MEASURABLE RELATIONSHIP BETWEEN BRIGHT GALAXIES AND THEIR FAINT COMPANIONS IN WHL J085910.0+294957, A GALAXY CLUSTER AT z = 0.30: VESTIGES OF INFALLEN GROUPS?

JOON HYEOP LEE1,2, HYE-RAN LEE1,2, MINJIN KIM1,2,3,5, KWANG-IL SEON1,2, SANG CHUL KIM1,2, SOLUNG-CHUL YANG1,3,5, CHANG HEE REE1, JONG CHUL LEE1, HYUNJIN JEOG1,2, JONGWAN KO1, and CHANGSU CHO1

1 Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea; jhl@kasi.re.kr
2 Korea University of Science and Technology, Daejeon 305-350, Korea
3 The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
4 CEOU/Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea

Received 2013 September 26; accepted 2014 June 24; published 2014 July 30

ABSTRACT

The properties of satellite galaxies are closely related to their host galaxies in galaxy groups. In cluster environments, on the other hand, the interaction between close neighbors is known to be limited. Our goal is to examine the relationships between host and satellite galaxies in the harsh environment of a galaxy cluster. To achieve this goal, we study a galaxy cluster WHL J085910.0+294957 at z = 0.30 using deep images obtained with CQUEAN CCD camera mounted on the 2.1 m Otto Struve Telescope. After member selection based on the scaling relations of photometric and structural parameters, we investigate the relationship between bright (M_i < -18) and their faint (-18 < M_i < -15) companions. The weighted mean color of faint companion galaxies shows no significant dependence (<1σ to bootstrap uncertainties) on cluster-centric distance and local luminosity density as well as the luminosity and concentration of an adjacent bright galaxy. However, the weighted mean color shows marginal dependence (~2.2σ) on the color of an adjacent bright galaxy when the sample is limited to bright galaxies with at least two faint companions. By using a permutation test, we confirm that the correlation in color between bright galaxies and their faint companions in this cluster is statistically significant with a confidence level of 98.7%. The statistical significance increases if we additionally remove non-members using the Sloan Digital Sky Survey photometric redshift information (~2.6σ and 99.3%). Our results suggest three possible scenarios: (1) vestiges of infallen groups, (2) dwarf capturing, and (3) tidal tearing of bright galaxies.

Key words: galaxies: clusters: individual (WHL J085910.0+294957) – galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation

Online-only material: color figures

1. INTRODUCTION

Today, it is widely accepted that the properties of galaxies are significantly affected by their environments. Galaxies in high-density environments tend to have red colors, early-type morphologies, high masses, poor gas reservoirs, and low star formation rates (e.g., Dressler 1980; Kauffmann et al. 2004; Baldry et al. 2006; Park et al. 2007; Poggianti et al. 2008; Lee et al. 2010), although such dependence of galaxy properties on environments moderately varies according to the environmental scales (Blanton & Berlind 2007) or the definition of environmental parameters (Muldrew et al. 2012; Haas et al. 2012). It has been also revealed that such trends of environmental effects vary as a function of redshift (e.g., Butcher & Oemler 1984; Scoville et al. 2013). For example, the locally observed relationship between star formation and local density is already established at z ~ 0.5 (Goto et al. 2003), but it appears to be reversed at z ~ 1, which means that galaxies at high redshifts tend to form stars actively at high-density environments (Elbaz et al. 2007; Cooper et al. 2008; Popesso et al. 2011).

Galaxy clusters are the highest density environments in the universe and are thought to accelerate the evolution of galaxies by various mechanisms. In such high-density environments, member galaxies frequently experience galaxy–galaxy close encounters, which can cause galaxy harassment (Moore et al. 1996, 1999) and galaxy–galaxy hydrodynamic interaction (Park & Hwang 2009). The deep gravitational potentials of galaxy clusters may also often give rise to the interaction between galaxies and the cluster potential itself (Merritt 1984; Gnedin 2003). Moreover, since galaxy clusters typically have a large amount of hot gas with high pressure, the internal gas contents of galaxies can be strongly affected by the mechanisms such as ram pressure stripping (Gunn & Gott 1972; Quilis et al. 2000) and strangulation (Larson et al. 1980; Bekki et al. 2002). On the other hand, in less dense environments like galaxy groups or fields, the tidal interactions between close neighbors or interactions with satellite galaxies also become an important driver for the galaxy evolution. Byrd & Valtonen (1990) and many other following studies have shown that the physical properties of galaxies (morphology, color, gas and dust contents, star formation, active galactic nucleus activities, and so on) are significantly influenced by the tidal interactions between individual galaxies (e.g., Hernández-Toledo et al. 2006; Perez et al. 2006; Coziol & Pichau-Frayn 2007; Bessiere et al. 2012; Lee et al. 2012; Patton et al. 2013).

In a small galaxy group consisting of a bright host galaxy and its satellites, the collective properties of the satellite galaxies are expected to affect the properties of the host galaxy through the accretion of satellites onto the massive galaxy (Paudel et al. 2013). As well as such merger events, gas looting by hydrodynamic interaction is another channel for how host and satellite galaxies affect each other—typically massive host galaxies tend to deprive their satellites of gas (a good example is the Milky Way Galaxy and the Large Magellanic Cloud; e.g., Mastroietro et al. 2005). It is also known that the tidal
stripping efficiency of satellites depends on the morphology of their host galaxy as well as their own morphologies (Chang et al. 2013). Satellite galaxies in a group seem to suffer transformation in color and morphology, possibly through strangulation, disk fading, galaxy mergers, or close tidal encounters (George et al. 2013). As a result, the luminosity function and spatial distribution of satellites depend on the properties of their host galaxy (Lares et al. 2011) and the properties of satellite galaxies are known to be sensitive to the group properties such as halo mass, local density, and dynamical state (Peng et al. 2012; Carollo et al. 2013; Woo et al. 2013). The early-type fraction of satellites is found to be significantly higher in a halo with an early-type host galaxy than in a halo with a late-type host galaxy with the same mass (so-called “galactic conformity”; Weinmann et al. 2006; Ann et al. 2008). More recently, Phillips et al. (2013) argued that the satellites of bright isolated galaxies show differences in their star formation activities according to the host properties, in the sense that 30% of satellites around quiescent host galaxies suffer star formation quenching, while 0% around star-forming host galaxies do.

From these environmental effects in different (large and small) scales, one question rises: how do the effects in different scales work in a high-density environment such as a galaxy cluster? In other words, in a galaxy cluster where the large-scale environmental effects are strong, how significant are the effects of small-scale interactions? It was previously pointed out that due to the high velocity dispersion of a galaxy cluster, the encounter time between cluster galaxies is too short to produce tidal energy enough to significantly affect galaxy structure (Merritt 1984; Byrd & Valtonen 1990; Boselli & Gavazzi 2006). From observational data, Park & Hwang (2009) showed that the properties of galaxies suddenly start to depend on the cluster-centric distance at fixed neighbor environment with a characteristic scale of 1–3 × virial radius, which implies that the effect of direct galaxy–galaxy tidal interactions is less significant in a galaxy cluster, although they argued that the galaxy–galaxy hydrodynamic interactions still play an important role even in a cluster environment. The current consensus is that the role of tidal interactions between galaxies is not crucial to determine the properties of galaxies in a galaxy cluster. However, the galaxy sample in most previous studies are limited to bright galaxies, and faint dwarf galaxies are hardly considered; for example, Park & Hwang (2009) used a sample of galaxies with $M_r \leq -17$. Thus, currently it is not certain whether the properties of bright cluster galaxies are related to their faint companions or not. In other words, the close relationship between host and satellite galaxies shown in a group scale is yet to be investigated in galaxy cluster environments. Our goal is to statistically address the relationships between bright cluster galaxies and their faint companions (i.e., their possible satellites).

