



A Complete Spectroscopic Census of A2029: A Tale of Three Histories

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Abstract

A rich spectroscopic census of members of the local massive cluster A2029 includes 1215 members of A2029 and its two infalling groups, A2033 and the Southern Infalling Group. The two infalling groups are identified in spectroscopic, X-ray, and weak-lensing maps. We identify active galactic nuclei (AGNs), star-forming galaxies, E+A galaxies, and quiescent galaxies based on the spectroscopy. The fractions of AGN and post-starburst E+A galaxies in A2029 are similar to those of other clusters. We derive the stellar mass (M_*)–metallicity relation of A2029 based on 227 star-forming members; A2029 members within $10^9 M_\odot < M_* < 10^{9.5} M_\odot$ are more metal-rich than Sloan Digital Sky Survey galaxies within the same mass range. We utilize the spectroscopic index D_n4000 , a strong age indicator, to trace past and future evolution of the A2029 system. The median D_n4000 of the members decreases as the projected clustercentric distance increases for all three subsystems. The D_n4000 – M_* relations of the members in A2029 and its two infalling groups differ significantly, indicating the importance of stochastic effects for understanding the evolution of cluster galaxy populations.

Key words: galaxies: clusters: individual (A2029, A2033) – galaxies: distances and redshifts – galaxies: evolution – large-scale structure of universe – surveys

Supporting material: machine-readable table

1. Introduction

Galaxy clusters probe the effects of high-density environments on galaxy evolution. Hubble & Humason (1931) recognized that cluster regions contain earlier types of galaxies. Many recent studies investigate differences among galaxy populations in clusters and lower-density regions (Dressler 1980; Balogh et al. 1999; Rines et al. 2005; Boselli & Gavazzi 2006; Haines et al. 2013, 2015; Paccagnella et al. 2016). In general, cluster galaxies are red, old, and quiescent compared with their counterparts in the low-density regions. This environmental dependence on the galaxy properties is expected in the hierarchical structure formation model; cluster galaxies formed and evolved earlier in denser, more massive halos.

Galaxy evolution in the cluster environment is complex; interactions with the intracluster medium (ICM), with other cluster member galaxies, and with the global tidal field of the cluster are important. When a galaxy falls into the cluster environment, interaction with the ICM gas may remove gas from individual galaxies (e.g., Gunn & Gott 1972; Larson et al. 1980; Moore et al. 1996). The impact of cluster environment depends on galaxy properties, including mass, morphology, and gas content (e.g., Christlein & Zabludoff 2005; Blanton & Moustakas 2009; Peng et al. 2010). Thus, a large and complete sample of members is required to reduce systematic effects on the study of cluster galaxy evolution.

Early studies identified cluster members based on photometric galaxy catalogs (e.g., Oemler 1974). Alternative methods include control field subtraction (Paolillo et al. 2001) and red sequence selection (de Propris & Pritchet 1998). Red sequence selection is widely used for identifying clusters from huge galaxy surveys (Hao et al. 2010; Oguri 2014; Rykoff et al. 2014). However, cluster member catalogs built with this approach are often contaminated by foreground/background interlopers (Sohn et al. 2018a).

Dense spectroscopic surveys are critical for cluster member selection and for spectroscopic typing. Many previous studies use large stacked samples of spectroscopically identified cluster members derived from several superimposed clusters (e.g., Lewis et al. 2002; Haines et al. 2013, 2015; Paccagnella et al. 2016). The use of stacked cluster samples may introduce systematic issues originating from the diversity of cluster properties (e.g., redshift, mass, dynamical status of the sample clusters).

A dense and complete spectroscopic survey of a single galaxy cluster resolves some of these systematic issues. Recent studies examine cluster galaxy properties based on a few hundred spectroscopic members identified in dense spectroscopic surveys (Rines et al. 2002; Hwang et al. 2012a; Smith et al. 2012; Tyler et al. 2013; Geller et al. 2014; Lee et al. 2015; Deshev et al. 2017; Sohn et al. 2017; Habas et al. 2018). These spectroscopic surveys enable studies of cluster galaxy populations (e.g., quiescent/star-forming, active galactic nuclei [AGNs], and post-starburst galaxies), as well as the statistical distribution of cluster members (e.g., luminosity, stellar mass, and the central velocity dispersion functions; Rines & Geller 2008; Agulli et al. 2014, 2016; Sohn et al. 2017; Song et al. 2017). More importantly, this approach allows the properties of the galaxy clusters to be connected to their member properties (Hwang & Lee 2009; Deshev et al. 2017).

A2029 is a massive cluster at $z = 0.078$ with an unusually rich spectroscopic survey (Tyler et al. 2013; Sohn et al. 2017, 2018b). This cluster is one of the best-sampled clusters in the universe. Moreover, A2029 has been studied based on multiwavelength photometry, spectroscopy, weak-lensing, and X-ray observations (Clarke et al. 2004; Bai et al. 2007; Hicks et al. 2010; Walker et al. 2012; Paterno-Mahler et al. 2013; Tyler et al. 2013). Based on the extensive data set, Tyler et al. (2013) examine the star formation activity of the member galaxies. Sohn et al. (2017) measure the luminosity, stellar

mass, and central velocity dispersion functions of the member galaxies.

The dynamical evolution of A2029 is complex. A2029 has a distinctive X-ray sloshing pattern identified from high-resolution *Chandra* X-ray imaging (Clarke et al. 2004; Paterno-Mahler et al. 2013). Comparison between the X-ray feature and hydrodynamic simulations suggests that A2029 experienced the accretion of a subcluster 2–3 Gyr ago (Paterno-Mahler et al. 2013). Furthermore, A2029 is currently massively accreting. Sohn et al. (2018b) investigate the structure of the A2029 system based on multiwavelength probes including the number density map of spectroscopic members, weak-lensing maps, and X-ray maps. They identify at least two subsystems, A2033 and SIG, within the infall region of A2029. These two subsystems will probably be accreted onto A2029 within a few gigayears. This complicated dynamical history and future make A2029 an interesting target for studying the connection between accretion and galaxy populations.

Here we examine the census of spectroscopic properties of A2029 member galaxies. We use a complete sample of ~ 1200 spectroscopic members in the A2029 system, including ~ 50 – 70 members in each of the two infalling groups. This rich data set enables a comparative study of galaxy populations in the cluster and its infalling groups. Combining the spectroscopic properties of the galaxy populations with the X-ray structure of A2029, we connect galaxy evolution in A2029 to its accretion history. Furthermore, currently differing galaxy populations in A2029, A2033, and SIG suggest diverse consequences of subcluster accretion on the resultant cluster population.

We describe the data in Section 2. We describe the spectroscopic member selection and physical properties of A2029 members in Section 3. In Section 4, we examine the spectroscopic census of the A2029 population; we identify AGNs and star-forming, post-starburst E+A, and quiescent galaxies. We connect evolution of the galaxy population in the cluster to past and future accretion of substructures in Section 5. We conclude in Section 6. We assume a standard cosmology of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ throughout.

2. Data

A2029 is one of the best-sampled clusters in the local universe (Tyler et al. 2013; Sohn et al. 2017, 2018b). The intensive redshift survey from Sohn et al. (2018b) includes 1215 spectroscopic members within $R_{\text{cl}} < 40'$ of the cluster center. Only Coma (Sohn et al. 2017) and A2142 (Munari et al. 2014), which have similar masses to A2029, have a comparable number (~ 1000) of spectroscopically identified members. The Virgo Cluster has ~ 1000 spectroscopically identified members (Kim et al. 2014), but it has much lower mass than A2029. The large number of spectroscopic members enables studies of the detailed physical properties of members within a single massive cluster.

We use the dense and complete A2029 spectroscopic survey from Sohn et al. (2018b), which extends the surveys of Tyler et al. (2013) and Sohn et al. (2017). Here we briefly describe the spectroscopic survey. More details are in Sohn et al. (2018b).

The basic photometric galaxy catalog is the Sloan Digital Sky Survey (SDSS) Data Release 12 (DR12). Extended sources with $\text{probPSF} = 0$ and brighter than $r = 22$ mag within $R_{\text{cl}} < 100'$ are the targets for the redshift survey. Throughout

this study, we use composite model (cModel) magnitudes after foreground extinction correction.

We first compile redshifts from previous surveys, including SDSS DR12. There are 3109 objects with SDSS redshifts. We add 439 redshifts from the literature (e.g., Bower et al. 1988; Drinkwater et al. 2010) through the NASA/IPAC Extragalactic Database (NED) and one redshift from the 1.5 m telescope on Mount Hopkins (Sohn et al. 2015).

Most of the spectra of A2029 galaxies were obtained with Hectospec mounted on the MMT 6.5 telescope. Hectospec is a fiber-fed multi-object spectrograph with a 1° diameter field of view (Fabricant et al. 2005). Using Hectospec, Tyler et al. (2013) measure the redshifts and $\text{H}\alpha$ equivalent widths (EWs) of 1369 galaxies in the A2029 field. Based on these measurements, they identify cluster members and examine the evolution of star-forming galaxies in the cluster environment. We compile the spectra from Tyler et al. (2013) through the MMT archive.¹

We carried out a deeper spectroscopic survey using MMT/Hectospec (Sohn et al. 2017, 2018b). These spectra of A2029 galaxies were also obtained using the 270 line mm^{-1} Hectospec grating. The spectra of all targets uniformly cover 3800–9100 Å with 6.2 Å spectral resolution. The typical exposure time was an hour per field.

To reduce the Hectospec data, we use the IDL HSRED v2.0 package.² The observed spectra are relatively flux-calibrated by correcting for the relative throughput as a function of wavelength (Fabricant et al. 2008). The flux measurements based on the calibrated spectra have $\sim 20\%$ uncertainties (Fabricant et al. 2008). We use RVSAO (Kurtz & Mink 1998) to measure the redshifts based on the cross-correlation of observed spectra with template spectra designed for this purpose (Fabricant et al. 2005). We visually inspect the cross-correlation redshift measurements and classify them into three groups: Q for high-quality fits, ? for ambiguous cases, and X for poor fits. We also classify the Hectospec spectra from Tyler et al. (2013) in the same way. We obtain a total of 2890 high-quality redshifts from all of the Hectospec observations. The typical redshift uncertainty of Hectospec redshifts is 32 km s^{-1} .

The spectroscopic survey of A2029 is 90% complete to $r = 20.5$ within $R_{\text{cl}} < 30'$ (see Figure 1 in Sohn et al. 2018b). In other words, within $R_{\text{cl}} < 30'$, 90% of the objects with $r < 20.5$ mag have a spectroscopic redshift, and the completeness varies little from one position to another. The survey completeness decreases outside $R_{\text{cl}} = 30'$, and the integrated completeness to $r = 20.5$ is 67% complete within $R_{\text{cl}} < 40'$.

3. Spectroscopic Properties of A2029 Cluster Member Galaxies

Based on the extensive spectroscopic sample, we explore the properties of galaxies in the A2029 region. We first identify cluster members and foreground/background galaxies using the caustic technique (Section 3.1). For the spectroscopically identified cluster members, we measure galaxy properties including stellar mass (Section 3.2), D_n4000 (Section 3.3), velocity dispersion (σ , Section 3.4), and emission-line fluxes (Section 3.5).

¹ <http://oirsa.cfa.harvard.edu/archive/search/>

² Originally developed by R. Cool and modified by the MMT Telescope Data Center.

3.1. Member Selection

We identify spectroscopic members of the A2029 system based on the relative rest-frame velocity difference versus projected distance, the $R-v$ diagram (see Figure 2 in Sohn et al. 2018b). In the $R-v$ diagram, the caustic pattern clearly separates cluster members from foreground and background galaxies (Diaferio & Geller 1997; Diaferio 1999; Serra & Diaferio 2013). Based on the caustic technique, we identify 1215 spectroscopic members of the A2029 systems.

