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Properties of Brightest Cluster Galaxies as a Function of Cluster Classification Type

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Abstract: We classified Abell clusters using the magnitude differences between two or three bright member galaxies and investigated how such classification was correlated with the properties of brightest cluster galaxies (BCGs). S-type BCGs being clearly brighter than the rest of the member galaxies were likely to be red, luminous, and evolved as early type galaxies. On the other hand, T-type BCGs being not dominant at all were less luminous than early type galaxies. A small fraction of BCGs was currently forming stars, and all of the star-forming BCGs were T-type BCGs. Active galactic nuclei were most frequent for S-type BCGs. Through these quantitative analyses of the BCG properties, we discussed the possible scenario of BCG formation and the differences between S-type and T-type of BCGs.

Keywords: galaxy clusters, brightest cluster galaxy, galaxy evolution

Introduction

Recent studies have shown that environment plays an important role for a galaxy to evolve and grow (e.g., Bahcall et al., 2003; De Lucia et al., 2006). Galaxy clusters are the most representative environment where the member galaxies reside. Dressler (1980) has presented that red, old early-type galaxies dominate galaxy clusters while blue, young late-type galaxies are located in field environment. This morphology density relation suggests the scenario that dense environment accelerates the evolution of galaxies from gas rich spirals to passive ellipticals (e.g., Moore et al., 1996; van Dokkum and Franx, 2001; Park et al., 2007).

Brightest cluster galaxies (hereafter BCGs) are the extreme cases that show result of environmental effect of a cluster (Sandage and Hardy, 1973; Schombert, 1986). BCGs are elliptical galaxies (Dubinski, 1998), which are further divided into several types; gE, D, Es and cD galaxies (Kormendy, 1989). These are in general the most massive galaxy that reside in the center of the potential well (e.g., Dubinski, 1998; De Lucia and Blaizot, 2007; Fasano et al., 2012; Liu et al., 2012; Donzelli et al., 2011; Park and Hwang, 2009). However, not all BCGs are in the same stage of evolution.

BCGs are thought to have suffered a distinct evolution from field elliptical galaxies due to their environment (De Lucia and Blaizot, 2007). For example, galactic cannibalism is the first possible scenario of BCG formation (e.g., Dubinski, 1998; Lin and Mohr, 2004). In this scenario, massive galaxies fall into the cluster center being driven by dynamical friction or tidal force. The galaxy that arrived first at the center takes place, and its luminosity and mass increases gradually by taking other galaxies (e.g., Ostriker and Tremaine, 1975; Hausman and Ostriker, 1978). The second theory for BCG formation is that BCGs grow from the star formation fueled by cooling flow to the cluster center (e.g., Cowie and Binney, 1977). The third one is the galactic mergers between several galaxies (e.g., Merritt, 1985; Dubinski, 1998). These BCG formation theory can be tested by

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investigating the properties of BCGs at different evolution stages, understanding how their environment, i.e., clustering properties are related to the properties of member BCGs. Studies for cluster morphology classification (e.g., Rostagni et al., 2011) is the first step for such work.

One of the major classification criteria for galaxy clusters is the Bautz-Morgan system (Bautz and Morgan, 1970), who used the magnitude difference between the first and second brightest galaxies in the cluster. From B-M classification, galaxy clusters are classified into BM I type which contains a centrally located cD galaxy, BM II type where the brightest galaxy is a giant elliptical, and BM III type which have no dominant single BCG. Another authors also have used magnitude differences between brightest galaxies in cluster to classify galaxy clusters (e.g., Struble and Rood, 1987). The biggest concern here is the foreground and background galaxy contamination, and the photometric errors in measuring the integrated magnitudes of galaxies. If we have spectroscopic redshifts and magnitudes for bright cluster galaxies from homogeneous survey, the reliability of cluster classification would be greatly increased.

With these considerations in mind, in this paper, we have classified Abell clusters into several types using SDSS imaging and spectroscopy data. In addition to that, we have investigated the properties of BCGs as a function of cluster type. Abell clusters (Abell, 1958; Abell et al., 1989), which is one of the most well-studied and distinguished catalogs for galaxy clusters, have been used in many works to study the properties of galaxy clusters and their member galaxies. Using Abell clusters that are surveyed in Sloan Digital Sky Survey (SDSS; York et al., 2000), we would be free from the non-member galaxy contamination since we will use spectroscopic redshifts for galaxies with r< 17.7 mag. High S/N SDSS imaging data will reduce photometric uncertainties, thus our classification of BCG and their clusters would be highly reliable.

In this paper, we used AB magnitude system (York et al., 2000). All magnitudes given are "MAG_MODEL" (Richardson et al., 1999) from the SDSS catalog archive. We used a flat cosmology model with Ω_m= 0.3, Λ_0=0.7, and H_0=70 km/s/Mpc.

Data

Cluster sample

Abell's catalog of galaxy clusters (Abell, 1958; Abell et al., 1989) was used as the primary start point of this study. Among 4073 clusters presented in Abell's catalog (Abell et al., 1989), we selected 1267 clusters of which coordinates are covered from SDSS Data Release 12 (hereafter DR12).