To achieve our goal, we carry out a case study of WHL J085910.0+294957, a galaxy cluster at $z = 0.30$, using two-band deep photometric data. The outline of this paper is as follows. Section 2 describes our observations, data reduction, and photometry. The analysis methods are shown in Section 3, including cluster member selection and parameter definitions. The results are presented in Section 4 and their implication is discussed in Section 5. Section 6 gives the conclusion. Throughout this paper, we adopt the following cosmological parameters: $h = 0.7$, $\Omega_M = 0.7$, and $\Omega_M = 0.3$.

6 This cluster is also called as CMBCG J134.79176+29.83268 or MaxBCG J134.79176+29.83268.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Target Information

Our target cluster WHL J085910.0+294957 was identified by using the Sloan Digital Sky Survey (SDSS; York et al. 2000) data in Koester et al. (2007), Wen et al. (2009), and Hao et al. (2010). They detected optically rich galaxy clusters based on the fact that rich clusters typically show tight red sequences and many of them have brightest cluster galaxies (BCGs) in their centers (maxBCG red-sequence method; see those papers for more details). Among the tens of thousands of galaxy clusters listed in Koester et al. (2007) and Hao et al. (2010), we first selected target candidates so that the telescope field-of-view (see Section 2.2) covers at least 1 Mpc diameter of the targets. After that, we chose WHL J085910.0+294957 at $z = 0.2998$ as the final target cluster, which shows very obvious clustering of bright galaxies in the visual inspection. The spectroscopic redshift of the BCG is available ($z = 0.2656$), but the representative redshift value was estimated from the photometric redshifts of the 35 member galaxies. The scaled richness is 41, which is defined as the number of E/S0 member galaxies brighter than 0.4$L^*$ and within $R_{200}$ of the cluster center, $R_{200}$ being the radius within which the density of galaxies with $-24 \leq M_r \leq -16$ is 200 times the mean density of such galaxies. Note that this value is larger than the measured richness, 35, which is the number of members found in their cluster-finding algorithm (Koester et al. 2007). The right ascension and declination (J2000) of the cluster are 8°59′10.8 and 29°49′57.9′′, respectively, which was determined from the coordinates of the BCG (Koester et al. 2007).

2.2. Observations

The observations were carried out on 2012 February 9–10 using the Camera for QUasars in EArly uNiverse (CQUEAN; Park et al. 2012) mounted on the 2.1 m Otto Struve Telescope in the McDonald Observatory, USA. CQUEAN is a CCD camera with 1024 by 1024 pixels and its field of view is 4′7 × 4′7 when mounted on the 2.1 m Telescope, which corresponds to 0′276 pixel$^{-1}$. CQUEAN is designed to efficiently detect long-wavelength visible and near-infrared light. During the two clear nights, total exposures are 13,700 and 17,460 s in the $r$ and $i$ bands, respectively. The stacked $i$-band image of WHL J085910.0+294957 is displayed in Figure 1. The typical seeing size ranges from 1′′5 to 2′′0, which corresponds to the physical scale of 6.7–8.9 kpc at $z = 0.3$.

In the observed images, the central BCG is clearly identified and several bright galaxies are found to be linearly aligned around the BCG. The existence of a distinct BCG indicates that this cluster started to be assembled long time ago (e.g., De Lucia & Blaizot 2007). However, the linear structure of bright galaxies implies that this cluster is not currently in a dynamically relaxed state.

2.3. Data Reduction and Photometry

The observed images were processed using the standard IRAF (Tody 1986) packages: pre-processing, aligning, and image combining. The Source Extractor (Bertin & Arnouts 1996) was used for our photometry of galaxies, in dual mode with $i$-band reference. Standard calibration and astrometry were conducted by comparing our catalog with the SDSS Data Release 7 (Abazajian et al. 2009). Figure 2(a) shows the distribution of stellarities along magnitude provided by the Source Extractor, in which we select the objects with...
Figure 1. Stacked $i$-band image of WHL J085910.0+294957, observed using the Otto Struve 2.1 m Telescope and CQUEAN CCD camera. The field of view is $4.7 \times 4.7$ and the dashed circle displays the analysis area with a radius of 400 pixels ($\sim 110''$).

stellarity $\leq 0.9$ as galaxies. Figure 2(b) displays the photometric error versus magnitude of the selected galaxies in our images. All magnitudes in this paper are in the AB system. To secure reasonable signal-to-noise ratios in detection, we use objects brighter than $i = 25.39$ ($M_i = -15$ at $z = 0.3$). At $i = 25.39$, the $i$-band magnitude uncertainty is about 0.2, which approximately corresponds to the signal-to-noise ratio of five. The depth of our observation is deeper by $\sim 4$ mag than that of the SDSS; our observation of newly added faint objects with $21 \lesssim i \lesssim 25$, which roughly corresponds to $0.01 L_\odot \lesssim L \lesssim 0.4 L_\odot$ at $z = 0.3$ (when the characteristic magnitude $i_* \approx 20$ is supposed; Harsono & De Propris 2007, and Section 3.1 in this paper).

The number of objects satisfying $i \leq 25.39$ and stellarity $\leq 0.9$ is 901. However, the outer parts of CQUEAN images suffer from vignetting as shown in Figure 1. Since the area farther than 400 pixels from the image center shows significant decrease in the mean background level (larger than 3$\sigma$ of local background fluctuation), we use only the objects within 400 pixels from the image center (the analysis area denoted with a dashed circle in Figure 1). The final catalog of galaxies includes 402 objects. The correction for foreground reddening has been carried out using the reddening map of Schlegel et al. (1998) and the reddening law of Cardelli et al. (1989): $E(B - V) = 0.029$, $A_r = 0.080$, and $A_i = 0.061$. $K$-correction has not been applied to the cluster galaxies.

3. ANALYSIS

3.1. Cluster Member Selection

The 402 galaxies selected in Section 2.3 are not necessarily the members of the galaxy cluster WHL J085910.0+294957, but this sample may include many foreground and background objects. If there exist some very strong intrinsic trends in the genuine cluster member galaxies, we may be able to catch signals for the trends even though we do not remove

---

7 The distance modulus adopted for this galaxy cluster is $m - M = 40.39$. 
control field subtraction (e.g., De Propris et al. 2001) and red sequence selection (e.g., De Propris et al. 2001). This galaxy cluster due to the observational limitation. It would be very difficult to secure the spectra of many faint dwarf galaxies in our sample. Moreover, even if there were chances to get clearer results, the best way to remove foreground and background contamination is to use their redshift information. For example, tight red sequences are easily found in most rich clusters even without member selection. The probability of multi-object spectroscopic observations, it would be very difficult to secure the spectra of many faint dwarf galaxies in this galaxy cluster due to the observational limitation.