Sohn et al. (2018b) examine the structure of A2029 based on spectroscopic, weak-lensing, and X-ray maps. There are two subsystems identified in all three maps in the infall region of A2029: A2033 and the Southern Infalling Group (SIG). The members of these two subsystems are well within the A2029 caustics (Figure 4 in Sohn et al. 2018b), indicating that two subsystems are dynamically connected to A2029. Based on a two-body model (Beers et al. 1982), Sohn et al. (2018b) suggest that these two subsystems are gravitationally bound to A2029 and will accrete onto A2029 within a few gigayears.

Following Sohn et al. (2018b), we define the A2029 system as containing the following three components: A2029, A2033, and SIG. There are 1215 spectroscopic members in this A2029 system within $R_{\text{proj}} < 8.8$ Mpc, where R_{proj} is the projected distance from the center of A2029. We also identify members of A2033 and SIG within $R_{\text{proj,group}} < 500$ kpc and $|\Delta cz|/(1 + z_{\text{group}}) < 2000$ km s⁻¹, where $R_{\text{proj,group}}$ is the projected distance from the center of the two subsystems and z_{group} is the central redshift of A2033 or SIG. A2033 and SIG consist of 57 and 70 members, respectively. At the projected distance to A2033 and SIG, the possible contamination by A2029 members is 8 and 18, respectively. We discuss the negligible impact of this contamination in Section 4.5. Hereafter, we refer to the 57 and 70 members as A2033 and SIG members. The remaining 1088 members in the A2029 system belong to the central cluster, A2029, and its infall region.

3.2. Stellar Mass

We determine the stellar mass of each A2029 member using the Le PHARE fitting code (Arnouts et al. 1999; Ilbert et al. 2006), which estimates a mass-to-light ratio based on χ^2 synthetic spectral energy distribution (SED) fitting. We compare the SDSS DR12 *ugriz* cModel magnitudes of individual galaxies with the stellar population synthesis (SPS) models generated by the Bruzual & Charlot (2003) code, with a Chabrier (2003) initial mass function (IMF), and three metallicities. A set of synthetic SED models includes different star formation histories, foreground extinction, and stellar population ages. We assume an exponentially declining star-forming history with an e -folding timescale $\tau = 0.1, 0.3, 1, 2, 3, 5, 10, 15$, and 30. We also use the Calzetti et al. (2000) extinction law with an $E(B-V)$ range of 0.0 to 0.6 and with stellar population ages between 0.01 and 13 Gyr. The Le PHARE code calculates the probability density function (pdf) for the stellar mass. Our estimated stellar mass is the median of the appropriate pdf.

The typical absolute uncertainty in the stellar mass measured from the SED fitting is ~ 0.3 dex (Conroy et al. 2009). Uncertainties in star formation history, metallicity, dust extinction, SED models, IMF, and the SED fitting method propagate to the uncertainty and systematic error in the stellar

mass. The stellar mass estimate based on the Le PHARE code is systematically lower by ~ 0.1 dex than the mass estimates from other approaches (Zahid et al. 2014a). Thus, our mass estimates are only relatively accurate within the typical statistical uncertainty.

The stellar masses of the brightest galaxies of A2029 and A2033 we initially derive from SDSS DR12 are underestimated. Their SDSS DR12 cModel magnitudes are significantly overestimated: $r = 17.29$ for the A2029 Brightest Cluster Galaxy (BCG) and $r = 17.44$ for the A2033 BCG. Their DR7 cModel magnitudes are more reasonable: $r = 13.59$ for the A2029 BCG and $r = 14.20$ for the A2033 BCG, similar to R -band magnitudes of these galaxies listed in NED. Therefore, we use the SDSS DR7 cModel magnitudes to estimate the stellar masses for these BCGs.

3.3. D_n4000

The D_n4000 index is the flux ratio between two spectral windows around the 4000 Å break (Bruzual 1983; Balogh et al. 1999). We use the D_n4000 index as a marker of the stellar population age. Following the definition from Balogh et al. (1999), we calculate the index as a ratio between the flux in the interval 4000–4100 Å and the flux in the interval 3850–3950 Å. The D_n4000 indices for A2029 galaxies come directly from the spectra obtained in the SDSS, BOSS, and Hectospec observations. The D_n4000 values measured for the same objects from the Hectospec and SDSS spectra agree to within $\sim 5\%$.

We measure D_n4000 for essentially every member of the A2029 system (1198 members, $\sim 98.6\%$). Because of the completeness of the D_n4000 measurement, investigations based on D_n4000 contain essentially no systematic bias.

The D_n4000 index is often used to distinguish star-forming and quiescent galaxies because of its bimodal distribution (e.g., Kauffmann et al. 2003; Woods et al. 2010; Geller et al. 2014). This bimodality results from the fact that the D_n4000 index is sensitive to the stellar population age. Sohn et al. (2017) identify quiescent galaxies in A2029 with $D_n4000 > 1.5$ to construct the velocity dispersion function. We follow this selection (see, e.g., Woods et al. 2010; Zahid et al. 2016a) for identifying quiescent galaxies in A2029.

3.4. Velocity Dispersion

Sohn et al. (2017) publish central velocity dispersion measurements of A2029 quiescent galaxies with $D_n4000 > 1.5$. They use central velocity dispersions from the Portsmouth reduction (Thomas et al. 2013) for the galaxies with SDSS spectroscopy. They also measure the central velocity dispersions for galaxies with Hectospec data. We follow their procedure to obtain central velocity dispersions of A2029 galaxies for this extended sample.

We first compile velocity dispersions from the Portsmouth reduction (Thomas et al. 2013) for the galaxies with SDSS spectroscopy. Because the velocity dispersions from the Portsmouth reduction are essentially identical to those measured from Hectospec (Fabricant et al. 2013), we use these measurements without significant corrections. To measure the velocity dispersion from the SDSS spectra, Thomas et al. (2013) use the Penalized Pixel-Fitting (pPXF) code (Cappellari & Emsellem 2004) and the stellar population templates from Maraston & Strömbäck (2011) that are based on the MILES

Table 1
Physical Properties of the Spectroscopic Members of A2029

Object ID	R.A. (deg)	Decl. (deg)	z	$\log M_*$ $M_\odot$	D_n4000	σ (km s ⁻¹)	Spec. Type ^a	E+A?
1237658780557836308	227.740259	5.766147	0.07731 ± 0.00010	10.90 ± 0.04	2.03 ± 0.04	281 ± 5	N	N
1237658780557836338	227.737793	5.762320	0.07593 ± 0.00007	8.22 ± 0.33	2.03 ± 0.07	105 ± 14	N	N
1237658780557836305	227.744635	5.770809	0.07455 ± 0.00007	10.91 ± 0.05	2.14 ± 0.04	329 ± 5	N	N
1237658780557836311	227.738249	5.754465	0.07726 ± 0.00009	10.20 ± 0.06	1.86 ± 0.04	238 ± 9	N	N
1237658780557836336	227.732202	5.761856	0.08085 ± 0.00014	-99.00 ± 0.00	1.82 ± 0.11	84 ± 31	N	N
1237658780557836342	227.749463	5.769346	0.07828 ± 0.00007	8.65 ± 0.19	1.91 ± 0.05	49 ± 17	N	N
1237658780557836316	227.735039	5.751555	0.07921 ± 0.00008	10.40 ± 0.04	2.08 ± 0.04	237 ± 6	N	N
1237658780557836337	227.732491	5.765348	0.07899 ± 0.00006	9.81 ± 0.11	1.88 ± 0.05	112 ± 10	N	N
1237658780557836369	227.731678	5.764879	0.07735 ± 0.00015	-99.00 ± 0.00	1.56 ± 0.09	123 ± 41	N	N

Note.

^a Spectroscopic type of the galaxies: S - star forming, C - composite, A - AGN, N - not available.

(This table is available in its entirety in machine-readable form.)

stellar library (Sánchez-Blázquez et al. 2006). The best-fit velocity dispersion is derived by comparing the spectra and the templates. From the Portsmouth reduction, we obtain 416 velocity dispersions for A2029 members. These velocity dispersions have a typical uncertainty of 7 km s⁻¹.

For galaxies with MMT/Hectospec spectra, we measure velocity dispersions with the University of Lyon Spectroscopic analysis Software (ULySS; Koleva et al. 2009). ULySS derives the best-fit velocity dispersion based on a chi-square fit of the Hectospec spectra to the stellar population templates. We use stellar templates constructed with the PEGASE-HR code and the MILES stellar library. We convolved these stellar templates to the Hectospec resolution with various velocity dispersions. To minimize the uncertainty in the velocity dispersion measurements, the fitting range is limited to the rest-frame spectral range 4100–5500 Å (Fabricant et al. 2013). We measure 765 velocity dispersions from Hectospec data. The median uncertainty of the Hectospec velocity dispersions is ~17 km s⁻¹.

We apply an aperture correction to the velocity dispersion measurements because SDSS and Hectospec obtain the spectra through 3'' and 1''5 fibers, respectively. We define the aperture correction following (Zahid et al. 2016b)

$$\sigma_A/\sigma_B = (R_A/R_B)^\beta. \quad (1)$$

We use 270 quiescent objects with both SDSS and Hectospec velocity dispersions within the range of 100 km s⁻¹ < σ < 450 km s⁻¹ and $\Delta\sigma$ < 100 km s⁻¹ to determine β for the aperture correction. The best-fit parameter is $\beta = -0.059 \pm 0.014$, consistent with $\beta = -0.046 \pm 0.013$ from Zahid et al. (2016b) and $\beta = -0.054 \pm 0.005$ from Sohn et al. (2017).

We quote the central velocity dispersion within a fiducial physical aperture of 3 kpc (rest frame) following Zahid et al. (2016b) and Sohn et al. (2017). Throughout this paper, σ indicates the central velocity dispersion within the 3 kpc aperture. We use the velocity dispersion of quiescent galaxies with $D_n4000 > 1.5$, where the random motion of stars dominates over ordered stellar rotation (Zahid & Geller 2017). Table 1 lists the 140 velocity dispersions and D_n4000 values of A2029 members not included in Sohn et al. (2017). Previous measurements for 834 A2029 members are included in Table 2 of Sohn et al. (2017).

3.5. Emission-line Flux

We use emission-line strengths to study the physical properties including nuclear activity and metallicity of the late-type galaxies in A2029. We first collect the line fluxes for the objects with SDSS spectra measured by the MPA/JHU Group³ and the Portsmouth Group⁴ (Thomas et al. 2013). The MPA/JHU and Portsmouth catalogs include flux measurements of 273 and 288 galaxies in the A2029 field, respectively. The line flux measurements from the two catalogs are consistent within ~0.1 dex (~0.2 dex for [O II] $\lambda\lambda 3726+3729$; Thomas et al. 2013). Thus, the flux measurements from the MPA/JHU and Portsmouth catalogs are interchangeable. For 270 duplicated objects, we take the MPA/JHU value for further analysis.

We measure line fluxes for galaxies observed with the same Hectospec fitting procedure used in Zahid et al. (2013). The fitting procedure uses the MPFIT package (Markwardt 2009) implemented in IDL. We fit the continuum of each galaxy with the SPS model of Bruzual & Charlot (2003). We fit each emission line in the continuum-subtracted spectrum with a Gaussian and use the best-fit parameters to derive the line flux. We calculate the observational uncertainties in the line flux measurements by standard error propagation of the estimated uncertainties in the spectrum.

The flux measurements for the [O II] $\lambda\lambda 3726+3729$ doublet may be uncertain because the doublet is hardly resolved in the SDSS and Hectospec spectra (Thomas et al. 2013). This [O II] line is essential for estimating the metallicity of emission-line galaxies (e.g., Kobulnicky & Kewley 2004). Previous studies use the sum of the doublet when deriving the metallicity based on the SDSS and/or Hectospec spectra (Zahid et al. 2014a, 2014b; Wu et al. 2017). Following this procedure, we also use the sum of the [O II] doublet when we estimate the metallicity of A2029 galaxies (Section 4.2). We refer to the sum as [O II] $\lambda\lambda 3727$ hereafter.

