DISCOVERY OF NINE EXTENDED IONIZED GAS CLOUDS IN A z = 0.4 CLUSTER

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ABSTRACT

From deep Hα imaging data of Suprime-Cam/Subaru, we discovered nine extended ionized gas clouds (EIGs) around galaxies in the Abell 851 cluster (A851) at z = 0.4. We surveyed a 30 × 25 arcmin region, and the EIGs were found only near the cluster center (<2.3 arcmin ~ 750 kpc). The parent galaxies of the EIGs are star-forming or post-starburst galaxies, all of which are spectroscopically confirmed members of the cluster. Four out of the nine parent galaxies show distortion of stellar distribution in the disk, which can be a sign of recent interaction, and the interaction may have made the EIGs. On the other hand, six parent galaxies (one overlaps those exhibiting distortion) show Hα emission without stars, which implies ram pressure stripping. The spectrum of the brightest parent galaxy shows a post-starburst signature and resembles the Hα stripped galaxies found in the Coma cluster. Meanwhile, two brightest parent galaxies in A851 are more massive than the EIG parent galaxies in the Coma cluster. This is consistent with a “downsizing” of star-forming galaxies, though it is still within the statistical variance. We also analyzed Suprime-Cam data of another z = 0.39 cluster, CL0024+17, but found no EIGs. The key difference between A851 and CL0024+17 would have been the existence of a subcluster colliding with the main body of A851, in which six or seven out of the nine parent galaxies in A851 exist, and the fraction of EIGs in the subcluster is significantly higher than the main subcluster of A851 and CL0024+17.

Key words: galaxies: clusters: individual (Abell 851, CL0024+17) – galaxies: clusters: intracluster medium – galaxies: evolution – intergalactic medium

1. INTRODUCTION

Deep Hα imaging gives us a chance to detect extended ionized gas clouds (EIGs) in galaxies. EIGs were found in several nearby (z < 0.1) clusters (e.g., Gavazzi et al. 2001; Yoshida et al. 2002; Cortese et al. 2006; Sun et al. 2007, 2010; Yagi et al. 2007, 2010; Kenney et al. 2008; Arrigoni Battaia 2012; Fossati et al. 2012; Kenney et al. 2014). The gas would have been stripped from a galaxy (the parent galaxy) and observed in Hα emission. Though the mechanism of stripping and ionizing is not yet fully understood, it is thought that galaxy interaction (Toomre & Toomre 1972) and/or ram-pressure stripping (RPS; Gunn & Gott 1972) would have made EIGs in some cases.

The progenitor of EIG parents would have been gas-rich and therefore probably a star-forming galaxy before the stripping. The stripping would have weakened or ceased the star formation and the galaxy would transition into post-star formation and eventually quiescent phase. It is widely known that the fraction of blue galaxies, which are thought to be gas-rich star-forming galaxies, in a cluster increases with redshift z > 0.2 (Butcher–Oemler effect; Butcher & Oemler 1984). This implies that the major transition from a star-forming galaxy to a quiescent galaxy occurred in the cluster at z > 0.2. Moreover, many post-starburst galaxies are found in z ~ 0.4 clusters (Poggianti et al. 1999) compared with local clusters. Though gas stripping is not the only mechanism for transition, we can expect that gas-stripping events would have been more frequent in the distant clusters of galaxies. Nevertheless, no distant EIGs have been discovered so far; it is not clear whether such EIGs are quite rare at z ~ 0.4, or whether this is simply because no searches have been carried out yet.

In this paper, we report the detection of nine EIGs in Abell 851 (A851) and compare their parent galaxies with those found in the Coma cluster. We adopted WMAP nine-year cosmology (h0ΩMΩΛ = (0.697,0.282,0.718) (Hinshaw et al. 2013). The magnitudes are given in the AB system (Oke & Gunn 1983). The redshift is given in the local standard of rest frame.

2. IMAGING DATA

2.1. Target Clusters

We searched for extended Hα emitters at z ~ 0.4 in Suprime-Cam (Miyazaki et al. 2002) data in the public archive of the Subaru Telescope (SMOKA) (Baba et al. 2002). Two clusters were observed both in the broadband (W-S-Z; z-band) and in the narrowband corresponding to Hα: A851 at z = 0.405 in N-B-L921 (NB921) and CL0024+17 at z = 0.390 in N-B-L912 (NB912). The redshifts of these clusters are taken from Oemler et al. (2009) and Moran et al. (2007). The distance modulus is m-M = 41.74(A851) and m-M = 41.64(CL0024+17). Angular scales of 5.47 kpc arcsec−1(A851) and 5.33 kpc arcsec−1(CL0024+17) are adopted. The effective band transmission for z, NB912, and NB921 are (center, FWHM) = (9043 Å, 948 Å), (9137 Å, 130 Å), and (9194 Å, 130 Å), respectively. The redshift coverage for Hα emission is therefore z = 0.392 ± 0.010(NB912) and 0.401 ± 0.010(NB921), respectively.

http://smoka.nao.ac.jp/
Hayashino et al. (2003) reported the non-uniformity of NB921’s transmission function. This effect is investigated in Appendix B. Objects with a redder continuum tend to have large z-NB921 or z-NB912 color and may mimic the emission because the center wavelength of NB921 and NB912 is redder than that of the z band. We therefore used R-band (W-C-RC; center = 6500 Å, FWHM = 1170 Å) data to check the continuum color.