There are some alternative methods for the membership selection of cluster galaxies, such as control field subtraction (e.g., Paolillo et al. 2001) and red sequence selection (e.g., De Propris & Pritchet 1998). The control field subtraction is a statistical method typically used for deriving cluster galaxy luminosity functions. However, this is not suitable for our purpose because this method removes contamination not individually but statistically and collectively (in other words, we cannot distinguish whether a given individual galaxy is a member or not). On the other hand, the red sequence selection may be used for our study in the sense that it removes contamination individually. However, this method also has an obvious limitation because it selects only red galaxies and misses possible cluster members with blue colors.

In this paper, we extend the concept of red sequence selection method to choose individual member galaxies better. That is, we adopt three scaling relations of galaxies: color–magnitude relation (CMR), size–magnitude relation (SMR), and concentration–magnitude relation (ConMR).

In the CMR method, we select cluster members based on the color distribution expected at $z = 0.3$, which was estimated using the SDSS data as shown in Figure 3, instead of cutting a narrow range of colors as is done in the red sequence selection. To derive the $z = 0.3$ expected color distribution, we first corrected the systematic differences between the magnitudes and colors in this paper and those in the SDSS (mainly due to the difference in aperture definition), which were measured using six bright ($i < 18$) galaxies found both in the SDSS and our catalog to be

$$i_{TP} = i_{SDSS} + 0.0787,$$

$$r - i_{TP} = (r - i_{SDSS} - 0.1732),$$

where $i_{TP}$ and $(r - i)_{TP}$ denote the $i$-band magnitude and $r$–$i$ color in this paper (TP), respectively. The values of 0.0787 and −0.1732 are the medians for the six galaxies, where the sample interquartile ranges are 0.0123 and 0.0109 for $\Delta i$ and $\Delta (r - i)$, respectively. After that, the expected colors of SDSS galaxies with spectroscopic redshifts when they moved to $z = 0.3$ were calculated using the method of Blanton et al. (2003). We defined envelopes including 95% of those SDSS galaxies as shown in Figure 3, which we regard as the expected CMR range at $z = 0.3$. With this criterion, 194 of 402 galaxies are selected as cluster members.

The second scaling relation is the SMR (e.g., Trujillo et al. 2004; Nair et al. 2010; Lee et al. 2013). Although the SMR is not tight enough to select cluster members accurately, we can use it to remove objects with obviously unreasonable sizes (i.e., too deviated from the SMR). This is possible because the angular...
galaxies within ±i sample with least-squares fit in the size–magnitude diagram using our galaxy select the cluster members goes as follows. (1) Derive the linear and the SMR estimated using our own data, the process to spectroscopic data. With the dispersion value from the SDSS physical scale at given absolute magnitude) from the SDSS, we brought only the estimation and total luminosity definition. Hence, instead of the SMR in our data with that in some others such as the SDSS apparent magnitudes.

show difference in the relation between their angular sizes and sizes are the combinations of physical sizes and redshifts. Since the ratio of luminosity distance to angular diameter distance is (1 + z)², the objects at different redshifts are expected to show difference in the relation between their angular sizes and apparent magnitudes.

In this selection, however, it is not easy to directly compare the SMR in our data with that in some others such as the SDSS data because the size is a parameter sensitive to background estimation and total luminosity definition. Hence, instead of using the SMR itself from the SDSS, we brought only the dispersion in the SMR (more exactly, the size dispersion in physical scale at given absolute magnitude) from the SDSS spectroscopic data. With the dispersion value from the SDSS and the SMR estimated using our own data, the process to select the cluster members goes as follows. (1) Derive the linear least-squares fit in the size–magnitude diagram using our galaxy sample with i ≤ 25.39. (2) Build a sub-sample including galaxies within ±0.27 in log R50, from the estimated linear relation, where R50, is the semimajor axis length of ellipse containing 50% of the Petrosian flux in the i band. Here, the dispersion cut 0.27 is the value from the SDSS SMR, which includes 95% of the SDSS galaxies. (3) Using the sub-sample, re-estimate the linear least-squares fit. (4) Repeat (2) and (3) one more time, resulting in a total of three times iteration for the clipping and fitting process.

The final estimated SMR is

\[ \log(R50/kpc) = -0.0486 \times M_i - 0.2126. \] (3)

We reject the objects deviated by more than 0.27 in log R50, from this relation, as shown in Figure 4. As a result, 46 of 402 (or 28 of the CMR-selected 194) objects are rejected from our cluster member sample because they are too large or too small compared to their magnitudes.

Similarly, we select cluster members in the ConMR, as presented in Figure 5. The light concentration itself is a parameter that is hardly affected by redshift, but concentration values are known to strongly depend on absolute magnitudes in the sense that more luminous galaxies tend to be more concentrated on average (e.g., Lee et al. 2008). This fact can be used in rough selection of cluster members; for example, Lieder et al. (2012) used the Sérsic index cut to select faint members of the Virgo Cluster, where the Sérsic index is closely related to light concentration (e.g., Graham et al. 2001). Here, we apply a selection process similar to the selection based on the SMR described in the previous paragraphs. The clipping range is selected to be ±0.7 in R90/R50(i), which was derived from the ConMR of the SDSS galaxies with spectroscopic information, including 95% of the SDSS galaxies. R90/R50(i) is the ratio between semimajor axis lengths of ellipses containing 90% and 50% of the Petrosian flux in the i band.

The final estimated ConMR is

\[ \log(R90/R50(i)) = -0.1105 \times M_i + 0.0166. \] (4)

We reject the objects deviated by more than 0.7 in R90/R50(i) from this relation at Mi > −18, but we do not reject highly concentrated galaxies at Mi ≤ −18 because bright early-type galaxies often have very high concentration values (e.g., Bernardi et al. 2010). As a result, 21 of 402 (or 10 of the CMR- and SMR-selected 166) objects are rejected from our cluster member sample due to their unusual concentration values. The
final cluster members are selected by applying the three criteria simultaneously, which yields the final sample of 156 galaxies.

Note that the SMR and ConMR selections have a risk at faint end because the sizes of very faint objects can be mis-measured. Our SMR and ConMR criteria may reject such potentially mis-measured objects. However, if there is a problem in size measurement for a given object, the flux measurement for that object may also have a problem and thus it may be better to reject such an object for higher reliability in the analysis.

Among the selected cluster members, we define galaxies with $M_i \lesssim -18$ as bright galaxies, which yields 65 bright galaxies, and the ones with $M_i > -18$, closer than 100 kpc to individual bright galaxies as their faint companions (possible satellites). These bright galaxies and their faint companions do not necessarily have genuine host–satellite relationships harboring dark matter halos, to confirm what dynamical information of those objects is required. Thus, we regard those galaxies as candidates for genuine host and satellite galaxies. The magnitude cut of $M_i = -18$ is much fainter than typical characteristic luminosity in a galaxy luminosity function, but the fraction of blue cloud galaxies is known to start increasing significantly at about this magnitude (De Propris et al. 2013). In Figure 6, the bimodal distribution of galaxy luminosity is quite well divided into bright and faint groups by the $M_i = -18$ cut.