We adopt a dust extinction correction based on the Cardelli et al. (1989) extinction curve. We assume an intrinsic $H\alpha/H\beta$ ratio of 2.86 (case B recombination; Osterbrock & Ferland 2006). The AGNs in A2029 may have a different intrinsic $H\alpha/H\beta$ ratio (e.g., $H\alpha/H\beta \sim 3.0$; Dong et al. 2008; Baron et al. 2016). We apply AGN diagnostics (see Section 4.1) with

³ <https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/>

⁴ https://www.sdss3.org/dr10/spectro/galaxy_portsmouth.php

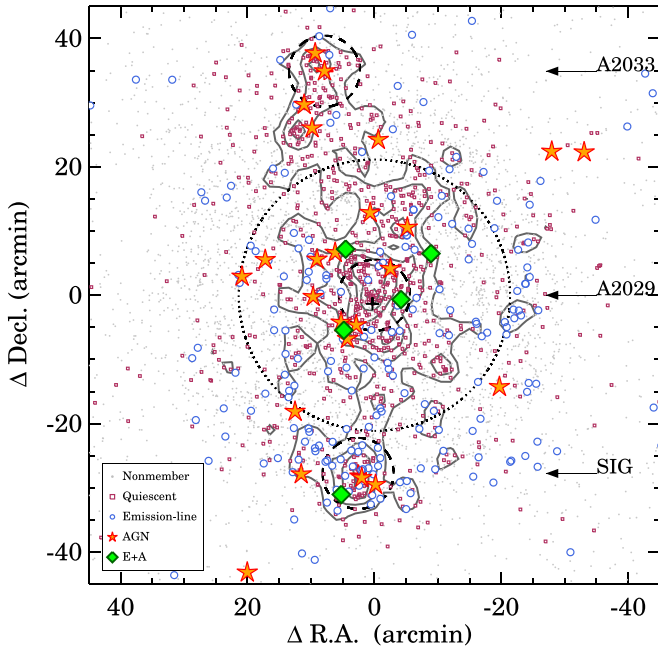


Figure 1. Spatial distribution of galaxies in the A2029 field. Gray dots are spectroscopic targets. Red squares are quiescent ($D_n4000 > 1.5$) A2029 members, and blue circles are the star-forming population ($D_n4000 \leq 1.5$) in A2029. Red stars and green diamonds indicate AGNs and E+A galaxies, respectively. The underlying contour shows the number density of A2029 members. The labels and arrows mark the position (decl.) of each system. The dotted circle centered on A2029 shows $R_{cl} = R_{200} = 1.91$ Mpc. The dashed circles centered on A2033 (north), A2029 (center), and SIG (south) show $R_{cl} = 500$ kpc.

different intrinsic Balmer ratios to test the effect of the dust correction. The number of AGNs does not change when we use a Balmer ratio in the range of 2.86–3.10. Thus, we simply use the Balmer ratio of 2.86 regardless of the type of object.

Fabricant et al. (2008) show that the line flux measurements for the same objects from Hectospec and SDSS spectra agree to within $\sim 4\%$. Thus, we use the line flux measurements from Hectospec and SDSS spectra without any correction.

4. Census of A2029 Member Galaxies

Here we examine a census of A2029 cluster members based on the complete spectroscopic sample. The complete survey enables statistical analysis of the galaxy populations in the cluster without significant sample selection bias. The number of members is large enough to avoid the stacking techniques often used to explore cluster populations (Balogh et al. 1999; Haines et al. 2013; Paccagnella et al. 2016).

Figure 1 summarizes the galaxy populations. Figure 1 displays the spatial distribution of spectroscopic targets in the A2029 field. Gray dots are spectroscopically identified nonmembers of A2029. Blue circles and red squares indicate spectroscopic members with $D_n4000 \leq 1.5$ and $D_n4000 > 1.5$, respectively. Gray contours show the number density of the spectroscopically selected A2029 members. A black plus sign marks the position of the BCG (IC 1101). Red stars show AGNs (Section 4.1). We examine the stellar mass and metallicity relation based on the members with emission lines (blue circles; Section 4.2). Green diamonds mark the position of post-starburst (E+A) galaxies (Section 4.3). Finally, we discuss the D_n4000 distribution of the members of A2029 and of the infalling systems A2033 and SIG in Section 4.5.

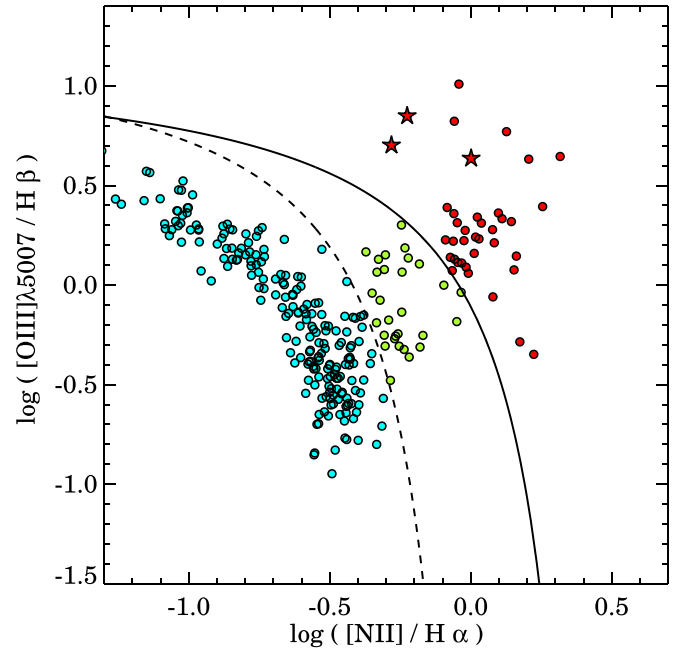


Figure 2. BPT diagram for A2029 members. The solid line shows a theoretical upper limit for starburst galaxies (Kewley et al. 2001), and the dashed line represents the boundary for pure star-forming galaxies (Kauffmann et al. 2003). There are 277 emission-line objects: 210 star-forming galaxies (cyan), 29 composite objects (green), and 38 AGNs (red). The stars indicate the *Chandra* X-ray point sources.

4.1. AGNs in A2029

We adopt the widely used BPT diagnostic diagram (Baldwin et al. 1981) to determine the spectral types of emission-line galaxies. We require line fluxes with signal-to-noise ratio ($S/N > 3$) for $H\alpha$, $H\beta$, $[O III] \lambda 5007$, and $[N II] \lambda 6584$, for AGN diagnosis. There are 277 objects ($23\% \pm 1\%$) with reliable emission-line fluxes among 1215 A2029 system members.

Figure 2 shows the $[O III]/H\beta$ versus $[N II]/H\alpha$ diagram for A2029 emission-line objects. The dashed and solid lines are the theoretical boundaries where purely star-forming (Kauffmann et al. 2003) and extreme star-forming galaxies (Kewley et al. 2001) would appear, respectively. The objects with a high $[O III]/H\beta$ and $[N II]/H\alpha$ ratio compared to the extreme star-forming galaxies are AGNs. We also classify star-forming and “composite” objects based on their relative positions with respect to the model lines.

In A2029, there are 38 AGNs, 29 composite objects, and 210 star-forming galaxies. The overall AGN fraction, i.e., N_{AGN}/N_{member} , is $\sim 3\%$. The AGN fraction is similar to the AGN fractions measured in individual clusters ($\sim 0.5\% - 9\%$; Deshev et al. 2017; Habas et al. 2018). However, a direct comparison among the AGN fractions is not trivial because the magnitude limit and spectroscopic completeness of other cluster redshift surveys vary.

We measure the AGN fraction in fixed magnitude ranges for a fairer comparison with cluster AGN fractions in the literature. Hwang et al. (2012b) measure the AGN fractions from three volume-limited samples extracted from stacked SDSS spectroscopic samples in eight clusters. The three volume-limited samples they used are a bright sample with $-22.5 \leq M_r < -20.5$ and $0.04 \leq z \leq 0.1434$, an intermediate-luminosity sample with $-20.5 \leq M_r < -19.5$ and $0.04 \leq z \leq 0.0927$, and a faint sample with $-19.5 \leq M_r < -18.5$ and $0.04 \leq z \leq 0.0593$.

Table 2
Chandra X-Ray Point Sources in the A2029 Field

Chandra ID	R.A. _x	Decl. _x	f_x^a	Object ID ^b	θ_{offset}^c (arcsec)	z	Membership	Spec. Type
CXO J151100.4+054921	227.751875	5.82251	$6.88^{+0.45}_{-0.44}$	1237658780557836762	0.18	0.5463	N	Galaxy
CXO J151106.3+054122	227.776623	5.68966	$67.25^{+2.93}_{-2.89}$	1237655744020087024	0.48	0.0807	Y	AGN
CXO J151037.2+054814	227.655344	5.80391	$9.14^{+0.66}_{-0.65}$	1237658780557771187	0.29	1.2232	N	Quasar
CXO J151123.4+054041	227.847748	5.67819	$5.63^{+0.73}_{-0.73}$	1237655744020087171	1.21	0.9294	N	Quasar
CXO J151133.6+054546	227.890377	5.76302	$11.11^{+0.77}_{-0.77}$	1237662268074033709	0.50	0.0847	Y	AGN
CXO J151038.9+055329	227.662125	5.89141	$1.24^{+0.37}_{-0.37}$	587736546849063315	2.54	0.2973	N	Comp
CXO J151127.3+053943	227.864084	5.66196	$2.53^{+0.60}_{-0.60}$	1237655744020087813	2.15	0.7881	N	NA
CXO J151025.3+055026	227.605677	5.84075	$1.12^{+0.32}_{-0.33}$	1237662268073902520	1.87	0.0745	Y	Galaxy
CXO J151045.9+055557	227.691550	5.93273	$0.05^{+0.64}_{-0.05}$	587736546849064050	2.63	0.5669	N	Quasar
CXO J151141.2+051809	227.921920	5.30258	$34.67^{+4.96}_{-4.92}$	1237662267537228077	0.09	0.0842	Y	AGN

Notes.

^a X-ray flux in units of 10^{-14} erg s⁻¹ cm⁻².

^b SDSS Object ID (DR12 or DR7) for the optical counterparts.

^c Offset between the X-ray source and the SDSS optical counterpart.

To compare with this result, we estimate the AGN fraction in the bright magnitude range of $-22.5 \leq M_r < -20.5$. The AGN fraction, $\sim 10.0\% \pm 1.7\%$, in the bright sample is similar to the bright sample of Hwang et al. (2012b), $\sim 7.6\% \pm 0.3\%$. The AGN fractions of A2029 in the intermediate and faint magnitude ranges are negligible.

Most A2029 AGNs (92%) are located in galaxies with $M > 10^{10} M_\odot$; 14 (37%) AGN host galaxies have $M > M_{\text{star}} = 10^{10.7} M_\odot$ (Sohn et al. 2017). The mass distribution of A2029 AGN host galaxies differs from that of A85, where half of the AGNs reside in low-mass galaxies with $M < 10^{9.5} M_\odot$ (Habas et al. 2018). Pimbblet et al. (2013) examine the variation of AGN fraction as a function of host galaxy mass based on a stacked sample of six clusters. They show that more massive cluster galaxies are more likely to host AGNs. We find a similar trend; the AGN fraction is higher for A2029 members with larger stellar mass.

