RED STAR-FORMING GALAXIES AND THEIR ENVIRONMENT AT $z = 0.4$ REVEALED BY PANORAMIC H$\alpha$ IMAGING

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ABSTRACT

We present a wide-field H$\alpha$ imaging survey of the rich cluster CL0939+4713 (A851) at $z = 0.41$ with Suprime-Cam on the Subaru Telescope, using the narrow-band filter NB921. The survey is sensitive to active galaxies with star formation rates (SFRs) down to $\sim 0.3 M_\odot$ yr$^{-1}$ throughout the 27$''$ × 27$''$ field. We identified 445 H$\alpha$ emitters along the large-scale structures around the cluster. Using this sample, we find that (1) the fraction of H$\alpha$ emitters is a strong function of environment and shows a clear decline toward the cluster central region, and (2) the color of H$\alpha$ emitters is clearly dependent on environment. The majority of the H$\alpha$ emitters have blue colors with $B - I < 2$, but we find H$\alpha$ emitters with red colors as well. Such red emitters are very rare in the cluster center or its immediate surrounding regions, while they are most frequently found in groups located far away from the cluster center. These groups coincide with the environment where a sharp transition in galaxy color distribution is seen. This may suggest that dusty star formation activity tends to be involved in galaxy truncation processes that are effective in groups, and that it is probably related to the “pre-processing” that generates present-day cluster S0 galaxies. Finally, we confirm that (3) the mass-normalized integrated SFR in clusters (i.e., the total SFR within 0.5 × $R_{200}$ from the cluster center divided by the cluster dynamical mass) rapidly increases with look-back time following approximately $\propto (1 + z)^6$ and is also correlated with the cluster mass.

Key words: galaxies: active – galaxies: clusters: individual (A851) – galaxies: evolution

Online-only material: color figures

1. INTRODUCTION

It has long been known that properties of galaxies are strongly correlated with the environments in which those galaxies reside. Clusters of galaxies are dominated by red early-type galaxies with little star-forming activity, while the dominant population in low-density field are blue late-type galaxies with significant star formation (e.g., Dressler 1980; Lewis et al. 2002; Gómez et al. 2003). It is suspected that the growth of large-scale structures comes into play and alters galaxy properties during the course of hierarchical assembly. However, it is not yet clear what physical processes are actually responsible for shaping galaxy properties, depending on the environment. Distant clusters of galaxies, which tend to be in an active phase of mass assembly, are ideal sites for “directly” studying what is actually happening along with the cluster growth.

Cosmological simulations predict that galaxies and groups are assembled into massive clusters moving along filamentary structures (e.g., Millennium Simulation; Springel et al. 2005); in fact, wide-field observations of distant clusters of galaxies have revealed such filamentary large-scale structures around rich clusters up to $z \sim 1.3$ (e.g., Kodama et al. 2005; Tanaka et al. 2007a). These cluster-surrounding regions including infalling groups and/or filamentary structures are likely to play critical roles in the evolution of cluster galaxies. It is reported that the rest-frame ultraviolet (UV)–optical colors change sharply from blue to red in such medium-density environments (e.g., Kodama et al. 2001; Tanaka et al. 2005; Koyama et al. 2008), suggesting that at least some of the star-forming activities of cluster red galaxies are quenched through some environmental effects before entering the cluster core region. However, optical colors do not necessarily provide us with the full picture of star-forming activities of galaxies. In fact, some “red” galaxies involve, despite their red colors, a significant amount of dust-obsured star formation activity (e.g., Wolf et al. 2005, 2009; Davoodi et al. 2006; Koyama et al. 2008, 2010; Haines et al. 2008; Verdugo et al. 2008; Gallazzi et al. 2009; Mahajan & Raychaudhury 2009; Brand et al. 2009). Such galaxies might be the key population in the “transition phase” from blue active galaxies to red quiescent ones. Therefore, it is crucial to quantify star formation activity more robustly using not only colors but also other independent indicators of star formation.

For this purpose, the H$\alpha$ emission line ($\lambda_{\text{rest}} = 6563$ Å) is of great use as it is one of the best indicators of star formation. It directly reflects the UV radiation from O- and B-type stars in the H$\text{II}$ regions and is very well calibrated with local galaxies (Kennicutt 1998). The H$\alpha$ line is also much less affected by dust extinction or the metallicity effect compared to [O$\text{II}$] lines at a shorter wavelength ($\lambda_{\text{rest}} = 3727$ Å) or UV–optical colors, which are more commonly used in the studies of galaxies in the distant universe.