In addition to our main sample of cluster members described previously, we consider photometric redshifts (hereafter, photo-zs) retrieved from the SDSS for 43 bright objects within our analysis area. Since the SDSS photo-zs are not available at $i > 22$ and the photo-z estimation uncertainties are quite large (up to $\sim 0.1$ at $i \sim 21$ and even larger at $21 < i < 22$), the member selection based on only photo-zs is not suitable for our purpose, particularly for the selection of faint members. However, it is still useful to cross-check the photo-z membership with our selected bright members. Here, we select photo-z members as the objects at $0.2 \leq \text{photo-z} \leq 0.4$. This seems to be a somewhat generous criterion, but may be appropriate when we consider the large uncertainties in photo-z estimation.

This criterion yields 30 photo-z members and 13 photo-z non-members, which are overplotted in Figures 3–5. Note that five photo-z members are rejected in our main sample, while eight photo-z non-members are included. In the subsequent analysis, the sample without any additional notation indicates our main sample. On the other hand, “+ photo-z” notation means a sample in which five photo-z members are added to the main sample, while “− photo-z” notation indicates a sample in which eight photo-z non-members are removed from the main sample. Figure 7 shows the spatial distribution of our selected cluster members and the photo-z members and non-members.

### 3.2. Completeness and Reliability

As mentioned previously, our selection is not perfect, which means that considerable contamination may still remain. Thus, in this section, we estimate the completeness (how many genuine members we selected among all genuine members) and reliability (how many genuine members exist among all selected galaxies) in our cluster member selection.

Before doing this, however, we emphasize that some meaningful tendencies may be found if the intrinsic trends are strong enough, even though we do not remove contamination. The cluster red sequence mentioned in the beginning of Section 3.1 is a good example. It is certain that the intrinsic trends will be revealed more obviously if we select genuine cluster members better, which means that poor member selection will typically weaken the observed tendencies by adding random scatter to the intrinsic trends. In other words, if we detect some tendencies that cannot be the results of selection bias (discussed in Section 5.1), then the fact that the member selection was imperfect does not weaken the conclusion; on the contrary, we can assume that better member selection would reveal the tendencies more clearly.

Now, our strategy to estimate the completeness and reliability is as follows.

1. Estimate the completeness and reliability of the CMR selection using the photometric and spectroscopic catalogs of the SDSS galaxies.
2. Based on the completeness and reliability of the CMR selection, additionally estimate the effects of the SMR and ConMR selections.

For the first step, the idea is to compare our color criterion at given magnitude range with (1) the distribution of colors, artificially moved to $z = 0.3$, of the SDSS galaxies in the spectroscopic catalog; and (2) the distribution of apparent colors of the SDSS galaxies in the photometric catalog. In these comparisons, (1) shows what color distribution the galaxies will have at $z = 0.3$ (that is, those galaxies are the members of an artificially built $z = 0.3$ cluster), while (2) shows what the color distribution of the non-cluster field galaxies looks like (that is, they are contamination). To minimize the field-to-field variation effect for field galaxy properties, we use the SDSS galaxies in the $3' \times 3'$ field (except the central $10' \times 10'$ area; from the SDSS photometry catalog) centered on WHL J085910.0+294957 without K-correction for (2).
Figure 7. Stacked $i$-band image of WHL J085910.0+294957, with the selected cluster members highlighted (open squares). The spec-$z$/photo-$z$ members (open blue/red circles) and photo-$z$ non-members (crosses) are also denoted. (A color version of this figure is available in the online journal.)

Figure 8 shows an example for the estimation of completeness and reliability in our CMR selection. The magnitude range in Figure 8 ($20.0 < i < 22.0$ or $-20.4 < M_i < -18.4$ at $z = 0.3$) is the faintest range where the SDSS photometric catalog is complete ($5\sigma$ completeness at $i < 22$; York et al. 2000). The galaxies in our observation are the combination of the $z = 0.3$ galaxies (cluster members) and field galaxies:

$$C_{\text{obs}} = f_c C_c + f_f C_f,$$

where $C_{\text{obs}}, C_c,$ and $C_f$ are the color distributions of all observed galaxies, cluster members, and field galaxies, respectively; and $f_c$ and $f_f$ are the fractions of cluster members and field galaxies, respectively. Here, it is assumed that $C_c$ is like (1) or the solid line distribution in Figure 8, while $C_f$ is like (2) or the dashed line distribution in Figure 8.

To estimate the completeness and reliability, it should be determined how many galaxies in $C_c$ and $C_f$ satisfy our CMR selection criteria and how many do not. At $-20.4 < M_i < -18.4$ (Figure 8), the number of selected cluster members ($N_{\text{in}}$) is 38, while the number of the rejected galaxies ($N_{\text{out}}$) is 21. In addition, the number fraction of the galaxies satisfying our criteria at this magnitude range among $C_c$ galaxies is 95% by our selection of CMR criteria (see Section 3.1), while that among $C_f$ is measured to be 43% in Figure 8.

Now, $N_{\text{in}}$ and $N_{\text{out}}$ are expressed as follows:

$$N_{\text{in}} : N_{\text{out}} = 38 : 21 \approx 0.95N_c + 0.43N_f : 0.05N_c + 0.57N_f,$$

where $N_c$ is the number of genuine cluster members and $N_f$ is the number of field (foreground or background) objects. Then, $N_c$ and $N_f$ are simply calculated to be 24.29 and 34.71, respectively, and the reliability ($R$) is

$$R = \frac{0.95N_c}{0.95N_c + 0.43N_f} \approx 0.6072.$$

Thus, we approximate the completeness and reliability of our CMR selection at $-20.4 < M_i < -18.4$ to be 95% and 61%.
respectively. That is, at $-20.4 < M_i < -18.4$, it is expected that we secure 95% of all genuine cluster members with our CMR selection, but 39% of the selected objects may not be genuine cluster members.

These values are only for the CMR selection. Among the CMR-selected 38 objects at $-20.4 < M_i < -18.4$, 36 objects also satisfy the size and concentration criteria while 2 objects do not. As we apply more selection criteria, the completeness tends to decrease, while the reliability is expected to increase because more selection means possible rejection of more genuine members but rejection of even more non-members at the same time. However, since there is no appropriate control sample, unlike the CMR selection, it is difficult to accurately estimate the completeness and reliability after the additional selections for size and concentration. Thus, we simply estimate them under two extreme conditions. In the ideal case (that is, the size and concentration criteria rejected only non-members perfectly), the completeness would not vary (95%), whereas the reliability would increase from 61% to

$$R = \frac{0.95 N_c}{0.95 N_c + 0.43 N_f - 2} \approx 0.6410,$$

that is, 64%. On the other hand, if additional selections did not work at all and members and non-members are rejected randomly (that is, with $N_c:N_f \approx 24:35$ ratio), the reliability would not vary (61%), while the completeness ($C$) would be reduced from 95% to

$$C = \frac{0.95 N_c - 2 \times \frac{24}{24+35}}{N_c} \approx 0.9165,$$

Figure 8. Completeness and reliability test for the CMR selection at $20.0 < i < 22.0$. The shaded vertical stripes show our member selection criteria using the CMR, which are not lines but stripes because the criteria vary along magnitude. The solid line displays the color distribution of the SDSS galaxies moved to $z = 0.3$, while the dashed line shows the apparent color distribution of the SDSS galaxies in the $3 \times 3$ field centered on WHL 085910.0$+29$4957 without $K$-correction. Both distribution curves were normalized to their peak values. (A color version of this figure is available in the online journal.)
of galaxies in a cluster at $z = 0.3$ than does the color distribution of photo-z galaxies.