In order to investigate the properties of BCGs in cluster, it is necessary to identify the BCG for each cluster. For 1267 galaxy clusters covered in SDSS DR12, we obtained coordinates and *u*, *g*, *r*, *i*, and *z*-band magnitudes of the possible member galaxies in the bright end, and identified a galaxy that has the brightest *r*-band magnitude to be the BCG of the cluster. Possible member galaxies are obtained through the SDSS sky server* query applying two conditions. The first criterion is to select galaxies lying within 1Mpc radius from the cluster center. Sizes of the galaxy cluster could exceed 1Mpc. However, in general, BCGs are thought to be located close to the cluster center since they tend to exist near the bottom of cluster potential well. Therefore we think 1Mpc is a proper distance to search for BCGs. The second term is to select galaxies having spectroscopic redshifts similar to that of the galaxy cluster. We placed constraints that the difference between the spectroscopic redshift of a galaxy (z) and the redshift of the cluster (z_{cl}) is less than 10% of the redshift of the cluster, i.e., $|z_{cl}-z|<0.1\ z_{cl}$. By using this constraint, we could select galaxies within ±3000 km/s from the cluster mean when the cluster is at z=0.1. The value is chosen to be slightly larger than the typical velocity dispersion of galaxy clusters, since we noticed that for some cases, especially when the cluster redshift is larger than 0.1, the redshift of the cluster given in Abell et al.(1989) is slightly different from the SDSS

* http://skyserver.sdss.org/casjobs/

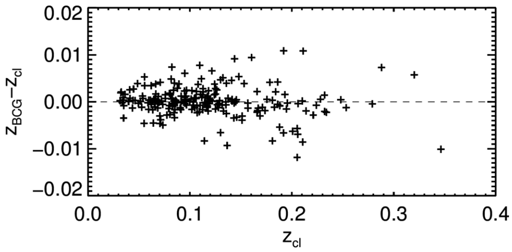

Fig. 1. Redshift difference between the selected BCG and the cluster (z_{BCG}-z_{cl}) as a function of cluster redshift. The redshift of the cluster is drawn from Abell et al. (1989) catalog.

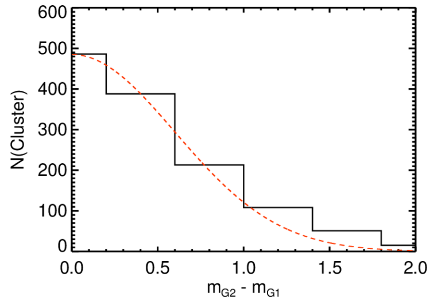

Fig. 2. Distribution of the magnitude difference between the two brightest member galaxies, (m_{G2}-m_{G1}). Dashed line indicates the half of the Gaussian distribution, derived through eyeball fitting.

redshift by Δz=0.01. The difference between the redshift of the cluster (z_{cl}) and the spectroscopic redshift of the BCG (z_{BCG}) is presented in Fig. 1.

In the following analysis, we only used galaxy clusters that have more than four spectroscopically observed member galaxies that satisfy the above two criteria. A small number of galaxy clusters of which BCG is not selected as spectroscopic target since their magnitude exceeds the saturation limit of SDSS spectroscopic survey is also excluded.

BCG classification

Previous studies on the luminosity function of the galaxy clusters have suggested that statistically, galaxy clusters tend to have universal luminosity function (e.g., Valotto et al., 1997). However, images of galaxy clusters show that the clusters still can be classified into several different types based on the characteristics of the galaxies at the bright end of the magnitude distribution. For example, several galaxy clusters have only one overwhelmingly bright elliptical galaxy near its center. Other galaxy clusters have two brightest galaxies with similar magnitudes, and there are galaxy clusters that do not have single dominant BCG. Based on these idea, we have classified galaxy clusters using the magnitude difference between the brightest member galaxies in the cluster.

For each galaxy cluster, we identified four most luminous galaxies in r-band. The r-band magnitude of the most luminous galaxy in the cluster is defined as m_{G1}, while m_{G2}, m_{G3}, and m_{G4} indicate the r-band magnitudes of the second, third, and fourth brightest galaxy. Then we calculated the magnitude differences (m_{G2}-m_{G1}), (m_{G3}-m_{G2}), and (m_{G4}-m_{G3}).

Figure 2 shows the distribution of the (m_{G2}-m_{G1}). The (m_{G2}-m_{G1}) distribution is described by the positive half of normal Gaussian distribution. Through the eyeball fitting, we derived standard deviation of the distribution. Galaxy clusters that have exceptionally large (m_{G2}-m_{G1}) would have exceptionally bright BCG that dominates other member galaxies. We have defined such galaxy clusters as "S-type" galaxy cluster, when "S" stands for "single" BCG. Quantitative criterion for S-type galaxy clusters is as follows.

$$(m_{G2}-m_{G1})\geq 1.2 \quad (1)$$

In the equation (1), 1.2 magnitude represents twice the standard deviation (i.e., 2σ) of the (m_{G2}-m_{G1}) distribution. Similarly, we have constructed (m_{G3}-m_{G2}) and (m_{G4}-m_{G3}) distribution to differentiate galaxy clusters with two competitive galaxies from other galaxy clusters, and galaxy clusters with several bright galaxies with similar luminosities. The former cluster is named as "D-type" galaxy cluster, and the latter as "T-type" cluster.