2.2. Reduction of Imaging Data

For the study of star-forming galaxies, the z and NB921 data of A851 were once analyzed by Koyama et al. (2011), and z and NB912 data of CL0024+17 were analyzed by Kodama et al. (2004). We re-analyzed the data with a correction of the fringe pattern that was skipped in the previous analyses. The detail of the fringe correction is given in Appendix A. The flux zero-point of the z band was calibrated using the SDSS3 DR9 catalog (Ahn et al. 2012), as in Yagi et al. (2013a). The Galactic extinction at A851 is $A_v = 0.046$ from NED, based on Schlafly & Finkbeiner (2011). We adopted $A_v = 0.020$ and used it for NB921 as well. The 1σ limiting surface brightness in a 2 arcsec aperture was 27.3 mag arcsec$^{-2}$ for both z and NB921. The flux measurement results of the z band and NB921 were consistent with Koyama et al. (2011). In the following analysis, we used the photometry of the B, R, and z bands from Koyama et al. (2011), and z-NB921 from the new analysis. For the search of EIGs in A851, we first estimated a model color of galaxies at $z = 0.405$ as $z-NB921 = 0.05$ using the theoretical spectral energy distribution (SED) of passive galaxies from Furusawa et al. (2000), which is based on the Kodama & Arimoto (1997) model. We therefore constructed a z-band subtracted NB921 image (NB-z image hereafter) so that the region with z-NB921 = 0.05 is gray. The slight difference in the point-spread function makes the center of the bright object positive. However, it does not affect the detection of EIGs.

For CL0024+17, we estimated z-NB912 $\sim$0.03 at $z = 0.390$. CL0024+17 was processed in the same way as A851 and the z-band subtracted NB912 image (we also call it the NB-z image hereafter) was constructed, so that z-NB912 = 0.03 is gray. We adopted $A_v = 0.070$ as the Galactic extinction.

A drizzled image of the A851 center taken in F814W with the Advanced Camera for Surveys of the Hubble Space Telescope (ACS/HST) was retrieved from the Mikulski Archive for Space Telescopes (MAST) archive. The F814W filter covers 7000–9500 Å, which corresponds to 5000–6800 Å in the rest frame. The data were used to see the morphology of the parent galaxies in A851.

2.3. Detection of EIG Candidates

Extended H$\alpha$ features were searched by an eye inspection in the NB-z image, and checked in a three-color composite image of R (blue), z (green), and NB921 (red). We identified nine candidates of EIGs. The list of their parent galaxies is sorted by the z-band magnitude (Table 1). It should be stressed that we surveyed a $30 \times 25$ arcmin region and the EIG candidates were found only around the cluster center ($\sim$2.3 arcmin). The cutouts from the NB-z image, the three-color composite image, and the ACS image in F814W are shown as Figure 1. In the left panels, the NB-z excess is indicated by a red contour. The surface brightness of the contour corresponds to $3\sigma$ of the NB-z image in a 2 arcsec aperture, which is NB921 26.2 mag arcsec$^{-2}$ if no continuum is contaminated. The green contour in the panels shows the isophote, which encloses 90% of the total flux in the z band. The EIG candidates from eye inspection showed an extension of the NB-z excess (red contour) over the 90% isophote. In the right panels, F814W band images are shown. Thanks to the high spatial resolution of ACS, we can see that most of the EIGs’ parent galaxies have a clumpy morphology.

As the extended NB-z excess features can be an accidental overlap of a distant object, we cannot conclude that they are EIGs at $z = 0.4$ without spectroscopic data. In the EIG study in the Coma cluster, however, all 14 candidates were found to be actual EIGs in the Coma cluster (M. Yoshida et al. 2015, in preparation). This implies that the extended narrowband excess features without continuum are highly likely to be EIGs.

In our analysis, EIG candidates were only found in A851 and no extended H$\alpha$ emission was found in CL0024+17. We therefore focus on A851 in the next section.

3. PROPERTIES OF THE EIGS AND THE PARENT GALAXIES IN A851

3.1. Follow-up Spectroscopy

Five out of the nine parent galaxies (C1–C5) are known spectroscopic members of A851, confirmed by Oemler et al. (2009) and/or F. Nakata et al. (2015, in preparation), while the others (C6–C9) did not have spectroscopic redshifts. We therefore performed a spectroscopic observation on 2013 October 31 UT with the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) at the Subaru Telescope. We used a multi-object spectroscopy mode, 300R grism, and SY47 order-cutting filter, which cover the wavelength range approximately from 4700 to 10,000 Å. The slit widths were 0.8 arcsec resulting in the spectral resolution of $\sim$10 Å. We obtained four 10 minute exposures. The wavelength was calibrated using night sky lines. In C6, C7, and C9, we identified emission lines and the redshifts were determined by them. C8 did not show emission but did show strong absorption features of H$\gamma$, H$\delta$, CaH+He, and CaK, which enabled us to determine the redshift. The measured redshifts are given in Table 1. C6–C9 had a redshift $\sim$0.395. In summary, the nine parents of the EIG candidates were confirmed to be a member of A851 clusters. We therefore assume that the nine EIG candidates are actually EIGs in A851 hereafter, though the final confirmation of the physical association between the parents and the EIGs requires further spectroscopy of EIGs, as tried for Coma cluster EIGs in Yagi et al. (2007) and Yoshida et al. (2012).