To examine the radial dependence of the AGN fraction, we compute the frequency of AGNs among cluster members at various normalized clustercentric radii. There is no clear variation in the AGN fraction within $R_{\text{cl}} < \sim 1.5R_{200}$, where the redshift survey is complete. The AGN fraction increases rapidly at $R_{\text{cl}} > 1.5R_{200}$, although the redshift survey is incomplete in this region. The radial dependence of the fraction of AGN and composite objects follows the same trend. The constant AGN fraction at the cluster center contrasts with Pimbblet et al. (2013), who found a significant decrease in the innermost region of six local clusters. Hwang et al. (2012b) examine more details of the radial AGN fraction by computing the AGN fraction for early and late types, separately. The AGN fraction in early types shows a radial dependence; the AGN fraction in late types changes little as a function of clustercentric distance. The majority of the AGN host galaxies in A2029 are late types ($\sim 66\%$); thus, the weak radial dependence in AGN fraction seems consistent with the results from Hwang et al. (2012b).

We also explore X-ray point sources in the A2029 field based on the Chandra Source Catalog (CSC) Release 2.0 (Evans et al. 2010). The CSC provides a list of X-ray point sources identified based on Chandra ACIS and HRI observations. The CSC lists 26 X-ray sources within $40'$ of the A2029 center. There are 10 X-ray sources with spectroscopic counterparts within $3''$ of the X-ray center; there are four

cluster members and six background sources with $z > 0.29$. Among the four X-ray-emitting cluster members, three are spectroscopic AGNs and one is an elliptical galaxy without emission lines. These three spectroscopic AGNs are luminous X-ray AGNs with X-ray luminosities of $(2.0\text{--}11.0) \times 10^{42}$ erg s⁻¹. Table 2 lists the X-ray point sources in the A2029 field.

4.2. The Mass–Metallicity (MZ) Relation

We derive the mass–metallicity relation, hereafter the MZ relation, for star-forming galaxies in A2029. The MZ relation of clusters is often measured based on a small sample of cluster galaxies or on stacked cluster samples (Ellison et al. 2009; Petropoulou et al. 2011; Robertson et al. 2012; Gupta et al. 2016). Petropoulou et al. (2012) investigate the MZ relation of four nearby clusters (Coma, A1367, A779, A634) based on SDSS spectroscopy. Here we derive the cluster MZ relation based on a large spectroscopic sample for a single cluster, A2029.

Similar to the sample we use for AGN identification, we select galaxies with line fluxes that have $S/N > 3$ for H α , H β , and [N II] $\lambda 6584$. We also require $S/N > 3$ in the [O II] $\lambda 3727$ flux measurement. Foster et al. (2012) show that S/N cuts on [O III] $\lambda 5007$ may introduce a bias at high metallicity. Thus, we do not apply an S/N cut on [O III] $\lambda 5007$. We identify 227 star-forming galaxies based on the BPT classification for this analysis. The number of star-forming galaxies increases slightly compared with the number (210) quoted in Section 4.1 because we do not exclude low [O III] $\lambda 5007$ objects.

We compute the metallicity of A2029 member galaxies based on the Kobulnicky & Kewley (2004) method. We first calculate R_{23} and O_{32} ratios:

$$R_{23} = \frac{[\text{O II}] \lambda 3727 + [\text{O III}] \lambda 4959 + [\text{O III}] \lambda 5007}{\text{H}\beta} \quad (2)$$

and

$$O_{32} = \frac{[\text{O III}] \lambda 4959 + [\text{O III}] \lambda 5007}{[\text{O II}] \lambda 3727}. \quad (3)$$

The MZ relation is often derived using EWs of the lines (Kobulnicky & Kewley 2004). Here we use line fluxes instead of EWs to compare directly with the results from Wu et al.

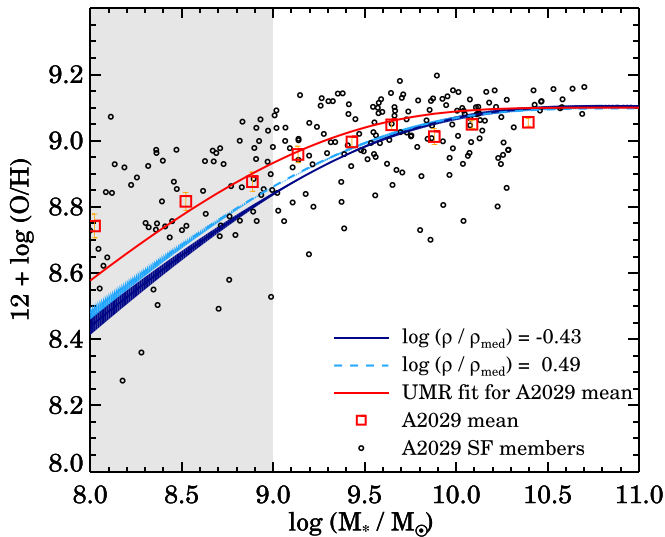


Figure 3. $12 + \log(\text{O}/\text{H})$ vs. stellar mass for A2029 members. Black circles show measurements for individual galaxies; red squares show the median. The solid and dashed lines display the mass–metallicity relations derived from SDSS galaxies in low- and high-density regions, respectively (Wu et al. 2017). The shaded region indicates the mass range we exclude when we compare the MZ relations from A2029 and with the SDSS galaxies.

(2017), who examine the environmental dependence of the MZ relation based on line fluxes from SDSS spectra. We assume that the flux ratio between [O III] $\lambda 4959$ and [O III] $\lambda 5007$ is 3 (Osterbrock & Ferland 2006) and simply use 1.33 times [O III] $\lambda 5007$ when we sum the [O III] line fluxes.

Kobulnicky & Kewley (2004) determine metallicities, i.e., $12 + \log(\text{O}/\text{H})$, of galaxies based on the relative positions of the R_{23} and O_{32} indices with respect to model grids. Following their method, we derive the metallicities of A2029 star-forming galaxies. The intrinsic uncertainty of individual metallicity measurements is ~ 0.1 dex (Kobulnicky & Kewley 2004).

Figure 3 shows the MZ relation for A2029 star-forming galaxies. Black circles are individual measurements for the A2029 system members, and the red squares are the median metallicities as a function of stellar mass. We compare the A2029 MZ relation with the MZ relation derived from SDSS galaxies at $z \sim 0.08$ in different density environments. Wu et al. (2017) examine the MZ relation of SDSS galaxies based on galaxies with $M > 10^9 M_\odot$ in various density environments. The 8 Mpc kernel density they used, $\log(\rho/\rho_{\text{med}})$, is the sum of the weighted, kernel-smoothed luminosities of galaxies within 8 Mpc normalized by the median density of the SDSS main galaxy sample (see more details in Wu et al. 2017). In Figure 3, we show the SDSS MZ relations for $\log(\rho/\rho_{\text{med}}) \sim -0.48$ (light blue) and ~ 0.43 (dark blue) for simplicity.

We fit the universal metallicity relation (UMR) formulation of Zahid et al. (2014a) to the median metallicities of A2029 galaxies. The UMR formulation is

$$12 + \log(\text{O}/\text{H}) = Z_0 + \log \left[1 - \exp \left(- \left[\frac{M_*}{M_0} \right]^\gamma \right) \right]. \quad (4)$$

In their study of environmental effects, Wu et al. (2017) use this UMR formulation. Because the impact of local density on Z_0 and γ is small, they fit the MZ relations with fixed Z_0 and γ

to quantify the environmental effect on M_0 . Following their approach, we use a fixed $Z_0 = 9.100$ and $\gamma = 0.505$. We note that the Z_0 and γ change little if we do not fix them for fitting the UMR formulation. The red solid line shows the best-fitting model with $M_0 = 8.86 \pm 0.04$. If we limit the fitting range to $M > 10^9 M_\odot$ identical to Wu et al. (2017), the M_0 is 9.05 ± 0.05 .

Wu et al. (2017) show that the best-fitting M_0 decreases significantly as the relative density increases. They also provide a relation between M_0 and the local density (Equation (15) in Wu et al. 2017). The 8 Mpc kernel density around A2029 is $\log(\rho/\rho_{\text{med}}) \sim 1$ (P.-F. Wu 2019, private communication): A2029 represents the highest-density region in the SDSS spectroscopic sample. The expected M_0 for the A2029 MZ relation based on the M_0 –local density relation is 9.12 ± 0.03 , consistent with the M_0 we derive.

The MZ relation for A2029 is similar to the SDSS MZ relation for the mass range $M > 10^{9.5} M_\odot$. We note that the MZ relation saturates in this mass range (Zahid et al. 2014a). In other words, the shape of the MZ relation in this mass range is insensitive to the sample redshifts and environments.

Interestingly, the A2029 population is more metal-rich than the SDSS field population for $M < 10^{9.5} M_\odot$. This comparison is only valid to $M = 10^9 M_\odot$, where the SDSS MZ relations were derived. This difference is more significant than the difference among the SDSS field samples in different density environments.

Petropoulou et al. (2012) also find higher metallicity at low stellar mass for members of four nearby clusters including Coma. In their sample, particularly Coma and A1367 galaxies, the cluster galaxies with $10^8 M_\odot < M_* < 10^9 M_\odot$ within $R_{\text{cl}} < R_{200}$ are metal-rich compared to their counterparts at $R_{\text{cl}} > R_{200}$. They suggest that the interaction between cluster galaxies and the ICM affects the metal content of low-mass galaxies in dense environments. Furthermore, the ICM tends to remove gas from these systems (e.g., Gunn & Gott 1972), supporting the suggestion of Wu et al. (2017) that these galaxies have less gas associated with them. The A2029 MZ relation supports these suggestions based on the additional comparison with SDSS field samples.

4.3. E+A Galaxies

An E+A galaxy has the spectrum of an elliptical galaxy along with strong Balmer absorption lines typical of A-type stars (Dressler & Gunn 1983; Couch & Sharples 1987). These galaxies are probably a post-starburst population where star formation was quenched within the past few gigayears (Caldwell et al. 1996; Zabludoff et al. 1996; Tran et al. 2003, 2004; Goto 2005).

The role of local environment in the formation and evolution of E+A galaxies remains unclear. Many studies examine the connection between local environment and the E+A phenomenon (Dressler & Gunn 1983; Zabludoff et al. 1996; Dressler et al. 1999; Blake et al. 2004; Poggianti et al. 2004; Quintero et al. 2004; Goto 2005; Paccagnella et al. 2017). At $z > 0.3$, E+A galaxies are more abundant in clusters than in the general field (Tran et al. 2003, 2004). Lemaux et al. (2017) show that the post-starburst fraction is similar in field, group, and cluster environments at $z > 0.6$. However, they also show that the

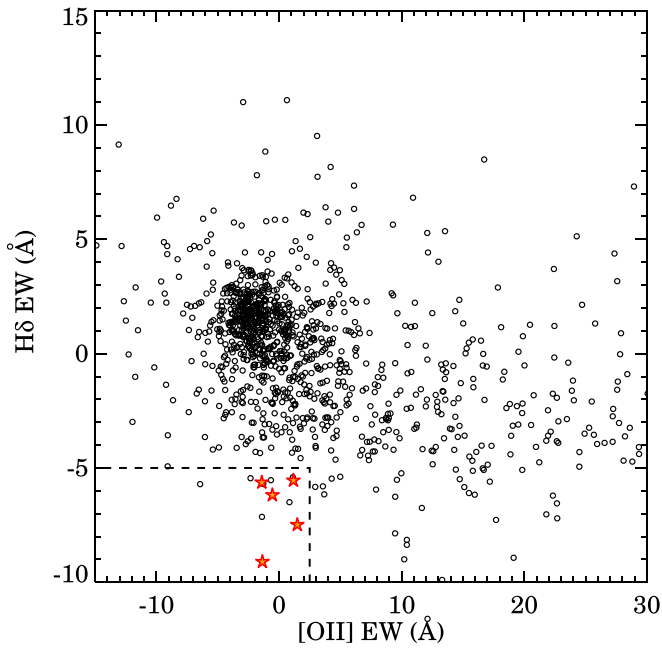


Figure 4. $H\delta$ EW vs. $[O II] \lambda 3727$ EW for members of the A2029 system. Blue dashed lines indicate the boundary we use for identifying E+A galaxy candidates. Black circles are A2029 spectroscopic members, and red stars are the five E+A galaxies in A2029.

ratio between the post-starburst and emission-line populations is larger in clusters than in lower-density regions.

