 233-289.
Dressler, A. 1980, ApJ, 236, 351-365.
Ferreras, I., Cayón, L., Martínez-González, and E., Benítez, N. 1999, MNRAS, 304(2), 319-326.
Fioc, M. and Rocca-Volmerange, B. 1997, A&A, 326, 950-962.
Fukugita, M., Ichikawa, T., Gunn, J.E., Doi, M., Shimasaku, K., and Schneider, D.P. 1996, AJ, 111(4), 1748-1756.
Fukugita, M., Shimasaku, K., and Ichikawa, Y. 1995, PASP, 107, 945-958.
Goto, T., Yamauchi, C., Fujita, Y., Okamura, S., Sekiguchi, M., Smail, I. et al. 2003, MNRAS, 346(2), 601-614.
Lintott, C., Schawinski, K., Slosar, A., Land, K., Bamford, S., Thomas, D. et al. 2008, MNRAS, 389(3), 1179-1189.
Lintott, C., Schawinski, K., Bamford, S., Slosar, A., Land, K., Thomas, D. et al. 2011, MNRAS, 410(1), 166-178.
Masters, K.L., Mosleh, M., Romer, A.K., Nichol, R.C., Bamford, S.P., Schawinski, K. et al. 2010, MNRAS, 405(2), 783-799.
Schawinski, K., Lintott, C., Thomas, D., Sarzi, M., Andreescu, D., Bamford, S.P. et al. 2009, MNRAS, 396(2), 818-829.
Schlafly, E.F. and Finkbeiner, D.P. 2011, ApJ, 737(2), 103.
Sereno, M. and Ettori, S. 2015, MNRAS, 450(4), 3675-3695.
Sohn, J., Geller, M.J., Zahid, H.J., Fabricant, D.G., and Diaferio, A. 2017, ApJS, 229, 20.
Shimasaku, K., Fukugita, M., Doi, M., Hamabe, M., Ichikawa, T., Okamura, S. et al. 2001, AJ, 122(3), 1238-1250.
Strateva, I., Ivezić, Ž., Knapp, G.R., Narayanan, V.K., Strauss, M.A., Gunn, J.E. et al. 2001, AJ, 122(4), 1861-1874.
Taylor, M.B. 2005, ASP Conference Series, 347, 29-33
York, D.G., Adelman, J., Anderson, J.E., Jr., Anderson, S.F., Annis, J., Bahcall, N.A. et al. 2000, AJ, 120(3), 1579-1587.
Zandivarez, A. and Martínez, H.J. 2011, MNRAS, 415(3), 2553-2565.
Zhang, Y. and Yang, X. 2017, arXiv:1707.04979.