"D-type" galaxy clusters are galaxy clusters with two similarly bright galaxies that are significantly brighter than the rest of the member galaxies. The alphabet "D" represents "double" BCGs. Since we got the standard deviation of the (m_{G3}-m_{G2}) distribution to be 0.3 magnitude following the same method described above, our quantitative criteria for D-type is as

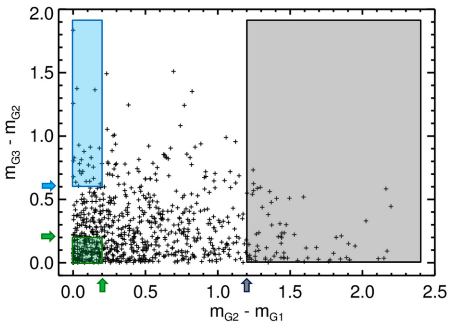

Fig. 3. Distribution of the (m_{G3}-m_{G2}) vs. (m_{G2}-m_{G1}). The black, blue, and green shaded regions represent ranges of magnitude differences for (m_{G2}-m_{G1}≥1.2), (m_{G2}-m_{G1}≤0.2, m_{G3}-m_{G2}≥0.6), and (m_{G2}-m_{G1}≤0.2, m_{G3}-m_{G2}≤0.2) clusters respectively. The arrows indicate the threshold values of the magnitude differences.

follows.

$$(m_{G2}-m_{G1})\leq 0.2,\ (m_{G3}-m_{G2})\geq 0.6 \quad (2)$$

In the equation (2), 0.6magnitude represents 2σ of the (m_{G3}-m_{G2}) distribution. Typical magnitude errors are less than 0.1, therefore we choose the (m_{G2}-m_{G1}) less than 0.2 to consider the two galaxies have similar luminosity considering the error propagation principle.

Some galaxy cluster have several brightest galaxies with similar magnitudes. We have defined such galaxy clusters as “T-type” galaxy cluster, taking “T” from “Triple or more”. Quantitative criteria for T-type is as follows.

$$(m_{G2}-m_{G1})\leq 0.2,\ (m_{G3}-m_{G2})\leq 0.2 \quad (3)$$

In the equation (3), 0.2 represents the sum of error limits of magnitudes. According to this criteria, galaxy clusters have three or more similar bright galaxies are selected.

Figure 3 shows the classification criteria for galaxy cluster type in (m_{G3}-m_{G2}) vs. (m_{G2}-m_{G1}) plot. Shaded regions indicate galaxy clusters of S, D, and T-type. When we refer to BCGs in S, D, and T-type clusters, we will use the expression of S-type BCG, D-type BCG, and T-type BCG.

Table 1 shows the number of BCGs in each type. We have 72 S-type, 26 D-type, 119 T-type BCGs in total.

Table 1. Number of BCGs in each type of galaxy clusters

Type	Classification Criteria	Number
S-type	(m_{G2}-m_{G1})≥1.2	72
D-type	(m_{G2}-m_{G1})≤0.2, (m_{G3}-m_{G2})≥0.6	26
T-type	(m_{G2}-m_{G1})≤0.2, (m_{G3}-m_{G2})≤0.2	119

Table 2. The number of BCGs in the MPA-JHU catalog

types	S-type	D-type	T-type
Number of BCGs	72	26	119
Number of BCGs in the MPA-JHU Catalog	54	20	71

The classification scheme using magnitude differences of member galaxies is comparable to that of Bautz-Morgan system (Bautz and Morgan, 1970). Especially, BM I type galaxy clusters are clusters with cD galaxy in the cluster center, while BM III type galaxy clusters are clusters with no dominant BCG. Therefore we compared our cluster classification with B-M classification of Abell clusters presented in Abell et al. (1989). 48% of the T-type clusters have been classified as BM III type, while 55% of the S-type clusters have been classified as BM I, I-II, and II. In case of D-type clusters, more than 75% of the D-type clusters are classified as BM III. Overall, our classification correlates with BM classification. Yet, there still are possibilities that our classification and BM classification do not agree with each other. This discrepancy is thought to be arisen from the addition of spectroscopically observed cluster member galaxies.

Spectroscopic properties of BCGs

The stellar mass, star formation rate, and emission line fluxes of BCGs are derived from the MPA-JHU value-added catalog for SDSS DR8**. We used SDSS plateID, fiberID, and MJD for galaxy spectra to identify a galaxy from the MPA-JHU catalog. Not all BCGs are included in MPA-JHU catalog, since the catalog is constructed with the galaxy spectra obtained until the DR8. Spectra from SDSS-III, i.e., Baryon Oscillation Spectroscopic Survey (BOSS) is not included. Table 2 shows the number of each type BCGs that are

* http://www.sdss3.org/dr12/spectro/galaxy_mpajhu/

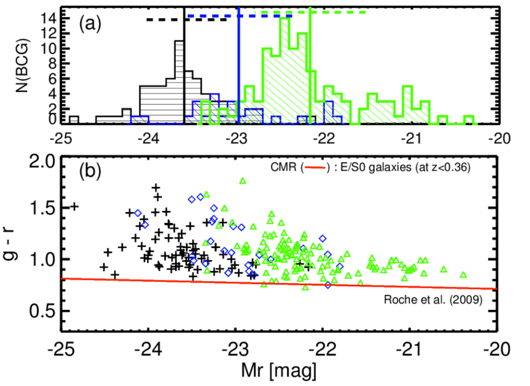

Fig. 4. Distribution of the *r*-band absolute magnitudes of BCGs of different types of clusters. **(Top panel):** Histogram of the *r*-band absolute magnitudes of BCGs. Black, blue, and green solid lines represents S, D, and T-type BCGs. Vertical lines show mean values of *r*-band absolute magnitudes of BCGs in different types of clusters. 1s scatter range for *r*-band absolute magnitudes are marked using dashed horizontal lines. **(Bottom panel):** (*g-r*) vs. M_r color-magnitude diagram of BCGs. Black crosses, blue diamonds, and green triangles represent S, D, and T-type BCGs. Red solid line shows the color-magnitude relation of local (z<0.36) early-type galaxies in SDSS DR6 (Roche et al., 2009).