We also obtained spectra of C1 and a bright spot of C2 (in the middle panel of Figure 1, a magenta clump seen in the north–northeast of the parent galaxy). The redshift of C1 was measured from [O$\Pi$], H$\beta$, H$\alpha$, and [N$\Pi$] emissions, and H$\alpha$ absorption was found to be $z = 0.4065 \pm 0.003$. The value is comparable to those in previous studies——$z = 0.4064$ (F. Nakata et al. 2015, in preparation) and $z = 0.4060$ (Oemler et al. 2009). The redshift of the C2 bright spot showed [O$\Pi$], H$\beta$, [O$\III$], H$\alpha$, and [N$\II$]. The measured redshift of the C2 bright spot was $z = 0.4063$, which is comparable to the redshift of the parent galaxy, $z = 0.4061$ by Oemler et al. (2009).
Table 1: EIG Parents in A851

| ID | R.A. (2000) | Decl. (2000) | $m_z$ | $\log (M_{*}/M_{\odot})_z$ | EIG size (kpc) | z-source* | Distortion | $H\alpha$ w/o stars |
|----|-------------|--------------|------|-----------------|---------------|-----------|------------|-----------------|
| C1 | 09°42′35″57′ | 46°59′39″3 | 17.8 | 11.8 | 0.4064 | 86 | N-F8-22 | n | y |
| C2 | 09°43′01″59 | 47°00′31″4 | 18.9 | 11.2 | 0.4061 | 46 | ODK09-365 | y | y |
| C3 | 09°42′30″59 | 47°00′47″9 | 19.0 | 10.5 | 0.3956 | 69 | N-F8-30 | y | n |
| C4 | 09°42′59″08 | 47°01′04″3 | 19.7 | 10.5 | 0.3961 | 27 | N-F8-26 | y | n |
| C5 | 09°42′59″37 | 47°00′56″5 | 20.1 | 10.8 | 0.3937 | 20 | ODK09-367 | y | n |
| C6 | 09°43′02″46 | 46°59′28″6 | 20.2 | 10.2 | 0.3929 | 31 | this study | n | y |
| C7 | 09°43′04″63 | 47°00′45″3 | 20.9 | 10.0 | 0.3968 | 32 | this study | ? | y |
| C8 | 09°43′04″38 | 47°00′10″0 | 20.9 | 10.6 | 0.393 | 24 | this study | n | y |
| C9 | 09°42′50″05 | 47°01′01″4 | 21.9 | 9.4 | 0.3957 | 21 | this study | n | y |

* Redshift reference and ID: N. F. Nakata et al. (2015, in preparation), ODK09: Oemler et al. (2009).

3.2. Nature of EIG Parents

In Figure 2, the color–magnitude diagrams of member galaxies selected by photometric redshift (phot-z) in Koyama et al. (2013) are plotted in the $z$ versus R–z plane. The color of parent galaxies is given in Table 3. The $z$ versus R–z at $z \sim 0.4$ corresponds to R versus B–R in the rest-frame at $z \sim 0$ and is comparable to the R versus B–R plot and the R versus g–r plot of nearby clusters (e.g., Figure 6 of Yagi et al. 2010) except for the zero-point offsets.

In Figure 2, the distribution of the EIG parents shows an offset from that of the other $H\alpha$ emitters (red open squares): EIG parents tend to have bluer R–z color and/or brighter z magnitude. Apparently the colors of EIG parents do not show a correlation with the z-band magnitude, which was observed in the Coma cluster (Yagi et al. 2010). In Figure 3, narrowband color excess (z-NB) versus z-band is plotted. Some parents show strong color excess while C1 and C8 show no excess. In the FOCAS spectra, C1 and C8 show strong Balmer absorption and resemble post-starburst (so-called E+A or k+a) galaxies. The variety of the color and the narrowband excesses suggest that EIG parents in A851 are a mixture of different origins and/or different stages of stripping.

Our new spectra of C6–C9 and the bright spot of C2 showed H$\alpha$-region-like line ratios. The [N II]/H$\alpha$ versus [O III]/H$\beta$ plot is shown as Figure 4 and the data are given in Table 2. The measurement method of the line ratios is the same as in Yagi et al. (2013b). C7 shows strong Balmer absorptions of stars of the galaxy. Using the GALAXIV stellar synthesis model (Bruzual & Charlot 2003), we estimated that equivalent widths of star absorption would be no larger than 14 and 8 Å at H$\alpha$ and H$\beta$, respectively. The correction of this extreme case is shown as a vector in Figure 4. Even after the correction, C7 has H$\alpha$-region-like line ratios. Four of the NB-z excess parents (C2–C4, C7) have data in the GALEX object catalog, and the UV–optical color in the observed frame is blue (NUV-R = 0.2–1.5). This also suggests that the stellar component is young. Moreover, the bright six galaxies (C1–C6) show Spitzer 24 μm emission larger than 200 μJy in the wide-field data used in Koyama et al. (2013). For a check of a possible active galactic nucleus (AGN) contribution to the 24 μm emission, we used the Spitzer IRAC flux in the Spitzer Enhanced Imaging Products Source List. C1–C7 have flux data in four bands (Table 3), and their two-color diagram is shown in Figure 5. Their colors were out of the empirical region of AGNs (Stern et al. 2005), except for one known AGN (C2). Though C1 is near the AGN region, it is not an AGN since the FOCAS spectrum of C1 does not show signs of an AGN; it shows a very weak [O III] emission and an H$\beta$ emission in a broad H$\beta$ absorption. The 24 μm emission would therefore be yet another sign of recent star formation in C1 and C3–C6. In the ACS data, almost all the parent galaxies have disk morphologies; some of them have highly disturbed spirals and the others look less disturbed (Figure 1).