In the local universe ($z \sim 0.1$), E+A galaxies are predominantly in the field or in poor groups (Zabludoff et al. 1996; Blake et al. 2004; Quintero et al. 2004; Goto 2005). A significant number of E+A galaxies were recently identified in local clusters: Coma (Poggianti et al. 2004) and A3921 (Ferrari et al. 2005). Paccagnella et al. (2017) provide a census of post-starburst galaxies based on the OmegaWINGS local cluster sample, which includes 32 clusters at $0.04 < z < 0.07$. They suggest that the fraction of these post-starburst galaxies increases slightly as the clustercentric distance decreases.

We identify E+A galaxies in A2029 with $H\delta$ EW $< -5 \text{ \AA}$ and $[O II] \lambda 3727$ EW $< 2.5 \text{ \AA}$ following the standard definition (Goto et al. 2003; Zahid et al. 2016a). A negative EW indicates absorption. The procedure we use to measure the $H\delta$ EW is outlined in Goto et al. (2003). We use the $H\delta$ (wide) definition: the blue continuum is 4030–4082 $\text{\AA}$, and the red continuum is 4122–4170 $\text{\AA}$. The $H\delta$ EW is the sum of pixels in the line at 4082–4122 $\text{\AA}$. The details of the $H\delta$ EW measure are described in Zahid et al. (2016a).

Figure 4 shows the $H\delta$ and $[O II] \lambda 3727$ EW distribution for the A2029 system members. The dashed lines indicate the boundary we use for identifying E+A galaxy candidates. There are 14 E+A galaxy candidates. We visually inspect the spectra of the E+A candidates to eliminate candidates with strong emission lines. The galaxies with strong emission lines are e(a) and A+em objects (Balogh et al. 1999; Poggianti et al. 1999), which may have ongoing star formation, or they may be AGNs. We reject these E+A candidates with emission lines from our E+A sample. We display the spectra of five E+A galaxies along with an example spectrum of an E+A candidate with emission lines rejected during visual inspection (Figure 5).

We identify four E+A galaxies within R_{200} of the main cluster and one E+A galaxy near SIG. The E+A galaxy in SIG

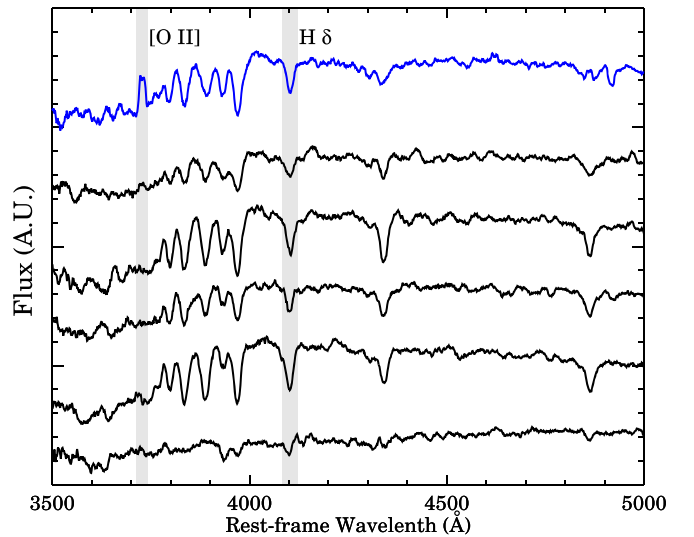


Figure 5. Rest-frame spectra of the five E+A galaxies (black) in the A2029 system. The fluxes of the spectra are arbitrarily shifted. The E+A galaxies are sorted by distance from the A2029 main cluster center: the top black spectrum is closest to the A2029 center. The spectrum at the bottom is from the E+A galaxy in SIG. The top spectrum shows a rejected E+A candidate with strong $H\delta$ absorption and emission lines. Note that this rejected E+A candidate has strong $[O II]$ emission.

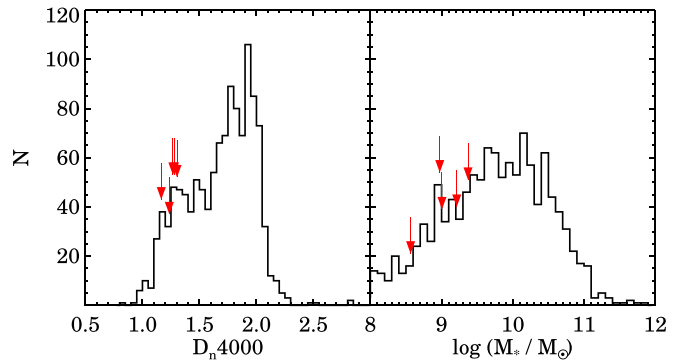


Figure 6. D_n4000 (left) and stellar mass (right) distribution of A2029 system member galaxies. Red arrows show the five E+A galaxies in A2029.

shows weak E+A features and has a low stellar mass. Green diamonds in Figure 1 mark the locations of these E+A galaxies. All of these E+A galaxies have projected radius $R_{cl} > 400$ kpc. The spatial distribution of the A2029 E+A galaxies suggests that the E+A galaxies may not survive near the cluster core. We note that projection effects are important for assessing the true spatial distribution of the E+A galaxies. Although the E+A galaxies in A2029 are projected well within R_{200} , their physical distances could be much larger than R_{200} .

Figure 6 shows the D_n4000 and the stellar mass (M_*) distributions of normal (histogram) and E+A (arrows) galaxies in A2029. E+A galaxies in different density environments and in different redshift ranges generally have $D_n4000 < 1.5$ (Balogh et al. 1999; Zahid et al. 2016a). The low D_n4000 reflects the post-starburst character of the E+A population. The E+A galaxies in A2029 are less massive than $M_* = 10^{10} M_\odot$ (see $M_{*,A2029} \sim 5 \times 10^{10} M_\odot$; Sohn et al. 2017). The E+A galaxies in Coma and A3921 are also mostly faint ($M_V \geq -20$) and thus probably have low stellar mass.

Historically, ram pressure stripping has been considered a plausible mechanism for turning off star formation in infalling

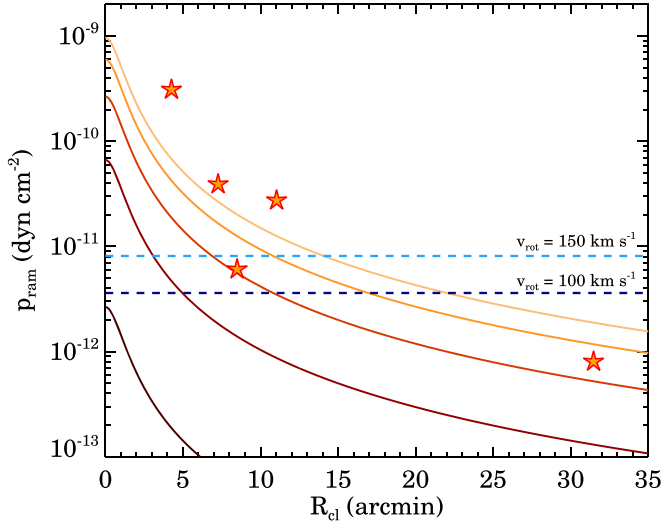


Figure 7. Ram pressure on a galaxy falling into A2029 with a relative velocity of 100, 500, 1000, 1500, and 2000 km s⁻¹ (solid lines from bottom to top) as a function of projected radial distance. The horizontal dashed lines show the restoring gravitational force per unit area of a disk galaxy with rotational velocity 100 (lower) and 150 km s⁻¹ (upper). Star symbols show the five E+A galaxies in A2029.

galaxies. Thus, we compute the ram pressure exerted on E+A galaxies based on the recipe from Gunn & Gott (1972). When a galaxy falls into a cluster, it feels ram pressure due to the ICM:

$$P_{\text{ram}} \approx \rho_{\text{ICM}} v^2, \quad (5)$$

where ρ_{ICM} is the ICM density and v is the relative velocity of the galaxy with respect to the ICM. However, we do not know the velocity of the ICM; thus, we simply used the relative velocity between the galaxy and the cluster mean. The restoring gravitational force per unit area can be estimated (Gunn & Gott 1972; Vollmer et al. 2001):

$$F = \Sigma_{\text{gas}} v_{\text{rot}}^2 R_{\text{disk}}^{-1}, \quad (6)$$

where Σ_{gas} is gas surface density, v_{rot} is rotational velocity of a disk, and R_{disk} is a disk radius. If the ram pressure exceeds the restoring gravitational force, the gas in the disk may be removed.

To estimate the ρ_{ICM} , we use the ICM density profile from Walker et al. (2012), who measure the radial gas density within $R_{\text{cl}} < 20'$ based on *Suzaku* X-ray observations. We fit a β model with a form $\rho_g = \rho_0 [1 + (r/r_c)^2]^{-\beta}$ to their gas density (Figure 4 in Walker et al. 2012). The best-fit model parameters are $\rho_g = 2.7 \times 10^{-26} \text{ g cm}^{-3}$, $r_c = 0.88 \text{ arcmin}$, and $\beta = 0.86$. The fitting parameters have large uncertainties, but they are acceptable for our purposes. Based on the fit, we calculate the ρ_{ICM} at the projected distance of A2029 E+A galaxies from the cluster center. We compute the ram pressure for each E+A galaxy using the ρ_{ICM} and the measured relative radial velocity with respect to the cluster mean.

Figure 7 shows the ram pressure on the five E+A galaxies as a function of the projected distance. Solid lines in Figure 7 plot the ram pressure from the ICM if a galaxy falls into A2029 with relative velocity 100, 500, 1000, 1500, and 2000 km s⁻¹. Here the ram pressure we compute is only indicative because we use the projected clustercentric distance and the one-dimensional velocity. These effects may well compensate for one another.

The dashed lines show the restoring gravitational force per unit area for a typical disk galaxy with rotational velocity 100 and 150 km s⁻¹. We assume a gas surface density of 10^{-21} cm^{-2} and disk radius of 5 kpc (Vollmer et al. 2001; Lee et al. 2017).

Our simplified approach facilitates quantitative calculation of ram pressure stripping and gravity on the E+A galaxies. Jaffé et al. (2018) discuss caveats, including projection effects in the orbit, inclination angle, and differences in disk models of the infalling galaxies. Resolving projection effects in the orbit is challenging. Thus, the ram pressure we calculate is only indicative of the possible role of ram pressure stripping.

The comparison in Figure 7 suggests that ram pressure is a possible explanation for all of the E+A galaxies in A2029. The ram pressure on the four E+A galaxies within the R_{200} of A2029 exceeds the restoring gravitational force. For the E+A galaxy in SIG, we probably underestimate the ram pressure because we only compute the impact from the ICM around the main cluster using the relative motion of the galaxy with respect to the main cluster. Direct detection of the stripped gas would be a strong test of the ram pressure model (e.g., Giovanelli & Haynes 1985; Lee et al. 2017; Jaffé et al. 2018).

4.4. Central Velocity Dispersions

The central velocity dispersion of a galaxy, reflecting stellar kinematics, may be one of the key observables connecting the galaxy and its dark matter halo (Schechter 2016; Zahid et al. 2016b). Based on the Illustris simulation, Zahid et al. (2018) show that the stellar velocity dispersion of the quiescent population is tightly correlated with the dark matter halo velocity dispersion. Thus, the stellar velocity dispersion is a good proxy for the dark matter halo properties.

Sohn et al. (2017) also discuss the power of the velocity dispersion to study cluster galaxy populations. Unlike luminosity or stellar mass, the velocity dispersion measurement is independent of systematic uncertainties in photometric data (i.e., crowded field photometry or the dependence on stellar IMF or star formation history of the stellar mass measurement). Sohn et al. (2017) measure the velocity dispersion function of quiescent members of the A2029 system. The velocity dispersion function is a tool for studying the dark matter halo distribution in analogy to the luminosity and stellar mass functions.