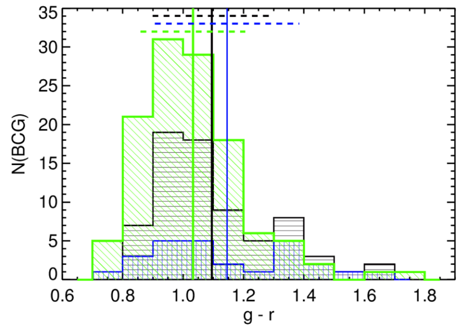

Fig. 5. (*g-r*) color histogram of BCGs of different types of clusters. Black, blue, and green solid lines represent S, D, and T-type BCGs. Vertical solid lines show mean values of (*g-r*) color. The 1s range from the color distribution is overplotted using the horizontal dashed lines.

matched with MPA-JHU catalog.

Results

Luminosities and colors of BCGs

Figure 4a shows the distribution of the *r*-band absolute magnitudes (M_r) of different types of BCGs. S-Type BCGs are marked as black, D- and T-type BCGs are marked as blue and green, respectively.

The magnitude ranges for BCGs in S-type, D-type, T-type galaxy clusters are $-24.8 \le M_r \le -22.2$ for S-type, $-24.1 < M_r < -21.8$ for D-type, and $-23.3 < M_r < -20.4$ for T-type. The average values of M_r are −23.6, −23.0, and −22.2 mag for S, D, and T-type. BCGs in the S-type cluster are the brightest galaxies among all BCGs, while the average luminosity of BCGs decreases for T-type clusters. The standard deviation of absolute magnitude distribution is the largest in the BCGs of T-type, suggesting that T-type galaxy clusters are far from being homogeneous. On the other hand, BCGs in the S-type clusters have relatively narrow range of magnitudes.

Previous studies (e.g., Deng et al., 2008; Vazdekis et al., 2001; Yoon et al., 2008; Roche et al., 2009) have shown that brighter early type galaxies have redder optical colors than the fainter early type galaxies. The tight correlation between the brightness and the color of early type galaxies is known as color-magnitude relation (hereafter CMR). In Fig. 4b, we have investigated the (*g-r*) vs. M_r CMR of BCGs. Regardless of the galaxy cluster morphological type, the CMR of the BCGs are roughly consistent with that of local early type galaxies (Roche et al., 2009) in the faintest end. At the same time, we see many BCGs above the CMR of local early type galaxies, which means BCGs are the reddest among entire early-type galaxies.

Optical colors of the BCGs of different types are not very different with each other (Fig. 5). Although the mean (*g-r*) colors of the T-type BCGs are bluer than that of D-type and S-type BCGs, the difference is less than the 1s scatter of the color distribution. This shows that except the faintest ones, BCGs have similarly red optical colors even compared to the early-type galaxies with comparable luminosity.

Spatial offset of the BCG from the cluster center

We calculated the distance between the BCG and

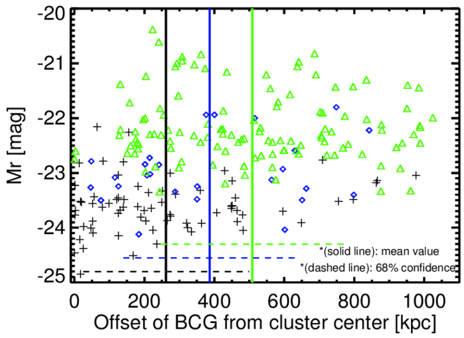

Fig. 6. M_r vs. spatial offset of BCGs from the cluster center. Black crosses, blue diamonds, and green triangles represent S, D, and T-type BCGs. Vertical solid lines show median values of BCG offset from the cluster center for the corresponding cluster types. Dashed lines again show the 1s range for the distribution.

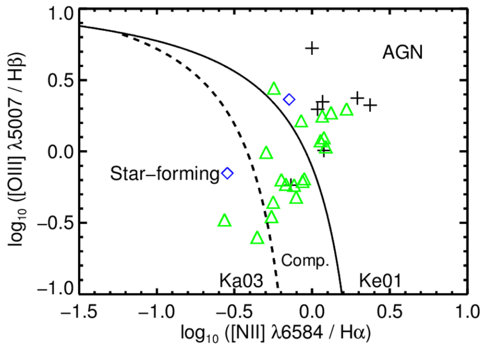

Fig. 7. The BPT diagram for emission line ratio diagnostics, [OIII]λ5007Å/Hβ vs. [NII]λ6584Å/Hα. Black crosses, blue diamonds, and green triangles represent S, D, and T-type BCGs with high ratios of signal-to-noise (S/N≥3) in four emission lines presented in this plot. Solid line (Kewley et al., 2006) and Dashed line (Kauffmann et al., 2003) are used to separate star-forming galaxies and AGN-dominated galaxies.

the cluster center ("offset") to see how the spatial offset changes as a function of BCG type. The cluster center coordinates are visually defined in Abell et al. (1989), in which the authors have selected galaxy clusters based on the visual surveys that estimate the apparent galaxy number densities. The cluster centers were also chosen "visually", looking for the approximate center that can represent the peak of the spatial distribution of the galaxies. Figure 6 shows the distribution of the spatial offset of the BCGs from the cluster center.