The stellar mass ($M_*$) of the parents was estimated using the recipe in Koyama et al. (2013). They verified that this method works reasonably well for star-forming galaxies (with an uncertainty of ~0.2 dex level) by comparing with the values derived from a multi-band SED fitting. We adopted the following equations for $z = 0.4$:

$$\log \left( M_*/10^{11}M_\odot \right) = -0.4(z - 20.07) + \Delta \log M,$$  \hspace{1cm} (1)

and

$$\Delta \log M = 0.054 - 3.81 \exp \left[ -1.28(B - z) \right].$$  \hspace{1cm} (2)

The estimated mass is given in Table 1. It should be noted that C2 has an AGN and the mass estimation has a larger uncertainty than others. The EIG parent galaxies in A851 are relatively more massive than those in the Coma cluster (Yagi et al. 2010). The stellar mass is $10^{9.4} - 10^{11.8} M_\odot$, and they would be giant galaxies.

In summary, most of the EIG parents in A851 are star-forming spiral galaxies and the others are post-starburst galaxies. The EIGs found in A851 are therefore expected to have been stripped or ejected gas from the parent star-forming/post-starburst galaxy.

3.3. Distribution of Parent Galaxies

The spatial distribution of the parents is shown in Figure 6. The EIGs were somehow detected only in the northern side of the cluster. The field of view of the ACS data is also shown in Figure 6. Note that the eye inspection was done in NB-z and R, z, NB images, and the ACS image that mainly covered the northern part did not affect the north–south inhomogeneity of EIGs.
Oemler et al. (2009) discussed that A851 consists of several subclusters. In Figure 7, the projected distance from the cluster center versus relative recession velocity to the cluster \((z = 0.405)\) is plotted. The different symbol represents member of each subcluster. Oemler et al. (2009) classified C1 and C2 as members of the cluster main body ("Core" subcluster), and C3 and C5 as members of northern subcluster ("North" subcluster). Figure 7 shows that most of the EIG parents except for C1 and C2 overlap the North subcluster members (open circles). C6 has a comparable redshift to the North subcluster while a Core member also exists near C6. In Figure 6, the celestial position of C6 is near the center of the cluster, while other North subcluster members exist in the northern part. We therefore assume that most of the parent galaxies not classified by Oemler et al. (2009) are members of the North subcluster, while C6 belongs to either the Core subcluster or the North subcluster.

4. Individual Parent Galaxies

In this section, we investigate each EIG parent. We checked two features that would provide some hints on the origin of each EIG by visual inspection. One of the hints is a distortion of the stellar distribution in the disk. Since RPS affects gas but not the stars, it basically does not move stars, while galaxy interaction will make apparent tidal features. However, it is not a crucial criterion, since there is a simulation that shows RPS can change the distribution of stars (Vollmer 2003; Steinhauser et al. 2012). Vollmer (2003) showed that the movement of gas changes the gravitational field and stars drift. In the simulation by Steinhauser et al. (2012), stars formed in the tail fall back to the parent galaxy, go through the disk, and change the stellar distribution. The other hint is whether Hα emission without stars exists. Since tidal force affects both stars and gas, EIG would overlap with the stripped stars. An example is Hα of
Stephan’s quintet (HCG 92). On the other hand, RPS works only on the gas in principle, and sometimes makes a long Hα tail without stars. As new stars formed in the stripped gas are sometimes found in EIGs (e.g., Yoshida et al. 2008; Yagi et al. 2013b), the overlap of stars does not always mean interaction, but Hα emission without stars, especially distant from the parent galaxy, suggests RPS. More detailed observational data are required to investigate further. Diagnostic line ratios and a kinematic structure of EIGs are useful parameters to reveal the nature of EIGs (e.g., Yoshida et al. 2008), which will be obtained by future spectroscopic observation of EIGs. In this work, we just showed the two features.

3.4.1. C1

The EIG from C1 was a long (>80 kpc) tail without a stellar counterpart. Moreover no obvious distortion of the disk can be seen. The tail would have been made by RPS.

As mentioned in Section 3.2, C1 was classified as a post-starburst (k+a) galaxy (Oemler et al. 2009). F. Nakata et al. (2015, in preparation) measured the equivalent width of [O iii] of C1 as EW([O iii]) = 11.3 Å; they classified it as e(a), emission with strong Balmer absorption. Our follow-up spectroscopy revealed that the core of C1 (a central 1 arcsec aperture) has strong (equivalent width ~100 Å) Hα + [N ii] emission, Hβ emission in a broad absorption, and no detectable [O iii] emission. The difference implies that star formation in C1 is compact and the slit spectrum is largely affected by slit position and aperture. C1 would be a galaxy with a central star-forming region in a post-starburst disk. Such coexistence was reported in some post-starburst galaxies (e.g., Matsubayashi et al. 2011; Swinbank et al. 2012). C1 shows an emission in Spitzer 24 μm data. Dressler et al. (2009) argued that such an IR detected k+a had a strong burst 2–5 × 10⁸ years before the observation epoch and has ongoing star formation. The galaxy would be in the final phase of a starburst about to change into a post-starburst phase.
In the ACS image in F814W, there was a sign of narrow streams toward the same direction as the Hα tail (Figure 8), but their positions do not always overlap the Hα emission. The streams may be a stellar component that was made in situ like the “fireball” features found in the Coma cluster (Yoshida et al. 2008, 2012). However, no compact Hα emission was recognized in the tail. The difference can be partly explained by the low signal-to-noise ratio (S/N) and low resolution of A851 data as discussed in Section 4.1.