Based on the updated catalog including new velocity dispersion measurements, we examine the relation between velocity dispersion and stellar mass for the A2029 quiescent galaxies. Figure 8 shows the velocity dispersion of A2029 quiescent members as a function of stellar mass color-coded by D_n4000 . A2029 members with larger stellar mass generally have higher velocity dispersions. The higher- D_n4000 galaxies tend to have higher velocity dispersions at a given stellar mass. These relations between velocity dispersion, stellar mass, and D_n4000 are also observed in Coma Cluster members (Sohn et al. 2017) and in the SDSS field galaxies (Zahid et al. 2016b).

The star symbols in Figure 8 display the brightest galaxies of A2029 and the two infalling groups, A2033 and SIG. We use SDSS DR7 photometry of the BCGs when we compute their stellar masses. The BCG of A2029 (IC 1101) has the largest velocity dispersion, $\sigma = 430 \pm 17 \text{ km s}^{-1}$, among the cluster members. The velocity dispersions of the brightest galaxies of SIG ($\sigma = 307 \pm 6 \text{ km s}^{-1}$) and A2033 ($\sigma = 357 \pm 6 \text{ km s}^{-1}$) are also very large.

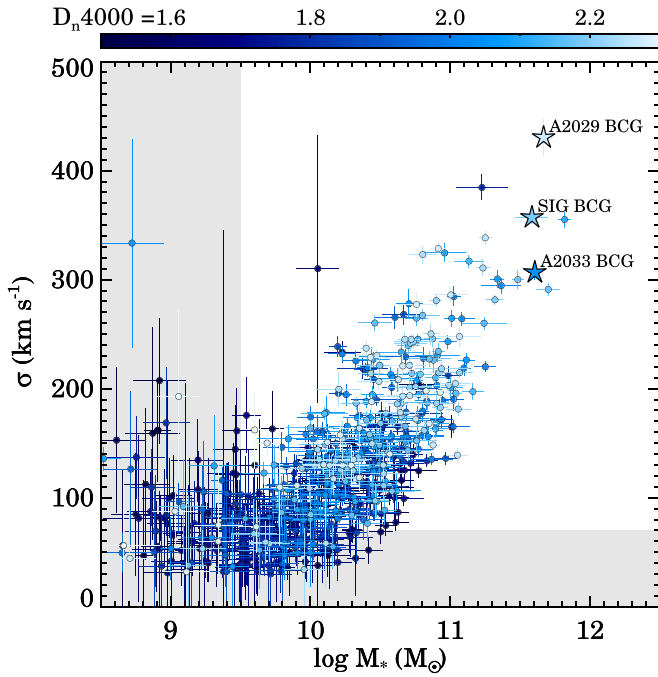


Figure 8. Velocity dispersion of A2029 member galaxies with $D_n4000 > 1.5$ as a function of stellar mass. The colors of the symbols indicate D_n4000 ; light blue indicates high D_n4000 , and dark blue indicates low D_n4000 . The star symbols show the brightest galaxies of A2029, A2033, and SIG. The gray area indicates the region where either the velocity dispersion measurements are not robust or where the spectroscopic survey is incomplete.

Interestingly, the velocity dispersions of the brightest galaxies in A2029 and its subsystems are roughly correlated with the masses of the systems. Sohn et al. (2018b) estimate the velocity dispersions of the A2029, A2033, and SIG systems: $\sigma_{\text{A2029}} = 967 \pm 25 \text{ km s}^{-1}$, $\sigma_{\text{A2033}} = 701 \pm 74 \text{ km s}^{-1}$, and $\sigma_{\text{SIG}} = 745 \pm 62 \text{ km s}^{-1}$. The relation between the central galaxies and the cluster velocity dispersions suggests a connection between the brightest galaxy properties and the properties of the host system.

4.5. D_n4000 Distribution

Analyses based on D_n4000 add another powerful probe (Balogh et al. 1999; Luparello et al. 2013). Balogh et al. (1999) investigate the differential evolution of galaxies in clusters and the field by tracing the D_n4000 distribution. Following this approach, we explore the D_n4000 distribution of A2029 galaxies to understand the evolution of galaxies within the cluster and the infalling groups.

The impact of cluster environment on galaxy evolution is intensively studied based on various tracers from multi-wavelength data. Many previous studies show evidence of environmental effects, including variation in color, morphological fraction, gas content, and (specific) star formation rates of galaxies in varying density environments (e.g., Oemler 1974; Rines et al. 2005; Boselli & Gavazzi 2006; Park et al. 2007; Blanton & Moustakas 2009; Thomas et al. 2010; Haines et al. 2015; Barsanti et al. 2018). In general, galaxies in dense regions are old and quiescent compared to their counterparts in less dense regions.

Tyler et al. (2013) examined environmental effects in A2029 based on the star formation activity of the cluster members. From *Spitzer* data and Hectospec spectra, they identified 444

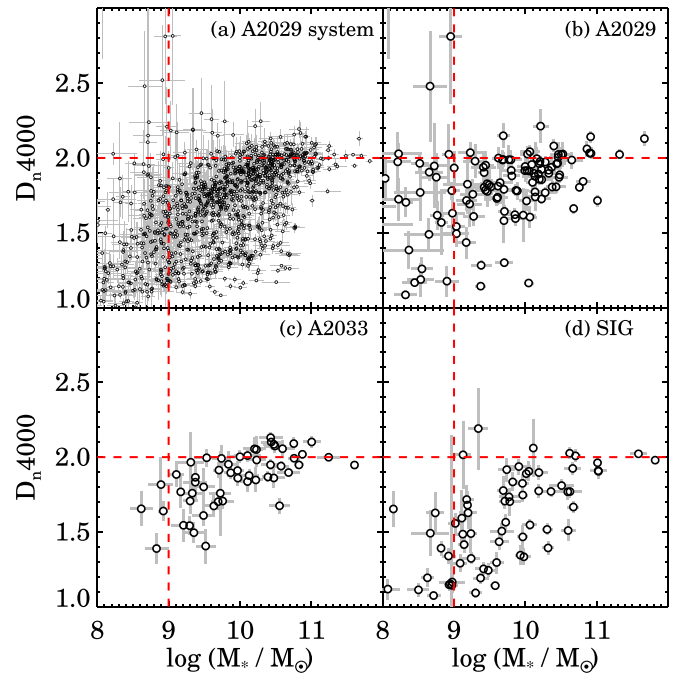


Figure 9. D_n4000 vs. stellar mass for members of (a) the A2029 system, (b) A2029 only, (c) A2033, and (d) SIG. Panels (b)–(d) show the members within $R_{\text{proj}} < 500 \text{ kpc}$ from the center of each system. The vertical dashed line shows $M = 10^9 M_\odot$. The dashed horizontal line is $D_n4000 = 2.0$.

A2029 spectroscopic members with $24 \mu\text{m}$ emission. For these spectroscopic members, they estimated star formation rates from the $24 \mu\text{m}$ and far-UV luminosities. They also derived star formation rates based on $\text{H}\alpha$ EWs from the Hectospec data. The star-forming galaxies in A2029 follow a star formation rate—stellar mass relation similar to field star-forming galaxies. The A2029 star-forming galaxies generally have higher star formation rates compared to the star-forming galaxies in Coma with similar stellar masses. Tyler et al. (2013) interpreted this difference as a marker of differing accretion histories of star-forming galaxies in A2029 and Coma.

The D_n4000 distribution of the entire A2029 system member galaxies is bimodal (Figure 6(a)). The population with $D_n4000 \gtrsim 1.5$ consists of old (mean stellar age $> 1 \text{ Gyr}$) and quiescent galaxies; the other population consists of emission-line galaxies (Woods et al. 2010). The quiescent fraction is high ($f_{D_n4000 > 1.5} = 69\%$) in A2029 as in other local clusters (Balogh et al. 1999; Deshev et al. 2017). The D_n4000 distribution of A2029 system members differs significantly from the D_n4000 distribution for field galaxies, where the $D_n4000 \leq 1.5$ population is dominant (e.g., Mignoli et al. 2005; Vergani et al. 2008; Woods et al. 2010). However, comparison between the quiescent fraction in the field and clusters is not trivial, because the D_n4000 index depends on a stellar mass (Kauffmann et al. 2003; Geller et al. 2014, 2016).

Figure 9(a) plots the D_n4000 of the members of the A2029 system as a function of stellar mass. The quiescent and star-forming populations of A2029 members are clearly distinct in this plot. A2029 members show a D_n4000 dependence on stellar mass; more massive galaxies tend to have larger D_n4000 . A similar D_n4000 dependence on stellar mass is observed in other cluster (e.g., A520; Deshev et al. 2017) and field samples (Geller et al. 2014, 2016; Haines et al. 2017). The fraction of quiescent galaxies in A2029 with $M < 10^{10} M_\odot$ is, as expected, much larger than the fraction measured in the field

at $0.1 < z < 0.2$ (Geller et al. 2016). Although the field quiescent fraction is not measured at exactly the same redshift, the higher quiescent fraction among less massive galaxies indicates that galaxies in a dense environment are generally older or more rapidly quenched compared to their counterparts in lower-density regions.

We plot the D_n4000 –stellar mass relations for A2029, A2033, and SIG members in Figures 9(b)–(d). For fair comparison, we use member galaxies within $R_{\text{proj}} < 500$ kpc from the center of each system. We estimated that there are 8 and 18 possible contaminating A2029 members at the distances of A2033 and SIG, respectively. To understand the impact of these A2029 contaminants, we randomly sample 8 and 18 A2029 members in an annulus covering the A2033 and SIG regions. We excluded A2033 and SIG members when we sample the possible A2029 contaminants. We repeat this random sampling process 10,000 times. The D_n4000 of the randomly sampled A2029 contaminants are uniformly distributed over the range of $1.0 < D_n4000 < 2.2$. In other words, the impact of contamination by A2029 members at the projected distances of A2033 and SIG has a negligible effect on the D_n4000 distribution of the subsystem members.

The D_n4000 distributions of A2029, A2033, and SIG members differ. Both the Kolmogorov–Smirnov (KS) and the Anderson–Darling (AD) k -sample tests reject the hypothesis that the D_n4000 distributions of A2029 and SIG members are derived from the same parent distribution ($p_{\text{KS,A2029-SIG}} = 3.5 \times 10^{-6}$ and $p_{\text{AD,A2029-SIG}} = 1.8 \times 10^{-7}$). In addition, the D_n4000 distributions of A2033 and SIG members are also not derived from the same parent distribution according to these tests ($p_{\text{KS,A2033-SIG}} = 1.5 \times 10^{-5}$ and $p_{\text{AD,A2033-SIG}} = 3 \times 10^{-7}$). However, both tests cannot reject the null hypothesis for the D_n4000 distributions of A2029 and A2033 members ($p_{\text{KS,A2029-A2033}} = 0.75$ and $p_{\text{AD,A2029-SIG}} = 0.5$). The median D_n4000 of A2029 members with $10^{10} M_\odot < M_* < 10^{11} M_\odot$ is $\sim 1.92 \pm 0.16$, and the less massive members have lower D_n4000 . In the same mass range, the median D_n4000 of A2033 members is slightly larger, but within the uncertainty ($\sim 1.99 \pm 0.11$). More importantly, A2033 members show a very tight D_n4000 distribution around $D_n4000 \sim 2.0$, indicating that the majority of the members were quenched at the same time. SIG members with similar mass show a much broader D_n4000 distribution. The differences in the D_n4000 distributions in the three subsystems suggest that the galaxy populations in the A2029 subsystems have very different histories even though they are part of the same larger bound system.