It appears that compared to other types of BCGs, S-type BCGs are more centrally located in the cluster. It is no surprise that S-type BCGs are located close to visually selected center since they seem to dominate the brightness distribution in cluster. Among 72 S-type BCGs, ~30% are located within ~100 kpc from the cluster center. Contrarily, the location of T-type BCGs are relatively far from the cluster center. Each type BCGs show wide ranges of spatial offset distribution from the cluster center, which means the scatter is rather large. Despite this large scatter, the difference between the median offsets for S-type and T-type BCGs is not negligible.

Interestingly, there were no D-type BCG that lies closer than 50 kpc from the cluster center. It would be more interesting to see whether these S, D, or T-type BCGs are correlated to the X-ray morphologies of intracluster medium of these clusters through further studies.

AGN activity of BCGs

Before we go on to the study of star formation in galaxies, we investigate the possibilities of hosting Active Galactic Nucleus (AGN) inside the BCG. If the AGN is present in early type galaxy, the emission lines from the AGN may dominate the spectrum of the galaxy (e.g., Bang and Ann, 2009). In that case, the SFRs calculated from the measured emission line fluxes could be overestimated. In order to resolve the issue, we checked the emission line ratios of BCGs.

Figure 7 shows BPT diagram (Baldwin et al., 1981) that is used to distinguish between AGNs and star-forming galaxies for BCGs. Among 54 S-type BCGs, we found six (11%) BCGs that are located above the AGN line and one BCG at composite region. On the other hand, ~12% of the T-type BCGs are classified as AGN-dominated systems while the other ~14% falls in composite region. There exists two T-type BCGs below the AGN line that is classified as star-forming galaxies. We excluded BCGs that are classified as AGN or composite in the following analysis for star formation in these galaxies.

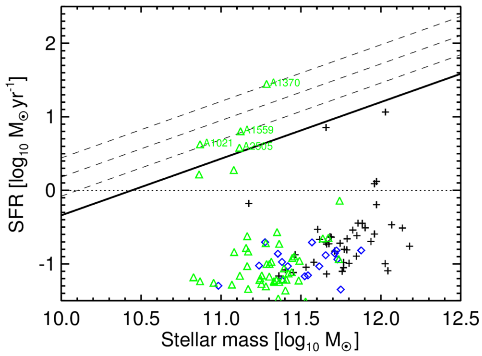

Fig. 8. SFR vs. Stellar mass diagram of BCGs. Black crosses, blue diamonds, and green triangles represent Star-Forming BCGs (SFBCGs) of S, D, and T-types. Horizontal dotted line shows the SFR of $1M_{\odot}yr^{-1}$. From top to bottom, dashed lines show the upper limit of 68% confidence level of local star-forming main sequence, star-forming main sequence, lower limit of 68% confidence for star-forming main sequence (Elbaz et al., 2007). Black solid line indicates the 2s lower limit (i.e., 95% confidence level) of star-forming galaxies at z~0.

Star formation activity of BCGs

Specific star formation rate (sSFR), i.e., star formation rate divided by the stellar mass, is used to diagnose the current ongoing star formation in galaxies compared to the previous star formation (Cooper et al., 2008; Shim, 2013). Galaxies with high specific star formation rate is thought to be actively forming stars. Compared to the star formation rate, specific star formation is more sensitive to ongoing star formation, therefore we investigated star formation rates of BCGs as a function of stellar mass.

Figure 8 shows SFR vs. stellar mass plot for BCGs. BCGs classified as AGNs or composite system based on BPT diagram (Fig. 7) are excluded in this plot. Most BCGs are populated under the solid line that represents 2s lower limit of local star forming main sequence (Elbaz et al., 2007). Considering that most if not all BCGs are passive elliptical galaxies, this is naturally expected. However, we also see that some BCGs do have high star formation rate close to that of star forming galaxies with the similar stellar mass. We marked the Abell number of such BCGs beside the symbols.

Table 3. Number of Star-Forming BCGs

	S-type	D-type	T-type
Total number of BCGs	54	20	71
Number of BCG with SFR>1$M_{\odot}/yr$	4	0	6
Fraction (%) of BCG with SFR>1$M_{\odot}/yr$	7.4	0	8.5
Number of SFBCGs	0	0	4
Fraction (%) of SFBCGs	0	0	5.6

We define those BCGs which have high SFR for the stellar mass as Star-Forming BCGs (hereafter SFBCGs). The criterion for SFBCGs is as follows.

$$SFR_{BCG}[M_{\odot}yr^{-1}]>2.7(M_{*}/10_{11}M_{\odot})^{0.77} \quad (4)$$

We summarize the numbers of SFBCGs in each cluster type in Table 3. We do not have any D-type or S-type SFBCGs. In case of S-type BCGs, we have a small number of BCGs that are marginally under the SFBCG criteria. Although it is difficult to place a firm conclusion since the number of BCG sample is limited, the fraction of SFBCGs is higher for T-type BCGs compared to other types of BCGs.