There are several caveats in our completeness and reliability estimation. First, the SDSS spectroscopic catalog includes both cluster and field galaxies, not purely cluster galaxies, which may result in inaccurate estimation of $C$ and $R$. Since the color distribution of galaxies in a galaxy cluster is typically narrower than that in low-density fields, the actual membership reliability may be lower. Nevertheless, since it is difficult to determine a typical color distribution in a galaxy cluster due to the cluster-to-cluster variation, we used such a mixed distribution from the SDSS. Second, similarly, our field galaxy control sample from the SDSS photometric catalog may not be perfect. Although we use the surrounding $3' \times 3'$ field to minimize the field-to-field variation, there still exists a possibility that the actual color distribution of background and foreground galaxies in our observed field is different from that of the control field galaxies. Moreover, even some galaxies in the control field may have redshifts of $\sim 0.3$, which is an uncertainty factor in our $C$ and $R$ estimation. However, the number of galaxies in our control field is as many as 136,000 at $i \leq 22$, while there are only 90 (before member selection) detected galaxies at $i \leq 22$ in our analysis area. This implies that even if there are several more galaxy clusters with $z = 0.3$ in our control field, their effect will be very limited. Finally, the assumption that the field galaxy color distribution does not vary significantly at $i > 22$ is just an assumption, which is not guaranteed. This makes the uncertainty large in the estimation of $C$ and $R$ for faint galaxies.

3.3. Local Environmental Parameters

Figure 10 displays the spatial distribution of the selected cluster member galaxies. To quantitatively estimate the relationship between bright galaxies and their faint companions, we need to parameterize the physical properties of faint galaxies around each bright galaxy. This process is almost the same as that used to estimate the local environmental parameters. The basic idea is to use the mean or integrated quantities of galaxies around each bright galaxy, where those quantities may be number, luminosity, color, and so on. In this process, we adopt a spline kernel with $22'4$ ($\sim 100$ kpc at $z = 0.3$) radius for smoothing. For example, the luminosity density ($\Sigma$) is defined as

$$
\Sigma = \sum_{k=1}^{n} f_{sp}(d_k) \times 10^{-0.4M_k}/A,
$$

where $n$, $f_{sp}$, $d_k$, $M_k$, and $A$ are the number of galaxies in the local area, spline kernel function, projected distance to the local area center, absolute magnitude, and local area, respectively. For more details about the estimation of environmental parameters, see also Appendix A of Lee et al. (2010). In this paper, $i$-band local luminosity density is used as a parameter representing the local environment, instead of local number density that does not reflect various luminosities ($\sim$ various masses) of galaxies.

Since the spatial resolutions of our images are poor (up to $2'\times 9$ kpc), the only practical quantity to be parameterized for faint galaxies is color. We estimated the weighted mean $r-i$ color of faint companions $(r-i)_{\text{com}}$ around each bright galaxy, as follows:

$$
(r-i)_{\text{com}} = \frac{\sum_{k=1}^{n} f_{sp}(d_k) \times f_{L}(k) \times (r-i)_k}{\sum_{k=1}^{n} f_{sp}(d_k) \times f_{L}(k)},
$$

where $(r-i)_k$ is the color of each faint galaxy within $22'4$ from a given bright cluster galaxy. The faint galaxies mean the
selected cluster members are $-18 < M_i \leq -15$. In addition to the spline kernel weight according to the distance to the adjacent bright galaxy, the luminosity weight ($f_L$) is also applied, which is defined as

$$f_L(k) = 10^{-0.4(M_i(k)-18)},$$

where $M_i(k)$ is the $i$-band absolute magnitude of a given faint galaxy. Since fainter galaxies have larger photometric uncertainties, the luminosity weight is useful to reduce the influence of faint objects (with large uncertainties) on the weighted mean color of companions.

Figure 11 shows how dispersed the companion colors for a given bright galaxy. For bright galaxies with the number of faint companions larger than 1 ($N_{\text{com}} \geq 2$), the standard deviation of companion colors is as large as 0.79.

Several collective properties of faint companions for each bright galaxy are listed in Table 1. Among the 65 bright galaxies, 5 galaxies have no companions with $-18 < M_i \leq -15$, which are excluded in the subsequent analysis. The number of faint companions for each bright galaxy is not large: 2.66 on average for all 65 bright galaxies or 2.88 on average for 60 bright galaxies with at least one faint companion. The mean separation between bright galaxies and their faint companions is $15''-16''$ (corresponding to 67–71 kpc at $z = 0.3$) or 12–13 $R_{50,\text{bri}}$, where $R_{50,\text{bri}}$ is the half-light radius of each bright galaxy.

### 4. RESULTS

The main goal of this paper is to investigate the relationship between bright galaxies and their faint companions in a galaxy cluster. To achieve this goal, we need to first check the environmental effects because the cluster environment is known to strongly affect the properties of galaxies on a large scale (e.g., Park et al. 2007; Adams et al. 2012; Pimbblet & Jensen 2012). From numerous previous studies, now it is well known that galaxies in high-density environments or galaxy clusters tend to be redder than galaxies in low-density environments or fields (Bamford et al. 2009; Hansen et al. 2009; Weinmann et al. 2010; Cibinel et al. 2013). However, such trends are not obvious in our sample, as shown in Figures 12 and 13.

Figure 12 presents the dependence of $(r - i)_{\text{com}}$ on cluster-centric distance, in which no meaningful trend is found. The
estimated correlation slopes are very small and not significant (<1σ) to the bootstrap uncertainties. This may be partially due to the color integration within 100 kpc radius, which can wash out the color dependence on local environment. However, even when the dependence on cluster-centric distance for the individual colors of faint galaxies is tested, its significance to the bootstrap uncertainty is just ~1.5σ, which is still statistically insignificant. Similarly, \((r-i)_{\text{com}}\) does not show any significant dependence on local luminosity density in Figure 13. These results do not necessarily indicate that the colors of faint companions are not affected by local environments because the uncertainty is large due to possible contamination. However, at least in our sample, the local environmental effect is not detected.

Since the local environments of the cluster do not significantly affect the colors of faint galaxies, we now test the effect of adjacent bright galaxies on \((r-i)_{\text{com}}\). Figure 14 shows the relationship between \((r-i)_{\text{com}}\) and the bright galaxy luminosities, in which no statistically significant dependence is found. As presented in Figure 15, the dependence on the light concentrations of bright galaxies is not significant either. These results show that the luminosities and light profiles of bright galaxies do not significantly influence the colors of their faint companions, at least in our sample.