5. Discussion

5.1. A Picture of Galaxy Evolution in the A2029 System

The dense spectroscopic survey of A2029 offers a comprehensive view of the galaxy populations in A2029 based on a cleanly selected, large sample of members with little contamination by foreground/background galaxies. Taking advantage of the rich sample of A2029, we can study the details of the galaxy properties in a single cluster. The D_n4000 distribution of A2029 system members (Section 4.5) provides a probe of the morphology–density relation in the cluster environment, complementary to the usual considerations of star-forming galaxies. Because quiescent galaxies dominate clusters, D_n4000 provides a denser tracer than the properties of the star-forming populations. Here we discuss the implications

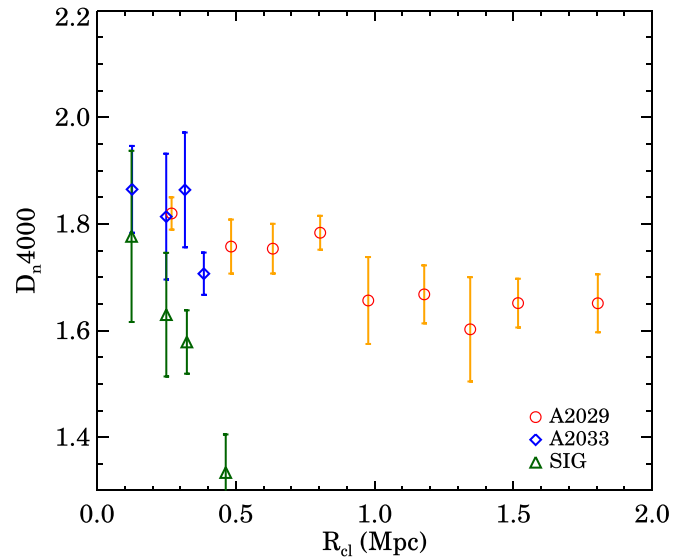


Figure 10. Median D_n4000 as a function of clustercentric distance from the center of A2029 (red circles), A2033 (blue diamonds), and SIG (green triangles).

of the D_n4000 distribution of A2029 members for the cluster evolutionary history.

We first examine the properties of the star-forming populations in A2029 and its substructures. Here the star-forming galaxies are objects with $D_n4000 < 1.5$. Within 500 kpc from the center of each substructure, there are 9, 2, and 16 star-forming galaxies with $\log(M/M_*) > 9$. The fraction of star-forming objects in the three substructures ($R_{\text{cl}} < 500$ kpc) varies significantly. In A2029, $10\% \pm 3\%$ of galaxies are star-forming. A2033 contains few star-forming galaxies ($5\% \pm 3\%$). In contrast, SIG includes a significant fraction ($29\% \pm 7\%$) of star-forming galaxies. Furthermore, the E+A galaxy abundance seems to follow the star-forming galaxy distribution; E+A galaxies are absent in A2033.

The D_n4000 index is a powerful age indicator of the stellar population. Aside from age, D_n4000 is affected by the metallicity (Kauffmann et al. 2003; Woods et al. 2010). For example, the D_n4000 of quiescent galaxies can vary up to $\sim 20\%$ for a large range of metallicity, $0.8\text{--}2.5 Z_\odot$ (Kauffmann et al. 2003). However, the metallicity of quiescent galaxies in a single cluster often has only a small variation (Rakos et al. 2007). Thus, metallicity probably has little impact on the interpretation of the D_n4000 distribution of A2029 system members.

Figure 10 displays the median D_n4000 of the members of A2029, A2033, and SIG as a function of projected distance from the cluster (group) centers. We estimate the median D_n4000 using A2029 members within R_{200} ($=1.91$ Mpc) and the A2033 and SIG members within 500 kpc, respectively. The dashed circles in Figure 1 indicate the boundaries we use for investigating the D_n4000 variation. We only use the members with $\log(M_*/M_\odot) > 9.0$ when we calculate the median D_n4000 .

The median D_n4000 of the galaxies in the primary cluster A2029 (red circles) declines as a function of projected distance. There is a slight fluctuation at larger radius perhaps resulting from the contamination by members of infalling groups. The decline of D_n4000 is consistent with the decreasing mean

D_n4000 in the outskirts of clusters derived from a stacked sample of 15 clusters at $z \sim 0.3$ (Balogh et al. 1999).

Remarkably, the median D_n4000 values of the galaxies in the two infalling groups A2033 (blue diamonds) and SIG (green triangles) also decrease as the projected distances from their respective centers increase. The decline of median D_n4000 for A2033 members follows the trend for A2029 members. SIG members show a similar decline, but the median D_n4000 values are much lower than for A2029 and A2033 members.

Figure 10 has two important implications. The D_n4000 gradients in the A2029 systems are consistent with the general picture of environmental effects (quenching) on galaxy evolution (e.g., Oemler 1974; Dressler 1980; Balogh et al. 1999; Christlein & Zabludoff 2005; Rines et al. 2005; Boselli & Gavazzi 2006; Peng et al. 2010; Rasmussen et al. 2012; Haines et al. 2015; Barsanti et al. 2018). The impact of local environment on galaxy evolution depends on galaxy mass (Peng et al. 2010). Because we limit our sample to $\log(M/M_\odot) > 9.0$, where the survey is complete, the D_n4000 gradients in the A2029 systems are robust. In addition, we derive the median D_n4000 variation among the three A2029 subsystems using the galaxies in two stellar mass bins $9.0 < \log(M_*/M_\odot) \leq 10.0$ and $10.0 < \log(M_*/M_\odot) \leq 11.0$. The D_n4000 gradients are the same but with larger uncertainties due to the smaller number of objects.

The decreasing D_n4000 in the two infalling groups as a function of projected distance suggests that galaxies are “processed” within the group environment and prior to infall into the main cluster. Previous studies investigate the fraction of star-forming galaxies or star formation activity in galaxy groups (e.g., Balogh et al. 2004; Wilman et al. 2005; Jeltema et al. 2007; McGee et al. 2011; Rasmussen et al. 2012). They show the decline of star formation activity (or the fraction of star-forming galaxies) in the group centers. D_n4000 provides a denser tracer of this galaxy processing based on the entire group population, including both star-forming and quiescent populations.

Projection effects and contamination by interlopers with high radial velocities are important in interpreting the analyses of cluster populations (Rines et al. 2005). Combining their extensive redshift surveys with a projected Navarro–Frank–White profile, Rines et al. (2005) estimate the fraction of “infall interlopers,” galaxies within $R_{\text{proj}} < R_{200}$, but $R_{3D} > R_{200}$. They suggest that at least 20% of non-emission-line galaxies and 50% of emission-line galaxies are infall interlopers. The A2029 sample includes these infall interlopers, certainly. Indeed, some emission-line galaxies with large relative radial velocities lie near the center of A2029. These galaxies most probably lie within the extended infall region because the A2029 system is so well separated from the foreground/background in redshift space.

The median D_n4000 distribution is a robust probe of the environmental effect in spite of projection effects. The Rines et al. (2005) estimate indicates that contamination by “infall interlopers” is more significant for the star-forming population (or lower- D_n4000 population). If we could remove contamination by the interlopers, a larger fraction of star-forming galaxies would be excluded from the sample than quiescent galaxies. Thus, the median D_n4000 gradient is likely to be even steeper.

Identifying the physical mechanisms for environmental effects is not straightforward. Gravitational interactions among galaxies may disturb the gas dynamics in galaxies, resulting in

either star formation or rapid consumption of gas. Hydrodynamic interaction between galaxies and baryonic matter in their environment can also be responsible for differential evolution of galaxies in dense environments (e.g., ram pressure stripping; Gunn & Gott 1972). Presumably, all of these physical processes work together and result in the differential evolution of galaxies in a cluster. Regardless of the physical mechanism, the results we derive based on complete spectroscopy suggest that these evolutionary processes are important throughout the A2029 system.

5.2. Tracing the Merger History of A2029

The obvious X-ray sloshing pattern in A2029 in the deep *Chandra* observations (Clarke et al. 2004; Paterno-Mahler et al. 2013) indicates that the dynamical history of A2029 is complex. This sloshing pattern in a galaxy cluster can form as a result of a merger with a subcluster (ZuHone et al. 2010). Comparison between the observed A2029 sloshing pattern and hydrodynamic simulations (ZuHone et al. 2010) suggests that A2029 accreted a subcluster about 2–3 Gyr ago (Paterno-Mahler et al. 2013). We compare this timescale with other indicators of the cluster history. We refer all considerations to the age of the universe at $z_{\text{A2029}} = 0.078$.

Paterno-Mahler et al. (2013) suggest that the subcluster that produced the sloshing pattern moved from the southeast to the northwest passing to the west of A2029. Intriguingly, A2033 is now located to the northwest of A2029, suggesting that A2033 may be a candidate system that produced the sloshing pattern. The offset between the X-ray emission and the BCG and the quiescent-dominated population and lack of star-forming galaxies in A2029 also may be evidence of a possible past interaction between A2029 and A2033.

We check for evidence of a feature in the D_n4000 index corresponding to the accretion time suggested by the X-ray sloshing pattern. We assume that member galaxies of the accreted subcluster became quiescent galaxies ($D_n4000 = 1.5$) when the subcluster accreted by A2029 produced the sloshing pattern. We then compute the “current” D_n4000 of these galaxies based on the assumption that the subcluster interaction occurred either 2 or 3 Gyr ago.

We simulate the time evolution of D_n4000 for a galaxy after star formation is quenched (see Zahid et al. 2015). We assume a model quiescent galaxy with solar metallicity that forms stars with a constant rate for 1 Gyr before quenching. For this model galaxy, we construct a synthetic spectrum of a quiescent galaxy using the Flexible Stellar Population Synthesis (FSPS; Conroy et al. 2009; Conroy & Gunn 2010). D_n4000 is measured from the spectrum as the model galaxy ages.

Figure 11(a) shows the time evolution of D_n4000 . Red and blue lines show the change of D_n4000 as a function of time for a galaxy that became quiescent 2 and 3 Gyr ago, respectively. For comparison, we show the epoch when a galaxy with $D_n4000 = 2.0$ became quiescent (the black line, ~ 7 Gyr ago). The galaxies that became quiescent 2 and 3 Gyr ago have $D_n4000 = 1.76$ and $D_n4000 = 1.84$, respectively. In other words, in a simple accretion picture, the galaxies that accreted onto A2029 when the interaction occurred should have D_n4000 in between 1.76 and 1.83.