Discussion

Regardless of the types of BCGs, BCGs are in general classified as red elliptical galaxies. However, our study have shown that S-type BCGs and T-type BCGs are clearly distinguished in terms of their luminosity. S-type BCGs are the brightest BCGs among all BCGs, whereas T-type BCGs are the faintest ones. The magnitude range of S-type BCGs is much narrower than other types of BCGs, therefore we suggest that S-type BCGs may be treated as relatively homogeneous galaxy population which consist of bright, evolved galaxies. BCGs have been used as a standard candle because of the low scatter (~0.3 mag) in their absolute magnitude (Whiley et al., 2008). To be used as a standard candle, it should be guaranteed that the cluster and BCG in it is an evolved, S-type BCGs.

The luminosity of the BCG for the cluster is correlated with the dominance of the BCG in the cluster. The result we found from above sections is that if there exist several bright galaxies of similar magnitudes in the cluster, the luminosity of the BCG decreases. Based on the hierarchical merging scenario of galaxy formation (Dubinski, 1998; De Lucia and Blaizot, 2007), we expect galaxies grow through merging of smaller galaxies. The fact that S-type BCGs are the brightest among the entire types of BCGs, and also S-type BCGs have narrow range of magnitude, suggest that these types of BCGs are likely to be the most evolved elliptical galaxies.

Color-magnitude distribution of BCGs show that BCGs have redder color compared to that of local early type galaxies (Roche et al., 2009). Naturally expected from CMR is that S-type BCGs, brightest among all, are redder than T-type BCGs that are faintest. However, the mean (*g*-*r*) color of the different types of BCGs are similar with each other. Although the scatter is large, we notice that D-type BCGs have even redder (*g*-*r*) color compared to that of S-type BCGs. The color of a galaxy reflects the integrated color from stellar population that consist a galaxy. The red colors of galaxies may result from higher metallicity or old stellar population. Therefore the fact that BCGs have redder colors compared to average CMR suggests the possibility of early exhaustion of gas that can fuel further star formation inside these BCGs. D-type BCGs that contain a competitive companion galaxy with a similar luminosity are more likely to grow "old" compared to other isolated ellipticals.

Significant fraction of BCGs are partly or entirely powered by AGN. The fraction of AGN-dominated or AGN-star formation composite system among BCGs reaches ~10%. The fraction of composite system is higher in T-type BCGs than S-type BCGs. While no S-type BCGs are classified as star formation dominated, there exist two T-type BCGs that are star formation dominated. This shows that S-type and T-type BCGs may be in different evolution stage, i.e., while the central black hole in T-type BCGs is still developing, S-type BCGs show already evolved or past nuclear activity.

Excluding the AGN-dominated or composite systems, several 'star-forming' BCGs are found to have relatively high specific SFR. All SFBCGs are T-type BCGs, which consist ~6% of the entire T-type BCGs. Star formation seems to be shut off in all S-type BCGs. There is no D-type SFBCGs either, supporting the idea that these BCGs with comparative companion are not able to produce stars any more due to the lack of the gas reservoir. Further morphological or kinematic investigation on SFBCGs would provide valuable insights on the factor that causes star formation in BCGs, however it is beyond the scope of this paper.

Summary

We have classified Abell clusters based on the *r*-band magnitude differences between bright galaxies, and investigate the properties of BCGs as a function of cluster type. The conclusion of this study is as follows.

1. From 1267 Abell clusters covered in SDSS, we have identified 72 S-type, 26 D-type, and 119 T-type BCGs using the magnitude differences between bright member galaxies.

2. S-type BCGs are brighter than D-type or T-type BCGs. In terms of standard deviation in the brightness distribution, S-type BCGs have the smallest standard deviation, which means this type of BCGs may be used as standard candle while other types of BCGs may not. S-type BCGs tend to be concentrated to the center of the cluster than any other types of BCGs.

3. Comparing optical CMR of BCGs with that of the local early type galaxies, BCGs tend have redder color. This supports the scenario of early shut out of star formation during the BCG growth. The mean (*g*-*r*) colors of BCGs were more or less consistent for different types of clusters.

4. ~10% of the entire BCGs are AGN-dominated systems. We see higher fraction of composite systems in T-type BCGs than S-type BCGs, which suggests that T-type BCGs may still be in a stage of AGN development.

5. Although the fraction is less than a few %, there exist star-forming BCGs that have SSFR comparable to that of local star-forming galaxies. These consist

~6% of the T-type BCGs. We conclude that T-type BCGs are still in the process of growing, while S-type BCGs have passed such stage long ago.

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References

Abell, G. O., 1958, The distribution of rich clusters of galaxies. The Astrophysical Journal Supplement Series, 3, 211-288.

Abell, G. O., Corwin, H. G., Jr., and Olowin, R. P., 1989, A catalog of rich clusters of galaxies. The Astrophysical Journal Supplement Series, 70, 1-138.

Bahcall, N. A., McKay, T. A., Annis, J., Kim, R. S., Dong, F., Hansen, S., Goto, T., Gunn, J. E., Miller, C., Nichol, R. C., Postman, M., Schneider, D., Schroeder, J., Voges, W., Brinkmann, J., and Fukugita, M., 2003, A merged catalog of clusters of galaxies from early Sloan Digital Sky Survey data. The Astrophysical Journal Supplement Series, 148(2), 243-274.

Baldwin, J. A., Phillips, M. M., and Terlevich, R., 1981, Classification parameters for the emission-line spectra of extragalactic objects. Publications of the Astronomical Society of the Pacific, 93, 5-19.

Bang, J. and Ann, H. B., 2009, Star formation rate and AGN in barred galaxies, Journal of the Korean Earth Science Society, 34(5), 407-414.