Finally, the dependence of \((r-i)_{\text{com}}\) on the colors of bright galaxies is tested in Figure 16. Unlike the four parameters in the previous plots, the slopes are measurable in the sense that blue bright galaxies tend to have blue faint companions. Particularly for the sample with \(N_{\text{com}} \geq 2\) (Figure 16(b)), the slope \(\Delta(r-i)_{\text{com}}/\Delta(r-i)_{\text{hei}} = 0.360\) has 2.2σ significance to the bootstrap uncertainty, and for the “− photo-z” sample with \(N_{\text{com}} \geq 2\) (Figure 16(f)), the significance is as large as 2.6σ. These values are statistically not significant (<3σ) but marginal (>2σ). The correlation coefficients are as large as 0.375 and 0.464 in Figures 16(b) and (f), respectively. Although the statistical significances are mostly smaller than 1σ for the other quantities (cluster-centric distance, local luminosity density, bright galaxy luminosity, and bright galaxy light concentration), the bright galaxy color appears to considerably influence the colors of faint companions in our results.

5. DISCUSSION

5.1. Possible Uncertainties

It is very difficult to determine membership without velocity information in studies of galaxy clusters. Thus, any method only based on image data may have large uncertainty in member selection, which affects the results. Here, several factors that may mislead the results in our analysis are listed and their actual effects are discussed.

The first is the low reliability in our member selection. According to our estimation in Section 3.2, the reliability is at
Figure 13. Correlation between the mean colors of faint companions and the $i$-band luminosity density ($\Sigma$) around their adjacent bright galaxies. The luminosity density was normalized by the mean luminosity density of the entire analysis area ($\Sigma_0$). No significant dependence on local luminosity density is found. (A color version of this figure is available in the online journal.)

Figure 14. Correlation between the mean colors of faint companions and the $i$-band absolute magnitudes of their adjacent bright galaxies. No significant correlation is found. (A color version of this figure is available in the online journal.)
minimum 43% and at maximum 83% at $-15.5 < M_i < -15.0$, which means that almost three of five cluster members are falsely selected in the worst case. However, as mentioned in Section 3.1, falsely selected members are expected to make the trends or correlations in our results more unclear by mixing out the signal with scattered noise because falsely selected members must be foreground or background objects with random properties. It is not reasonable that their properties have any correlation with their close (in projected distance) bright galaxies. That is, the low reliability in member selection does not weaken the significance of our finding; on the contrary, our results might become even more obvious if we selected cluster members better.

Second, the deblending process of the Source Extractor may not have worked perfectly. That is, small fluctuations in the surface profile of a bright galaxy may have been regarded as faint companion galaxies, which can cause a false correlation between the colors of bright galaxies and their “faint companions.” If the “faint companions” were over-deblended ambient light of a bright galaxy, it would be natural that they had colors similar to that of the bright galaxy. Although our member selection method is expected to have removed a significant number of those overdetected light fluctuations, it may not be perfect. However, as shown in Figure 10, most faint companions are not so close to the bright galaxies. As mentioned in Section 3.3, the mean distance from faint companions to their adjacent bright galaxies is as large as 15", which is typically 12 times larger than the half-light radii of the bright galaxies.

Because a faint companion closer to its adjacent bright galaxy has a larger weight in the $(r - i)_{\text{com}}$ calculation, we additionally checked the distance to the closest faint companion from each bright galaxy, finding that its mean value is 7.6 or 6.4 $R_{50,\text{bri}}$, which is not a very small distance either. Hence, even if falsely deblended objects are included in our final sample, it may be very rare and not enough to critically influence our results.

Third, if redder bright galaxies have preferentially brighter companions around them, then the companion galaxies may naturally have redder colors due to the well-known CMR. To check this possibility, we tested the relationship between the colors of bright galaxies and the mean luminosities of their faint companions. The mean luminosity of faint companions ($L_{i,\text{com}}$) is defined as

$$L_{i,\text{com}} = \frac{\sum_{k=1}^{n} f_{sp}(d_k) \times L_i(k)}{\sum_{k=1}^{n} f_{sp}(d_k)},$$

(13)

where $L_i(k)$ is the luminosity of each faint companion galaxy. We converted $L_{i,\text{com}}$ into absolute magnitude ($M_{i,\text{com}}$) and estimated its dependence on the bright galaxy color in a way similar to those of Figures 12–16. As a result, we found that the correlation slope between $(r - i)_{\text{bri}}$ and $M_{i,\text{com}}$ is $a = 0.292 \pm 0.177$ with a correlation coefficient of $cc = 0.039$ for the $N_{\text{com}} \geq 1$ sample. This result is not so different for the $N_{\text{com}} \geq 2$ sample: $a = 0.227 \pm 0.167$ with $cc = 0.038$. That is, we cannot find any meaningful correlation between the bright
galaxy color and the companion galaxy luminosity. Note that even if we ignore the bootstrap uncertainty, the slope indicates the opposite relationship: redder bright galaxies tend to have less luminous companions.

Finally, the marginal “signals” in Figure 16 may be results of coincidence due to small-number statistics. Since the total number of our selected cluster members at \( M_i < -15 \) is only 156, this concern may be reasonable. To resolve this issue, we carried out permutation tests (e.g., Good 1994), which are statistical tests suitable for distinguishing whether a correlation exists between two variables: in this case, the colors of bright galaxies and the weighted mean colors of their faint companions. The brief procedure of this test is as follows. First, we shuffled the colors of all faint galaxies in our analysis area and calculated the weighted mean color of (shuffled) faint companions for each bright galaxy. Subsequently, from this random sampling, Figures 12–16 were redrawn and their correlation coefficients were measured. After repeating such a random sampling 1000 times, we estimated the confidence level for each correlation by comparing the original correlation coefficient with the distribution of correlation coefficients in the random samples. The results are summarized in Table 2. From this test, we confirm that the results in Figures 16(b) and (f) are not by chance due to small-number statistics. The correlation coefficients in Figures 16(b) and (f) are as large as 0.375 with a confidence level of 98.7% and 0.464 with a confidence level of 99.3%, respectively, which obviously shows that the bright galaxies are correlated in color with their faint companions.

5.2. Origin of the Color Correlation

As shown in Phillips et al. (2013), bright host galaxies and their faint satellite galaxies show close relationships in isolated groups, which is not strange because a lot of evidence supports that host and satellite galaxies often influence each other (e.g., Larens et al. 2011; Chang et al. 2013; Paudel et al. 2013). However, it is possible that such close relationships are sustained even in the harsh environment of a galaxy cluster, in which direct galaxy–galaxy interactions hardly affect galaxy properties (Merritt 1984; Park & Hwang 2009). In our results, the answer seems to be a cautious “yes.” That is, the close relationships in photometric properties between bright galaxies and their faint companions are marginally detected even in a galaxy cluster. In Section 5.1, we discussed about the possibilities that these results were not real, but several possible uncertainties in our analysis are not likely to artificially produce the correlations.