Our NB-z image shows elongated Hα from the center and possible Hα absorption in the disk, which is consistent with the spectroscopic classification. Such post-starburst galaxies with elongated Hα tails were also found in the Coma cluster, such as GMP 2910, GMP 3071, and GMP 3779 (Yagi et al. 2007, 2010). The stellar mass of C1 ($6 \times 10^{11} M_\odot$) is, however, much larger than those of galaxies in the Coma cluster ($10^9 - 10^{10} M_\odot$).

3.4.2. C2

The EIG from C2 includes a bright spot near the galaxy and extended and clumpy Hα emission to the northeast. The line ratios from our FOCAS spectrum show that the bright spot would be an HII region (Figure 4).

The ACS image in F814W shows a sign of stars along the Hα extension. This resembles the fireball features found in the Coma cluster (Yoshida et al. 2008, 2012). The spectra of C2 is classified as e(n) by Oemler et al. (2009), following the classification by Dressler et al. (1999) which is consistent with the result from IRAC/Spitzer color discussed in the previous section. Strong 24 μm emission of C2 (3.5 mJy) would be because of the AGN. Since the EIG has a spatial offset from the core and the spectrum of the spot in the EIG shows signs of a HII region, this EIG is unlikely to be of AGN origin. C2 shows an asymmetry of stellar distribution. On the other hand, it has
extended H\(\alpha\) emission that seems to have no association with stellar emission.

### 3.4.3. C3

C3 shows loose and disturbed spiral arms and H\(\alpha\) emitting regions along the arms. Its appearance implies that it is interacting with a neighbor spiral to the northeast. The projected distance between them is 50 kpc. An EIG may have been created by the interaction, though the redshift of the neighbor is currently not available. C3 has a redshift of \(z = 0.3956\) and is classified as a member of the North subcluster by Oemler et al. (2009).

### 3.4.4. C4

C4 shows a flocculent disk and smooth extension of H\(\alpha\) toward the southeast. EIG may be a result of interaction with C5. The difference of the recession velocity of C4 and C5 is somehow as large as 720 km s\(^{-1}\). Though C4 is not cataloged in Oemler et al. (2009), its position and redshift suggest that it is a member of the North subcluster.

### 3.4.5. C5

In the ACS image, C5 shows several remote and compact objects in the south–southwest, which are thought to be star clusters. The direction is the same as the H\(\alpha\) extension. The distortion of the disk, the remote star clusters, and the H\(\alpha\) emission may be a result of the interaction with C4.
However, it shows a slight sign of Hα emission without stars in the southeast direction. C5 is cataloged as a member of the North subcluster. The spectrum of C5 is classified as e(a) by Oemler et al. (2009). The spectral class is thought to be a dust-obscured starburst (Poggianti et al. 1999; Dressler et al. 1999, 2009; Oemler et al. 2009).

3.4.6. C6

An EIG is barely recognized toward the west. There is no counterpart in the F814W image and therefore it could be a pure gas-stripping event by RPS. The FOCAS spectrum showed strong Balmer emissions (Hα, Hβ, Hγ, and Hδ emissions), and [O ii], [S ii], and a sign of [He i] 5876 emissions. As shown in Figure 7, C6 could be a member of either the North subcluster or the Core subcluster.

3.4.7. C7

Three remote Hα regions are recognized to the southeast. Its appearance resembles that of some dwarf galaxies in the Coma cluster (e.g., GMP 4232) and those found in z = 0.2 clusters (Cortese et al. 2007). The FOCAS spectrum of the parent galaxy showed Hδ and Hγ emissions in absorption, indicating that it is in a transition from a star-forming phase to a quiescent phase. As discussed in Section 3.2, the strong Balmer absorption would also affect [O iii]/Hβ and [N ii]/Hα, but the diagnostic line ratios after maximum correction are still
comparable to those of H II regions. Since the ACS/HST image did not cover C7, it is unclear whether the stellar distribution in the disk shows a distortion or not.

3.4.8. C8

In the ACS image, a chain of two galaxies is recognized to the south of C8. Hα emission follows the chain and then turns to the west, where no stellar counterpart is seen. In the FOCAS spectrum of C8, the northern galaxy shows the typical signatures of a post-starburst galaxy, with a blue continuum, strong Hδ absorption, and no emissions.

3.4.9. C9

C9 is a compact spiral with a warped disk in the ACS image. The Hα extension is toward the northeast without a stellar counterpart, and resembles a ram pressure stripped object. The parent galaxy showed Hα, Hβ, and Hγ emissions. In the FOCAS spectrum, this spatial extension was also recognized in Hα and Hβ.