Bautz, L. P. and Morgan, W. W., 1970, On the classification of the forms of clusters of galaxies. The Astrophysical Journal, 162, 149-153.

Cooper, M. C., Newman, J. A., Weiner, B. J., Yan, R., Willmer, C. N., Bundy, K., Coil, A. L., Conselice, C. J., Davis, M., Faber, S. M., Gerke, B. F., Guhathakurta, P., Koo, D. C., and Noeske, K. G., 2008, The DEEP2 galaxy redshift survey: the role of galaxy environment in the cosmic star formation history. Monthly Notices of the Royal Astronomical Society, 383(3), 1058-1078.

Cowie, L. L. and Binney, J., 1977, Radiative regulation of gas flow within clusters of galaxies-A model for cluster X-ray sources. The Astrophysical Journal, Part 1, 215, 723-732.

De Lucia G., Springel V., White S. D. M., Croton D., and Kauffmann G., 2006, The formation history of elliptical galaxies. Monthly Notices of the Royal Astronomical Society. 366, 499-509.

De Lucia G. and Blaizot, J., 2007, The hierarchical formation of the brightest cluster galaxies. Monthly Notices of the Royal Astronomical Society. 375, 2-14.

Deng, X. F., He, J. Z., Luo, C. H., Wu, P., and Xin, Y., 2008, The correlations among color, morphology, and luminosity for the main galaxy sample of the SDSS data release 5. Acta Physica Polonica B, 39(4), 965-977.

Donzelli, C. J., Muriel, H., and Madrid, J. P., 2011, The luminosity profiles of brightest cluster galaxies. The Astrophysical Journal Supplement Series, 195(2), 15-22.

Dressler, A., 1980, Galaxy morphology in rich clusters - Implications for the formation and evolution of galaxies. The Astrophysical Journal, 236, 351-365.

Dubinski, J., 1998, The origin of the brightest cluster galaxies. The Astrophysical Journal, 502, 141-149.

Elbaz, D., Daddi, E., Le Borgne, D., Dickinson, M., Alexander, D. M., Chary, R. R., Starck, J., Brandt W. N., Kitzbichler, M., MacDonald, E., Nonino, M., Popesso, P., Stern, D., and Vanzella, E., 2007, The reversal of the star formation-density relation in the distant universe. Astronomy & Astrophysics, 468(1), 33-48.

Fasano, G., Vanzella, E., Dressler, A., Poggianti, B. M., Moles, M., Bettoni, D., Valentinuzzi, T., Moretti, A., D'Onofrio, M., Varela, J., Couch, W. J., Kjærgaard, P., Fritz, J., Omizzolo, A., and Cava, A., 2012, Morphology of galaxies in the WINGS clusters. Monthly Notices of the Royal Astronomical Society, 420(2), 926-948.

Hausman, M. A. and Ostriker, J. P., 1978, Galactic cannibalism. III-The morphological evolution of galaxies and clusters. The Astrophysical Journal, Part 1, 224, 320-336.

Kauffmann, G., Heckman, T. M., Tremonti, C., Brinchmann, J., Charlot, S., White, S. D., Ridgway, S, E., Brinkmann, J., Fukugita, M., Hall, P. B., Ivezic, Ž., Richards, G. T., and Schneider, D. P., 2003, The host galaxies of active galactic nuclei. Monthly Notices of the Royal Astronomical Society, 346(4), 1055-1077.

Kewley, L. J., Groves, B., Kauffmann, G., and Heckman, T., 2006, The host galaxies and classification of active galactic nuclei. Monthly Notices of the Royal Astronomical Society, 372(3), 961-976.

Kormendy, J., 1989, Did elliptical galaxies form by mergers or by dissipative collapse?. The Astrophysical Journal, Part 2-Letters, 342, L63-L66.

Lin, Y. T. and Mohr, J. J., 2004 K-band properties of galaxy clusters and groups: brightest cluster galaxies and intracluster Light. The Astrophysical Journal, 617(2), 879.

Liu, F. S., Mao, S., and Meng, X. M., 2012, Star formation activities in early-type brightest cluster galaxies. Monthly Notices of the Royal Astronomical Society, 423(1), 422-436.

Merritt, D., 1985, Relaxation and Tidal Stripping in Rich Clusters of Galaxies. III-Growth of a massive central galaxy. The Astrophysical Journal, Part 1, 289, 18-32.

Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A., 1996, Galaxy harassment and the evolution of clusters of galaxies. Nature, 379, 613-616.

Ostriker, J. P. and Tremaine, S. D., 1975, Another evolutionary correction to the luminosity of giant galaxies. The Astrophysical Journal, 202, 113-117.

Park, C., Choi, Y. Y., Vogeley, M. S., Gott III, J. R., Blanton, M. R., and SDSS Collaboration, 2007, Environmental dependence of properties of galaxies in the Sloan Digital Sky Survey. The Astrophysical Journal, 658(2), 898-916.

Park, C. and Hwang, H. S., 2009, Interactions of galaxies in the galaxy cluster environment. The Astrophysical Journal, 699(2), 1595-1609.

Richardson, T. S., Bailer, H., and Banerjee, M., 1999, Specification searches using MAG Models. In Proceedings, ISI Conference, Helsinki.

Roche, N., Bernardi, M., and Hyde, J., 2009, Spectral-based k-corrections and implications for the colour-magnitude relation of E/S0s and its evolution. Monthly Notices of the Royal Astronomical Society, 398(3), 1549-1562.