Figure 11(b) displays the D_n4000 distribution of A2029 members with $\log(M/M_\odot) > 9.0$ within $R_{\text{cl}} < R_{200}$ ($=1.91$ Mpc). We limit the mass range to minimize systematic effects due to the incompleteness of the survey. We also plot the

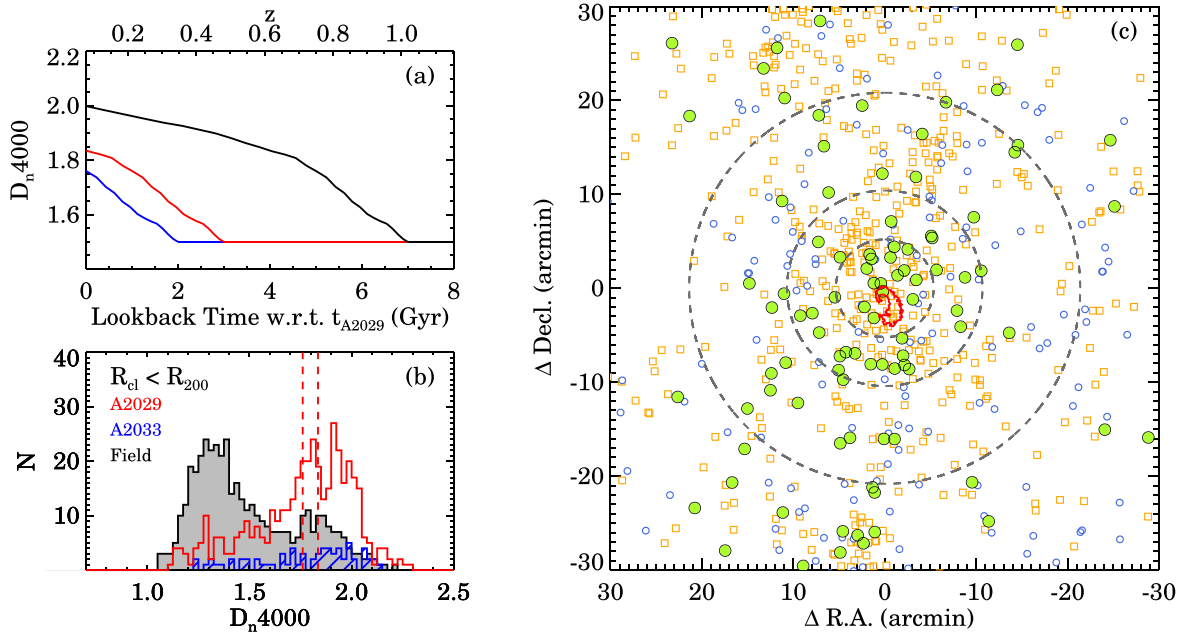


Figure 11. (a) Time evolution of D_n4000 . Blue, red, and black lines show the D_n4000 evolution of a model galaxy if it became quiescent 2, 3, and 7 Gyr ago with respect to the age of the universe at z_{A2029} , respectively. (b) D_n4000 distribution of A2029 members with $\log(M/M_\odot) > 9.0$ within $R_{cl} < 1.91$ Mpc $= R_{200}$ (open histogram). The hatched histogram is the D_n4000 distribution of A2033 members within the same mass range within $R_{cl} < 500$ kpc. The filled histogram is the field D_n4000 distribution obtained from the SHELS (Geller et al. 2014) and the hCOSMOS (Damjanov et al. 2018). Field galaxies have $D_n4000 > 1.5$, $M_* > 10^9 M_\odot$, and $0.0 < z \leq 0.2$. The vertical dashed lines mark the D_n4000 of the model galaxies that became quiescent 2 and 3 Gyr ago. The comparison suggests that the excess of A2029 members at $1.76 < D_n4000 \leq 1.84$ is significant. (c) Spatial distribution of the A2029 members with $1.76 < D_n4000 \leq 1.84$ (green star symbols). Red squares and blue circles are A2029 members with $D_n4000 > 1.5$ and $D_n4000 \leq 1.5$, respectively. The red line displays the X-ray sloshing pattern from *Chandra* observations (Paterno-Mahler et al. 2013). The dashed circles indicate $R_{cl} = 0.25R_{200}$, $0.5R_{200}$, and $1.0R_{200}$.

D_n4000 distribution of A2033 members (the hatched histogram).

For comparison, we also investigate the D_n4000 distribution of field galaxies from surveys, including the Smithsonian Hectospec Lensing Survey (SHELS) F1 and F2 survey (Geller et al. 2014). We also include the D_n4000 distribution from the similarly observed hCOSMOS survey (Damjanov et al. 2018), a dense MMT/Hectospec spectroscopic survey of $r \leq 21.3$ galaxies in the COSMOS field. We first limit the field sample to $z \leq 0.2$, where the SHELS surveys are complete to a similar mass limit ($\log(M_*/M_\odot) \gtrsim 10^9$), comparable to the A2029 survey. Within this redshift range, the D_n4000 distributions of the field population are essentially identical (see Figure 8 in Geller et al. 2014). There are 4259 field galaxies at this redshift range.

D_n4000 for quiescent objects is insensitive to the aperture size within the redshift range $z \leq 0.2$. For example, Fabricant et al. (2008) investigated the impact of the fiber size using a galaxy sample with both Hectospec and SDSS spectra. At $z = 0.1$, Hectospec and SDSS fiber covers 1.4 and 2.8 kpc, respectively. Based on the galaxy sample, Fabricant et al. (2008) showed that there is no detectable difference between D_n4000 measurements from Hectospec and SDSS. They suggested that there is little variation in the underlying stellar population over a factor of 2 radial scales. In the redshift range we use for the SHELS field sample, the Hectospec fiber covers 0.7–2.8 kpc. Therefore, we expect that there is no significant variation in D_n4000 measurement due to the different physical coverages of the fibers.

In Figure 11(b), we note that the A2029 member galaxies show an excess at $1.76 < D_n4000 < 1.84$ (indicated by the vertical lines, as well as the dotted horizontal lines in Figure 9) separated from the dominant peak at $D_n4000 \sim 2.0$. The

D_n4000 distribution of A2033 members (the hatched histogram) does not show a similar excess. The D_n4000 distribution of field galaxies also looks different: the $D_n4000 < 1.5$ population is dominant. There is a slight excess at $D_n4000 \sim 1.8$ in the field D_n4000 distribution, near the secondary peak of the A2029 D_n4000 distribution. However, this excess is much less distinctive than the A2029 secondary peak. In addition, the field D_n4000 distribution does not show a dip at $D_n4000 \sim 1.9$, underscoring the significance of the secondary peak of A2029 members. The KS and the AD k -sample tests reject the hypothesis that the D_n4000 distribution of A2029 members and the field comparison sample at $D_n4000 > 1.5$ are derived from the same parent distribution ($p_{KS} = 1.0 \times 10^{-5}$ and $p_{AD} = 2.1 \times 10^{-9}$).

Figure 11(c) plots the spatial distributions of the galaxies within the narrow D_n4000 range $1.76 < D_n4000 < 1.84$ (green filled circles). Red squares and blue circles are other members with $D_n4000 > 1.5$ and $D_n4000 \leq 1.5$. The red line shows the X-ray sloshing pattern taken from Figure 7 in Paterno-Mahler et al. (2013). The galaxies in the D_n4000 range are located outside the sloshing pattern and show a strong concentration toward the cluster center.

It is interesting that the age of the galaxies in the D_n4000 range ($1.76 < D_n4000 < 1.84$) is consistent with the estimated time to produce the X-ray sloshing pattern. We speculate that the D_n4000 excess in the central region of A2029 could resolve from the subcluster interaction that produced the sloshing pattern. This speculation could be tested with other massive clusters with the X-ray sloshing pattern. At the moment, a sizable objective sample of massive clusters observed in the same way as A2029 does not exist. We are carrying out a survey for this purpose (J. Sohn et al. 2019, in preparation).

5.3. Three Subsystems, Three Different Galaxy Populations

The most striking feature in our spectroscopic survey of the A2029 infalling groups is their very different galaxy populations (Figure 9). Quiescent galaxies dominate in A2033, and star-forming galaxies dominate in SIG. They also differ substantially from the main cluster, which contains members with a broader D_n4000 distribution than for A2033 members and larger median D_n4000 than SIG members.

The difference in the D_n4000 distributions of A2033 and SIG does not result from the different subsystem masses because the total masses of A2033 and SIG do not differ significantly. Furthermore, the stellar mass distributions of the member galaxies are similar (Figure 9). The local galaxy number densities in A2033 and SIG are also comparable; in fact, the number density of SIG is slightly higher than for A2033 in the central region. This comparison suggests that there is a large stochastic component in the evolution of members of galaxy subsystems of similar mass.

The X-ray properties of A2033 and SIG provide an additional demonstration of the marked differences between them. Although A2033 and SIG have similar masses measured from multiple probes, including velocity dispersion and weak lensing, the X-ray properties are very different. A2033 is bright in the X-ray with a high temperature of 3.7 keV; SIG is not very bright in X-ray, and its morphology is disturbed. The disturbed morphology of SIG indicates that SIG may not be dynamically relaxed, possibly explaining the dominant young population among SIG members.

Sohn et al. (2018b) examine the evolutionary history of the A2029 system using the two-body model (Beers et al. 1982) to trace the accretion history of A2033 and SIG. They show that A2033 and SIG are gravitationally bound within the A2029 system. Based on the two-body model solution, SIG will accrete onto A2029 within ~ 2.3 Gyr. A2033 seems to be moving away from the primary cluster A2029, but it may accrete within ~ 2.8 Gyr given the uncertainties in cluster mass and radial velocity.

The impact of accretion of A2033 and SIG on the galaxy population of A2029 will differ significantly because of their totally different populations. As Figures 9(b) and (c) show, galaxies in A2029 and A2033 are old and quiescent. When A2033 falls onto A2029, only quiescent galaxies will be added to the original A2029 population. Star formation activity is already suppressed. This merger would be undetectable with the argument we apply to explore the accretion event that produced the sloshing pattern. In contrast to the accretion of A2033, the accretion of SIG will supply a younger population (star-forming galaxies) to A2029. The difference between the median D_n4000 values of SIG and A2029 members within $R_{cl} < 500$ kpc is ~ 0.18 , roughly corresponding to an effective age difference of ~ 2 Gyr. This merger could be detectable with the argument we apply to the sloshing pattern origin.

Our result suggests that stochastic effects are important in the evolution of galaxy populations in massive clusters. The impact of the accretion of an infalling group on the cluster galaxy population obviously depends on the galaxy population in the infalling systems. Sometimes, galaxies in the infalling group are already processed as much as or more than the cluster galaxies. In other accreting systems, there is a younger population that may include a substantial fraction of star-forming galaxies. Combining star formation activity with the dense tracer D_n4000 enables a more nuanced understanding of

the composition of groups and clusters, including age differences among the quiescent populations.

6. Conclusion

Based on a dense and complete spectroscopic survey, we examine the physical properties of galaxies in the local massive cluster A2029. The A2029 system is unusually rich with 1215 spectroscopic members. This rich sample enables a study of the cluster population within a single cluster, thus avoiding the common stacking technique. We examine the census of A2029 system members.

The AGN fraction in A2029 is 3%, consistent with the previous studies of AGN fraction in similarly massive systems. Most A2029 AGNs are bright ($M_r \leq -20.5$), massive ($M_* > 10^{10} M_\odot$) galaxies. Three of A2029's AGNs have X-ray counterparts in the *Chandra* X-ray point-source catalog.

We derive the stellar mass–metallicity (MZ) relation of A2029 and compare it with the SDSS field MZ relations (Wu et al. 2017). For $M_* > 10^{9.5} M_\odot$, the A2029 MZ relation is essentially identical to the field MZ relations. Interestingly, A2029 star-forming galaxies tend to have higher metallicity than the field galaxies in the mass range $10^{9.0} M_\odot < M_* \leq 10^{9.5} M_\odot$. This excess metallicity is also observed in the Coma Cluster. Interaction between these lower-mass galaxies and the ICM may affect their metal content.

We identify five E+A galaxies in A2029; four of them are within ~ 400 kpc of primary cluster center; one is near the SIG. These E+A galaxies have low D_n4000 (< 1.5) and low stellar mass ($10^{8.5} M_\odot < M_* < 10^{9.5} M_\odot$). The ram pressure for these objects probably exceeds the restoring gravitational force (Gunn & Gott 1972).

Sohn et al. (2018b) investigate the structure of A2029 based on this dense spectroscopy combined with X-ray and weak-lensing data. They identify at least two subsystems, A2033 and SIG, in the infall region of A2029. These subsystems are gravitationally bound to A2029, and they will possibly accrete onto A2029 in a few gigayears.

To explore connections between the galaxy populations in the main body of A2029 and the two infalling groups, we use the D_n4000 index, an age indicator. Remarkably, the D_n4000 –stellar mass relations of A2029, A2033, and SIG differ significantly. In both A2029 and A2033, galaxies with $M_* > 10^{10} M_\odot$ have higher $D_n4000 \sim 2.0$. The D_n4000 distribution of the A2029 members is broader than for A2033 members at a given stellar mass. The tight D_n4000 –stellar mass relation of A2033 members suggests that A2033 members became quiescent galaxies at the same time. In contrast, SIG, a subsystem with a mass similar to A2033, has the broadest D_n4000 distribution and contains members with generally lower D_n4000 than either A2029 and A2033. SIG members are the youngest population in the A2029 system. Thus, the future accretion of the aged A2033 and the young SIG promise a totally different impact on the resulting population of the main cluster.

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