4. DISCUSSION

4.1. Properties of Parent Galaxies: Comparison with the Coma Cluster

In A851, massive (>10^11 M☉) EIG parents are found (C1 and C2) that were not found in the Coma cluster (Yagi et al. 2010). Meanwhile, less massive and faint parents (<10^9 M☉) are not found.

The lack of faint parents in A851 is explained by the detection limit. The 3σ limiting surface brightness in the 2 arcsec aperture of the Coma cluster data was 27.5 mag arcsec^-2 in N-A-L671(NA671) (Yagi et al. 2010), and (center, FWHM) of NA671 are (6712 A,120 A) (Yagi et al. 2007). If we consider the cosmological dimming and the difference of the filter widths, it corresponds to 28.4 mag arcsec^-2 for Hα emission in NB921. Therefore, A851 data, whose limiting surface brightness is 27.3 mag arcsec^-2 in NB921, is 1.1 mag shallower for the same Hα emitting object in the Coma cluster. We binned and blurred the Coma cluster data of Yagi et al. (2010) so that the limiting surface brightness and resolution are comparable to the A851 data quality and checked the detectability. Only three or four (GMP2559, GMP3816, GMP3896, and, marginally, GMP2910) out of 14 will be recognized as extended Hα objects. The estimated mass of the four Coma cluster EIG parents are ~10^10 M☉, and three show star formation in the disk. These features resemble the EIG parents found in A851. The absence of detection of <10^9 M☉ EIG parents is therefore explained by the shallower limiting magnitude of the A851 data.

Meanwhile, the lack of bright EIG parents in the Coma cluster is not explained by the difference of the data quality. One possibility is that the typical EIG parents have changed since z = 0.4. The progenitor of an EIG parent would be an infalling galaxy from the surrounding field. At z = 0.4, a larger number of massive star-forming galaxies existed around clusters (e.g., Kodama et al. 2001). At z ~ 0, many of such massive star-forming galaxies around clusters have already fallen into the cluster, and probably have lost their gas. Moreover, the number of massive star-forming galaxies has decreased even in low-density fields because of the cosmic evolution. Thus massive EIG parent would be rare at z ~ 0.

Poggianti et al. (2004) argued that the post-starburst galaxies in the Coma cluster are less massive than those in z = 0.4 clusters. This “downsizing effect” is consistent with the result that a massive and post-starburst EIG parent exists in A851. Another possible answer is that it is simply a statistical fluctuation. If the expected number of bright EIG parents in a cluster is two, for example, the probability of no detection is 14%. EIG searches in more clusters will enable us to test the two possible hypotheses.

Regarding the spatial distribution, the detected EIGs are located at a projected distance of 0.2−0.8 Mpc from the center of the cluster (Figure 7). The range is comparable to those of Coma cluster EIGs (Yagi et al. 2010). Smith et al. (2010) surveyed gaseous stripping events in the Coma cluster using UV images and found that all but the least certain case (GMP5422) exist within 0.2−0.9 Mpc from the center. This suggests that the gaseous stripping also occurs in comparable environments. The results imply that EIGs would have a strong correlation with a cluster environment even though an interaction seems to be the origin of the stripping. Galaxy interaction may assist an effective gas stripping in infalling galaxies, as it would destabilize the gas in the galaxy.

4.2. Lack of EIGs in CL0024+17

In previous sections, we investigated EIGs in A851. In CL0024+17, we found no EIGs. There were several extended features in the NB912-z image, but they were all in the disk of galaxies. CL0024+17 is said to consist of several subclusters (Czoske et al. 2002). Two subclusters (A and B) are colliding head-on along the line of sight. The subclusters have redshifts of 0.395 (A) and 0.381 (B), and our narrowband NB912 covered the Hα at the redshift of both subclusters. The non-detection is therefore not because of the wider redshift distribution.

We check the image qualities of CL0024+17 and A851. The 3σ detection in NB912-z for CL0024+17 corresponds to 26.2 mag arcsec^-2 in NB912, which is comparable to the detection in A851; 26.2 mag arcsec^-2 in NB921. The seeing size of the CL0024+17 data (~1.2 arcsec) is better than that of A851 data (~1.5 arcsec). Therefore, the lack of detections of EIGs in CL0024+17 is not false, and it really lacks EIGs.

We then examine whether the difference between A851 and CL0024+17 could be explained by a statistical variance. It is natural to assume that the number of EIG parents follows Poisson statistics, and the expected number λ would be proportional to the number of the member galaxies in the cluster.

From statistics, N = 0 can be reproduced with a p value > 0.05 if 0 < λ < 3.0, where λ is the expected value of the Poisson distribution. Meanwhile, N = 9 sets 5.5 < λ < 13.8. Therefore, λ, the expected number of EIG parents, of A851 must be larger than that of CL0024+17 by at least a factor of 1.8.

The ratio of the member galaxies in the two clusters is calculated by statistical background subtraction (e.g., Binggeli et al. 1988). The projected number density of ~24<M*/<−19 objects at a projected distance of >1.5 Mpc from the center of the cluster is used as the background distribution. The density is subtracted from the projected number density of ≤1.5 Mpc. As CL0024+17 is thought to be a cluster merger along the line of sight (Czoske et al. 2002), the mass estimation from X-ray properties or velocity dispersion may be affected by the...
configuration (e.g., Umetu et al. 2010) and not suitable for comparison with A851. Our simple number count would therefore be a good method to estimate the cluster richness because it is even robust against the complicated geometry and because the Poisson statistics are additive.