Rostagni, F., Benoist, C., and Maurogordato, S., 2011, Morphological classification of galaxy clusters. Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, 185-189.

Sandage, A. and Hardy, E., 1973, The redshift-distance relation. VII Absolute magnitudes on the first three ranked cluster galaxies as functions of cluster richness and Bautz-Morgan cluster type: the effect of q_{o}. The Astrophysical Journal, 183, 743-758.

Schombert, J. M., 1986, The structure of brightest cluster members. I -Surface photometry. The Astrophysical Journal Supplement Series, 60, 603-693.

Shim, H., 2013, Global star formation efficiency of local galaxies, Journal of the Korean Earth Science Society, 34(5), 407-414.

Struble, M. F. and Rood, H. J., 1987, A catalog of morphological properties of the 2712 Abell clusters. The Astrophysical Journal Supplement Series, 63, 555-613.

Valotto, C. A., Nicotra, M. A., Muriel, H., and Lambas, D. G., 1997, The luminosity function of galaxies in clusters. The Astrophysical Journal, 479(1), 90.

van Dokkum, P. G. and Franx, M., 2001, Morphological evolution and the ages of early-type galaxies in clusters. The Astrophysical Journal, 553, 90-102.

Vazdekis, A., Kuntschner, H., Davies, R. L., Arimoto, N., Nakamura, O., and Peletier, R., 2001, On the origin of the color-magnitude relation in the Virgo cluster. The Astrophysical Journal Letters, 551(2), L127.

Whiley, I. M., Aragón-Salamanca, A., De Lucia, G., Von Der Linden, A., Bamford, S. P., Best, P., Bremer, M. N., Jablonka, P., Johnson, O., Milvang-Jensen, B., Noll, S., Poggianti, B. M., Rudnick, G., Saglia, R., White, S., and Zaritsky, D., 2008, The evolution of the brightest cluster galaxies since z~ 1 from the ESO distant cluster survey (EDisCS). Monthly Notices of the Royal Astronomical Society, 387(3), 1253-1263.

Yoon, J. H., Schawinski, K., Sheen, Y. K., Ree, C. H., and Sukyoung, K. Y., 2008, A spectrophotometric search for galaxy clusters in SDSS. The Astrophysical Journal Supplement Series, 176(2), 414-423.

York, D. G., Adelman, J., Anderson Jr, J. E., Anderson, S. F., Annis, J., Bahcall, N. A., Bakken, J. A., Barkhouser, R., Bastian, S., Berman, E., Boroski, W. N., Bracker, S., Briegel, C., Briggs, J. W., Brinkmann, J., Brunner, R., Burles, S., Carey, L., Carr, M. A., Castander, F. J., Chen, B., Colestock, P. L., Connolly, A. J., Crocker, J. H., Csabai, I., Czarapata, P. C., Davis, J. E., Doi, M., Dombeck, T., Eisenstein, D., Ellman, N., Elms, B. R., Evans, M. L., Fan, X., Federwitz, G. R., Fiscelli, L., Friedman, S., Frieman, J. A., Fukugita, M., Gillespie, B., Gunn, J. E., Gurbani, V. K., de Haas, E., Haldeman, M., Harris, F. H., Hayes, J., Heckman, T. M., Hennessy, G. S., Hindsley, R. B., Holm, S., Holmgren, D. J., Huang, C., Hull, C., Husby, D., Ichikawa, S., Ichikawa, T., Ivezic, Ž., Kent, S., Kim, R. S. J., Kinney, E., Klaene, M., Kleinman, A. N., Kleinman, S., Knapp, G. R., Korienek, J., Kron, R. G., Kunszt, P. Z., Lamb, D. Q., Lee, B., Leger, R. F., Limmongkol, S., Lindenmeyer, C., Long, D. C., Loomis, C., Loveday, J., Lucinio, R., Lupton, R. H., MacKinnon, B., Mannery, E. J., Mantsch, P. M., Margon, B., McGehee, P., McKay, T. A., Meiksin, A., Merelli, A., Monet, D. G., Munn, J. A., Narayanan, V. K., Nash, T., Neilsen, E., Neswold, R., Newberg, H. J., Nichol, R. C., Nicinski, T., Nonino, M., Okada, N., Okamura, S., Ostriker, J. P., Owen, R., Pauls4, A. G., Peoples, J., Peterson, R. L., Petravick, D., Pier, J. R., Pope, A., Pordes, R., Prosapio, A., Rechenmacher, R., Quinn, T. R., Richards, G. T., Richmond, M. W., Rivetta, C., Constance, H., Rockosi, M., Ruthmansdorfer, K., Sandford, D., Schlegel, D. J., Schneider, D. P., Sekiguchi, M., Sergey, G., Shimasaku, K., Siegmund, W. A., Smee, S., Smith, J. A., Snedden, S., Stone, R., Stoughton, C., Strauss, M. A., Stubbs, C., SubbaRao, M., Szalay, A. S., Szapudi, I., Szokoly, G. P., Thakar5, A. R., Tremonti, C., Tucker, D. L., Uomoto, A. Berk, D. V., Vogeley, M. S., Waddell, P., Wang, S., Watanabe, M., Weinberg, D. H., Yanny, B., and Yasuda, Naoki., 2000. The Sloan digital sky survey: Technical summary. The Astronomical Journal, 120(3), 1579-1587.

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