If we accept that the correlations are real, our results may be interpreted in three ways. The first is that a galaxy group consisting of a massive galaxy and its low-mass satellites may survive for a long time even after the group falls into a galaxy cluster. Today, more and more evidence is being found supporting the idea that massive galaxy clusters have grown by merging smaller groups and that galaxies have rapidly evolved in the galaxy group stage (so-called “pre-processing”; Zabludoff & Mulchaey 1998; Balogh et al. 2000; Hoyle et al. 2012; Vijayaraghavan & Ricker 2013). Small groups of galaxies fallen into a galaxy cluster are expected to be eventually broken up.
Those newly captured low-mass satellites may interact with the companions may not be in situ satellites of the bright galaxies. Dinescu et al. 2000; Bertin et al. 2003). That is, the current although massive neighbors just pass by (Bassino et al. 1998; low-mass galaxies coming close to it in a galaxy cluster, outskirts. Then the color correlations are expected to be stronger at cluster dynamical stages need to be compared. In addition, the trend into the cluster in relatively recent times, if this scenario is true, galaxies (or galaxy groups) at cluster outskirts may have fallen their faint companions will be stronger in dynamically younger mass galaxies, resulting in the color relationship between them. However, this picture should be checked in two major aspects. One is how efficient such capturing of low-mass galaxies by a massive galaxy is in a galaxy cluster. Based on simple numerical simulations, Bassino et al. (1998) showed that dwarf galaxies in a galaxy cluster are captured by massive galaxies up to 5%, but more elaborate and diverse tests are needed for the comparisons with the real galaxy clusters under various conditions. The other is what process makes the close relationships in photometric properties between a massive galaxy and its low-mass (captured) satellites, which requires changes in photometric properties of those galaxies after a capturing event. Even though direct tidal interactions between galaxies hardly happen in a galaxy cluster, hydrodynamic interactions may make them possible, and then not stars but the gases in a galaxy move to a close neighboring galaxy and cause additional star formation there (Park & Hwang 2009). Nevertheless, since a typical cluster center is known to be

| Figure | Condition | Sample* Size | Slopeb | Correlation Coefficient | Significance Level of Null Hypothesis (%) |
|--------|-----------|--------------|--------|-------------------------|----------------------------------------|
|        | (Cluster-centric distance) | | | | |
| 12     | $N_{\text{com}} \geq 1$ | 60 $-0.088 \pm 0.130$ | $-0.104$ | 45.3 |
|        | $N_{\text{com}} \geq 2$ | 45 $0.031 \pm 0.074$ | 0.047 | 78.2 |
|        | $N_{\text{com}} \geq 1$, + photo-z | 65 $-0.101 \pm 0.124$ | $-0.120$ | 34.1 |
|        | $N_{\text{com}} \geq 2$, + photo-z | 50 $-0.003 \pm 0.082$ | $-0.004$ | 97.8 |
|        | $N_{\text{com}} \geq 1$, - photo-z | 52 $-0.143 \pm 0.151$ | $-0.158$ | 27.3 |
|        | $N_{\text{com}} \geq 2$, - photo-z | 37 $0.001 \pm 0.087$ | 0.001 | 99.3 |
|        | (Local luminosity density) | | | | |
| 13     | $N_{\text{com}} \geq 1$ | 60 $0.030 \pm 0.039$ | 0.100 | 52.2 |
|        | $N_{\text{com}} \geq 2$ | 45 $0.011 \pm 0.030$ | 0.048 | 77.9 |
|        | $N_{\text{com}} \geq 1$, + photo-z | 65 $0.037 \pm 0.040$ | 0.120 | 37.3 |
|        | $N_{\text{com}} \geq 2$, + photo-z | 50 $0.021 \pm 0.032$ | 0.084 | 57.5 |
|        | $N_{\text{com}} \geq 1$, - photo-z | 52 $0.044 \pm 0.042$ | 0.145 | 28.0 |
|        | $N_{\text{com}} \geq 2$, - photo-z | 37 $0.027 \pm 0.033$ | 0.116 | 46.6 |
|        | (Bright galaxy $i$-band magnitude) | | | | |
| 14     | $N_{\text{com}} \geq 1$ | 60 $-0.001 \pm 0.014$ | $-0.011$ | 93.4 |
|        | $N_{\text{com}} \geq 2$ | 45 $-0.003 \pm 0.014$ | $-0.029$ | 86.0 |
|        | $N_{\text{com}} \geq 1$, + photo-z | 65 $-0.001 \pm 0.014$ | $-0.004$ | 97.0 |
|        | $N_{\text{com}} \geq 2$, + photo-z | 50 $-0.002 \pm 0.014$ | $-0.016$ | 91.1 |
|        | $N_{\text{com}} \geq 1$, - photo-z | 52 $-0.004 \pm 0.015$ | $-0.032$ | 82.0 |
|        | $N_{\text{com}} \geq 2$, - photo-z | 37 $-0.006 \pm 0.014$ | $-0.064$ | 71.6 |
|        | (Bright galaxy $i$-band light concentration) | | | | |
| 15     | $N_{\text{com}} \geq 1$ | 60 $-0.012 \pm 0.038$ | $-0.034$ | 83.6 |
|        | $N_{\text{com}} \geq 2$ | 45 $-0.030 \pm 0.045$ | $-0.096$ | 52.9 |
|        | $N_{\text{com}} \geq 1$, + photo-z | 65 $-0.010 \pm 0.037$ | $-0.026$ | 83.7 |
|        | $N_{\text{com}} \geq 2$, + photo-z | 50 $-0.024 \pm 0.046$ | $-0.072$ | 59.0 |
|        | $N_{\text{com}} \geq 1$, - photo-z | 52 $-0.007 \pm 0.040$ | $-0.021$ | 89.8 |
|        | $N_{\text{com}} \geq 2$, - photo-z | 37 $-0.025 \pm 0.051$ | $-0.079$ | 64.0 |
|        | (Bright galaxy $r$--$i$ color) | | | | |
| 16     | $N_{\text{com}} \geq 1$ | 60 $0.300 \pm 0.177$ | 0.206 | 8.9 |
|        | $N_{\text{com}} \geq 2$ | 45 $0.360 \pm 0.167$ | 0.375 | 1.3 |
|        | $N_{\text{com}} \geq 1$, + photo-z | 65 $0.226 \pm 0.161$ | 0.172 | 15.0 |
|        | $N_{\text{com}} \geq 2$, + photo-z | 50 $0.242 \pm 0.157$ | 0.271 | 6.3 |
|        | $N_{\text{com}} \geq 1$, - photo-z | 52 $0.398 \pm 0.183$ | 0.258 | 5.8 |
|        | $N_{\text{com}} \geq 2$, - photo-z | 37 $0.461 \pm 0.175$ | 0.464 | 0.7 |

Notes.

a The number of bright galaxies satisfying each condition.
b The error values are the bootstrap uncertainties.
c Results from permutation tests. The smaller value implies the stronger correlation.

by the strong tidal force in the gravitational potential of the galaxy cluster after sufficient time passes, and thus this scenario predicts that the color correlation between bright galaxies and their faint companions will be stronger in dynamically younger clusters. To confirm this scenario, galaxy clusters in various dynamical stages need to be compared. In addition, the trend along cluster-centric distance should be checked, too. Since the galaxies (or galaxy groups) at cluster outskirts may have fallen into the cluster in relatively recent times, if this scenario is true, then the color correlations are expected to be stronger at cluster outskirts.

Another scenario is that a massive galaxy may capture low-mass galaxies coming close to it in a galaxy cluster, although massive neighbors just pass by (Bassino et al. 1998; Dinescu et al. 2000; Bertin et al. 2003). That is, the current companions may not be in situ satellites of the bright galaxies. Those newly captured low-mass satellites may interact with the massive galaxy, resulting in the color relationship between them.
a hostile environment where most galaxies lose their gas and thus stop star formation activities (e.g., due to ram-pressure stripping; Gunn & Gott 1972), the plausibility of this scenario should be tested further, particularly in the sense of how much gas remains in the cluster galaxies for hydrodynamic interactions.