The background corrected projected number densities are $57 \pm 5 \text{ Mpc}^{-2}$ and $46 \pm 5 \text{ Mpc}^{-2}$ for A851 and CL0024+17, respectively. The number ratio of the cluster N(A851)/N (CL0024+14) is estimated as $1.2 \pm 0.2$. In the analysis, we adopted the center coordinate as $09^h 42^m 57^s.46, +46^\circ 58' 49'' 8$ for A851 and $00^h 26^m 35^s.67, +17^\circ 09' 43'' 1$ for CL0024+17 (Wen & Han 2013). We also tried different coordinates given in NED, but the result was not affected.

It should also be noted that there are still many H$\alpha$-emitting galaxies in the two clusters (Kodama et al. 2004; Koyama et al. 2011). Koyama et al. (2011) argued that the total star formation rate within $0.5 \times R_{200}$ is comparable in the two clusters. As $R_{200}$ of CL0024+17 (1.7 Mpc; Kodama et al. 2004) is smaller than that of A851 (2.13 Mpc; Koyama et al. 2011), more star-forming galaxies should exist in CL0024+17 within a fixed radius. The lack of EIGs in CL0024+17 is therefore not due to the lack of gas-rich parent galaxies.

We can therefore conclude that the difference of the EIG fraction of A851 and CL0024+17 is significant. It cannot be explained by the statistical fluctuation.

4.3. EIG Enhancement in Infalling Subcluster

In A851, two (or three, depending on the membership of C6) of the parents would be a member of the Core subcluster, and the other seven (or six) would be that of the North subcluster. Meanwhile, the richness of the North subcluster is supposed to be $1/8$ of the Core subcluster as the number ratio of confirmed members in Oemler et al. (2009) is 11/80. The recession velocity dispersions of the subclusters are $1079 \text{ km s}^{-1}$ (Core) and $295 \text{ km s}^{-1}$ (North), respectively (Oemler et al. 2009). These results suggest that the North subcluster would be smaller than the Core subcluster by an order of magnitude.

We examine the significance of the difference of $N = 3$ (Core) and $N = 6$ (North) in the ratio of 1/8. In this test, we assume that C6 is a member of the Core subcluster since the null hypothesis of the test is that the difference is not significant. $N = 3$ can be reproduced with a p value $>0.05$ if $1.0 < \lambda < 7.0$, and $N = 6$ can be reproduced with a p value $>0.05$ if $3.0 < \lambda < 10.5$. If $\lambda$ is proportional to the number of members of each subcluster, the difference is significant. The EIG fraction is therefore quite high in the North subcluster. The difference of the A851 Core subcluster and CL0024+17, meanwhile, is within the statistical variance, with $1 < \lambda < 3$.

The high EIG fraction rate in an infalling group resembles the case in Abell 1367 at $z = 0.02$, where many EIGs were detected around the Blue Infalling Group (Cortese et al. 2006). In the Coma cluster, the correlation between EIG parents and the infalling group was not recognized, but EIG parents tend to have a larger deviation in recession velocity (Yagi et al. 2010). The relative line-of-sight velocity of the group with respect to the cluster core is as large as $\sim 3000 \text{ km s}^{-1}$. During the course of its violent infall/merger onto the Core subcluster, some star-forming galaxies in the North subcluster may have been or are experiencing some environmental effects such as RPS and/or tidal interactions with neighbors, which then produced the signatures of EIGs.

4.4. Age of C1 Tail

The spectrum of C1 shows a post-starburst signature. If the termination of the starburst was caused by the stripping, it occurred within $\sim 10^7$ years.

If we assume that the beginning of the stripping is seen as the tip of the H$\alpha$ tail, we can date the age. Since the peak-to-peak recession velocity is $\sim 2 \times 2000 \text{ km s}^{-1}$ (Figure 7) and the relative recession velocity of C1 to the Core subcluster is $\sim 100 \text{ km s}^{-1}$, the tangential velocity of C1 is assumed to be $\sqrt{2000^2 - 100^2} \sim 2000 \text{ km s}^{-1}$. The projected length of the EIG, 86 kpc corresponds to movement for $4 \times 10^7$ years with the speed, and the far tip of the tail would be stripped from the parent $4 \times 10^7$ years ago in that case. Though the age is barely enough to cease the H$\alpha$ emission (e.g., Yagi et al. 2013b), the H$\alpha$ tail near the parent should have been stripped more recently and it would be difficult to stop H$\alpha$ emission widely in the disk. The spatially extended Balmer absorption requires a much longer time, e.g., $\sim 2 \times 10^8$ years.

One possible solution is that the tangential velocity is much smaller than $2000 \text{ km s}^{-1}$. If the tangential velocity is $\sim 400 \text{ km s}^{-1}$, for example, the tail length corresponds to $\sim 2 \times 10^8$ years. Another possibility is that the stripped gas is more extended than the apparent H$\alpha$ tail. Such extended gas clouds were found in H$\alpha$ or in X-ray (e.g., Oosterloo & van Gorkom 2005; Sun et al. 2007; Gu et al. 2013). The comparison of the length of H$\alpha$ tail and in other wavelengths is important for understanding the ionizing source of the H$\alpha$ emission and the fate of the stripped gas.

5. SUMMARY

We have discovered nine EIGs in a $z = 0.4$ cluster (A851). All their parents are spectroscopically confirmed members of the cluster and they all lie near the cluster center ($< 2.3 \text{ arcmin} \sim 750 \text{ kpc}$).

Six or seven of the parent galaxies would be members of the northern group of galaxies, the North subcluster (Oemler et al. 2009), which is probably just merging onto the core of the cluster main body (Core subcluster). In another $z = 0.4$ cluster, CL0024+17, we found no EIG candidates. The relative EIG fraction is significantly high in the North subcluster, while that of the A851 Core subcluster and CL0024+17 are comparable within a statistical fluctuation. The emergence of EIGs in the North subcluster of A851 may thus be related to the infall of the subcluster and the gas stripping therein due to some environmental effects.

Two massive (>10$^{11} M_\odot$) parent galaxies of EIGs are found in A851. The fact that no such massive parent galaxies are found in the Coma cluster at $z = 0.02$ is consistent with the downsizing effect, where the quenching process of galaxies is shifted to lower-mass systems as time goes on, though still this small sample size cannot reject the possibility that the difference of the massive parent galaxies in A851 and Coma may be a simple statistical fluctuation. More samples are required to draw a definitive conclusion about EIGs—the evolution, the environmental effect, the variance among clusters, and the effect of infalling groups.

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APPENDIX A
FRINGE CORRECTION OF SUPRIME-CAM DATA

The $z$, NB921, and NB912 data of Suprime-Cam suffer from a fringe pattern of atmospheric emissions. We perform a correction for this as follows.

First, the night sky images are flat fielded using dome flats. As the fringe pattern is approximately proportional to the sky brightness, we normalize the flat-fielded skys by the sky count. Then, a “median normalized fringe” is constructed in a two-pass procedure. In the first pass, a median image of the normalized flat-fielded sky is constructed. It is affected by objects in the night sky images. Such objects are detected by comparing each normalized image with the median image. In the second pass, the detected objects are masked in normalized sky images and their median is constructed. We use the output as the “median normalized fringe.”

In the real data, the fringe pattern is not always proportional to the background sky brightness. The scaling of the median normalized fringe is therefore calculated for each sky image of the target. We used two robustization techniques for the fitting

\[ s(x, y) = af(x, y) + b, \]

where $s(x, y)$ is the target sky image, $f(x, y)$ is the median normalized fringe, and the coefficients $a$ and $b$ are to be solved. First, $f(x, y)$ is sorted and binned into $N$ (we adopted $10^4$) data points and the median is taken $f'(n)$. The median of the corresponding $s(x, y)$ is assigned as $s'(n)$. Note that the data points are $\sim 8 \times 10^6$ in an image and $\sim 800$ points are obtained. Then,

\[ s'(n) = af'(n) + b \]

is fitted by the least median of squares method (Rousseeuw 1984). The example of the automatic fringe subtraction is shown as Figures A1 and A2. The higher-order residual remains, but is negligible in this study.

APPENDIX B
THE EFFECT OF NON-UNIFORMITY OF NARROWBAND FILTERS

As the prime focus of the Subaru telescope has a small F-ratio (F/2), the response function of narrowband filters is bell-shaped in general. The detectability of H$\alpha$ excess from narrowband imaging is therefore highly dependent on the redshift of the H$\alpha$ emission.

Meanwhile, a spatial non-uniformity of the transmission of the NB921 filter was reported by Hayashino et al. (2003). Hayashino et al. (2003) also measured the transmission of NB912 filter and presented this on their web page (not published). We examined the possibility that the non-detection of EIGs in CL0024+17 and outer part of A851 may be affected by this non-uniformity.

In Figure B1, the total throughput at three different positions and the H$\alpha$ wavelength at A851 subclusters are shown. The total throughput was calculated by multiplying the filter transmission by the quantum efficiency of CCDs, the transmittance of the primary mirror, and the extinction of a model atmosphere at airmass = 1 (Yagi et al. 2013a). The total throughput of NB921 at the center of the filter is offset by about 15 Å bluer than that at 11.5 arcmin from the center. The difference of the transmission may cause $\lesssim 40\%$ variation of H$\alpha$ throughput at different position in the field, depending on the redshift.
In the figure, the Hα wavelength of EIG parents of A851 are shown as open circles. Since the EIG parents were found within 3.3 arcmin from the filter center, the total throughput at the filter center (blue in Figure B1) would be affected. The redshift variation of the EIG parents would therefore make the variation of the total throughput by 35% p-p; EIGs in the North subcluster have better Hα throughput than those in the Core subcluster around the filter center.

In the outer part of A851, we can expect that the possible undetected EIG parents would have redshifts comparable to that of the Core subcluster since the mass of the subcluster and the number of members are larger than those of the North subcluster. Then, the throughput of Hα should be higher at the outer part of the filter, as shown in Figure B1. Moreover, the throughput of Hα at the redshift of the Core subcluster at the outer part is comparable to that at the redshift of the North subcluster around the center. We can therefore conclude that it was not due to the non-uniformity of NB921 that the detection of EIG parents was only around the center.

NB912 also shows such an offset by ∼10 Å at 11.5 arcmin as shown in Figure B2. However, as the wavelength of Hα at the redshift of CL0024+17 is near the peak of the transmission, the offset does not cause a large difference of the throughput of Hα between at the center and at 11.5 arcmin from the center compared with the effect of the variation of the redshift.

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