The last scenario is that a considerable number of the faint companions may have been tidally torn out from their adjacent bright galaxies. In other words, those companions may have been originally outer parts of bright galaxies, but may be separated by the tidal force of another massive galaxy or the galaxy cluster itself (so-called “tidal dwarf galaxies”; e.g., Duc & Mirabel 1998; Bournaud & Duc 2006; Sheen et al. 2009; Kaviraj et al. 2012). This scenario explains well why the colors of bright galaxies and their faint companions show good correlations. From a study using the SDSS data (Kaviraj et al. 2012), it was reported that the median separation between a host galaxy and its tidal satellites is \(~\sim 4.5 \, R_{50,\text{host}}\) and 95% of tidal satellites are within \(15 \, R_{50,\text{host}}\). These results show that the mean separation between tidal dwarfs and their host galaxies is smaller than that between the bright galaxies and their faint companions found in our result (\(~\sim 12 \, R_{50,\text{bn}}\)). Thus, our faint companions with large separations may not be tidal dwarfs, but a considerable number of our faint companions seem to be within the tidal dwarf domain (the 95% range given in Kaviraj et al. 2012). However, this scenario also needs to be tested by checking how frequently such tidal tearing events happen in a galaxy cluster.

6. CONCLUSION

We carried out a deep two-band photometric study of WHL J085910.0+294957, a galaxy cluster at \(z = 0.30\), to investigate the relationship between bright (\(M_f \leq -18\)) galaxies and their faint (\(\sim -18 < M_f < -15\)) companions in this galaxy cluster. While the weighted mean color of faint companion galaxies hardly depends on local environmental parameters (cluster-centric distance and local luminosity density) as well as the luminosity and concentration of bright galaxies (\(< 1\sigma\) significance), at least in our sample, it shows marginal dependence on the color of bright galaxies (\(~2.2\sigma\) significance) for the \(N_{\text{com}} \geq 2\) sample. The statistical significance increases to \(~2.6\sigma\) if we additionally remove non-members using the SDSS photometric redshift information from the main sample. After several possible uncertainties were discussed, we concluded that it is not plausible for those uncertainties to coincidentally produce the results in this paper. Using permutation tests, we confirmed that the correlation in color between bright galaxies and their faint companion is statistically reliable with a confidence level of 98.7% when the sample is limited to \(N_{\text{com}} \geq 2\), or 99.3% when photo-\(z\) non-members are removed.

We suggest three scenarios to interpret our results.

1. A massive galaxy containing a massive galaxy and its low-mass satellites may survive for a long time even after the group falls into a galaxy cluster. Thus, the close relationship between bright galaxies and their faint companions would be the vestige of infallen groups. To confirm this, it should be shown how the color correlations depend on the dynamical stages of clusters and the cluster-centric distances.

2. A massive galaxy may capture low-mass galaxies coming close to it in a galaxy cluster, whereas massive neighbors just pass by. To confirm this scenario, it should be checked how efficient such capturing is and how significantly the hydrodynamic interaction after capturing affects the colors of bright galaxies and their companions.

3. A considerable number of the faint companions may have been tidally torn out from bright galaxies. The efficiency of such tearing out should be tested.

To confirm any of the suggested scenarios, similar investigation for a larger sample of galaxy clusters with deep imaging is required as well as numerical simulations with resolutions high enough to distinguish faint dwarf galaxies. If the first scenario is true and the color correlation between bright galaxies and their faint companions becomes weaker as time goes after group infalling (possibly by loss of satellites due to cluster tidal force), then it is expected that the color correlation will disappear as a galaxy cluster becomes dynamically older. On the other hand, the color correlation may not disappear even after long time has passed in the second or third scenario, although currently we cannot give detailed predictions for those. To study this issue further, we are analyzing more galaxy clusters using deeper images.

We appreciate the anonymous referee who motivated significant improvement of this paper. All authors in the Korea Astronomy and Space Science Institute (KASI) are the members of Dedicated Researchers for Extragalactic AstronoMy (DREAM). M. Kim and S.-C. Yang were supported by the KASI-Carnegie Fellowship Program jointly managed by KASI and the Observatories of the Carnegie Institution for Science. This work was supported by the National Research Foundation of Korea (NRF) grant No. 2008-0060544, funded by the Korea government (MSIP).

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Adams, S. M., Zaritsky, D., Sand, D. J., et al. 2012, AJ, 144, 128
Ann, H. B., Park, C., & Choi, Y.-Y. 2008, MNRAS, 389, 86
Baldry, I. K., Balogh, M. L., Bower, R. G., et al. 2006, MNRAS, 373, 469
Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, ApJ, 540, 113
Bamford, S. P., Nichol, R. C., Baldry, I. K., et al. 2009, MNRAS, 393, 1324
Bassino, L., Muzzio, J. C., & Pérez, J. 1998, CeMDA, 72, 157
Belkku, K., Couch, W. J., & Shioya, Y. 2002, ApJ, 577, 651
Bernardi, M., Shankar, F., Hyde, J. B., et al. 2010, MNRAS, 404, 2087
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bertin, G., Liseikina, T., & Pegoraro, F. 2003, A&A, 405, 73
Bessiere, P. S., Tadhunter, C. N., Ramos Almeida, C., & Villar Martin, M. 2012, MNRAS, 426, 276
Blanton, M. R., & Berlind, A. A. 2007, ApJ, 664, 791
Blanton, M. R., Brinkmann, J., Csabai, I., et al. 2003, AJ, 125, 2348
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Bournaud, F., & Duc, P.-A. 2006, A&A, 456, 481
Butcher, H., & Oemler, A. J. 1984, ApJ, 285, 426
Byrd, G., & Valtonen, M. 1990, ApJ, 350, 89
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Carollo, C. M., Cibinel, A., Lilly, S. J., et al. 2013, ApJ, 776, 71
Chang, J., Macciò, A. V., & Kang, X. 2013, MNRAS, 431, 3533
Cibinel, A., Carollo, C. M., Lilly, S. J., et al. 2013, ApJ, 777, 116
Cooper, M. C., Newman, J. A., Weiner, B. J., et al. 2008, MNRAS, 383, 1058
Coziol, R., & Plauchu-Frayn, I. 2007, MNRAS, 375, 2
Coles, R., & Blaizot, J. 2007, MNRAS, 375, 2
Coles, R., & Prichet, C. J. 1998, AJ, 116, 1118
Dinescu, D. I., Majewski, S. R., Girard, T. M., & Cudworth, K. M. 2000, AJ, 120, 1892
Dressler, A. 1980, ApJ, 236, 351
Dressler, A. 1980, ApJ, 236, 351
Duc, P.-A., & Mirabel, I. F. 1998, A&A, 333, 813
Elbazi, D., Daddi, E., Le Borgne, D., et al. 2007, A&A, 468, 33
George, M. R., Ma, C.-P., Bundy, K., et al. 2013, ApJ, 770, 113
Gnedin, O. Y. 2003, ApJ, 589, 752