Taking advantage of the wide field of view of Suprime-Cam (Miyazaki et al. 2002) on the Subaru Telescope (Iye et al. 2004), panoramic narrow-band imaging of H$\alpha$ emitters in the distant cluster environment was first conducted by Kodama et al. (2004), who targeted the CL0024+16 cluster at $z = 0.39$ over a $\sim 27'' \times 27''$ area centered on the cluster. Following this study, Koyama et al. (2010) conducted wide-field narrow-band imaging of H$\alpha$ emitters in and around the RXJ1716+6708 cluster at $z = 0.81$. They used the wide-field near-infrared camera, MOIRCS (Ichikawa et al. 2006; Suzuki et al. 2008), on the Subaru Telescope, and spent eight pointings to neatly
cover the known filamentary structures found by Koyama et al. (2007). Finn et al. (2004, 2005) also performed Hα emitter surveys in the central regions of several EDisCS clusters at \(z \sim 0.6–0.8\) (EDisCS; White et al. 2005). More recently, Sobral et al. (2011) studied environmental dependence of star-forming activity at \(z \sim 0.8\) based on their Hα emitters sample from HiZELS (which includes several clusters in the COSMOS and the UKIDSS UDS fields). In spite of the great importance of Hα surveys of clusters and their surrounding regions to investigating environmental effects, the number of Hα surveys of clusters has still been very limited. Since clusters of galaxies are statistical objects by nature, we desperately need more Hα-based studies of distant clusters that cover a wide area and a long time baseline in order to discuss the environmental variation of star-forming galaxies and its evolution.

In this paper, we present an Hα emitter survey for another cluster at \(z \sim 0.4\), CL0939+4713 (A851). This is a very rich cluster and is one of the most famous intermediate redshift clusters. Intensive imaging/spectroscopic surveys of this cluster, including the \textit{MORPHS} survey (Smail et al. 1997), have been made by many authors using ground-based broad-band imaging (e.g., Dressler & Gunn 1992; Stanford et al. 1995; Iye et al. 2000; Kodama et al. 2001), narrow-band imaging (Belloni et al. 1995; Martin et al. 2000), optical spectroscopy (e.g., Dressler et al. 1999; Sato & Martin 2006a, 2006b; Oemler et al. 2009; F. Nakata et al. 2011, in preparation), \textit{Hubble Space Telescope} (HST) imaging including UV observation (e.g., Dressler et al. 1994a, 1994b; Smail et al. 1999; Buson et al. 2000), \textit{Spitzer} mid-infrared (MIR) imaging (Dressler et al. 2009), submillimeter 850 \(\mu\)m observation (Cowie et al. 2002), and Very Large Array (VLA) radio observation (Smail et al. 1999). This cluster has also been targeted by X-ray observations several times (Schindler & Wambsganss 1996; Schindler et al. 1998; De Filippis et al. 2003). The X-ray image of this cluster shows two prominent peaks in X-ray emission, suggesting that the A851 cluster is a dynamically young system.

The structure of this paper is as follows: In Section 2, we summarize our project and the concept of this paper. In Section 3, we show the selection technique of Hα emitters at \(z = 0.4\) and the derivation of Hα-derived star formation rates (SFRs) for the selected Hα emitters. Our main results and discussions are described in Sections 4–6, and we summarize our results in Section 7. Throughout this paper, we assume \(\Omega_M = 0.3, \quad \Omega_\Lambda = 0.7, \quad H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), which gives a 1′′ scale of 5.41 kpc at the most up-to-date redshift of the A851 cluster (\(z = 0.405; \quad \text{Oemler et al. 2009})\). Magnitudes are all given in the AB system.

2. DATA

2.1. PISCES Project

We have been conducting the Panoramic Imaging and Spectroscopy of Cluster Evolution with Subaru project (PISCES; Kodama et al. 2005). We widely observed X-ray-detected rich clusters at \(0.4 \lesssim z \lesssim 1.4\), primarily using Suprime-Cam on the Subaru Telescope, and discovered prominent large-scale structures around each cluster (Kodama et al. 2001; Tanaka et al. 2005, 2006, 2007a, 2007b, 2008, 2009a, 2009b; Nakata et al. 2005; Koyama et al. 2007, 2008). We also conducted wide-field mapping of star formation around several clusters by Hα or [O II] line using available narrow-band filters installed on Suprime-Cam or MOIRCS (Kodama et al. 2004; Koyama et al. 2010; Hayashi et al. 2010, 2011). The narrow-band imaging survey is powerful in the sense that it enables us to conduct a complete survey of star-forming activity in and around clusters. We can detect emission lines by imaging observations and can measure the line flux throughout the field at the same time (see also Section 3.1).

2.2. This Study

As a pioneering survey of our PISCES project, the A851 cluster was studied by Kodama et al. (2001). They performed \(BVR\) imaging of this cluster with Suprime-Cam covering a \(27' \times 27'\) field and found prominent large-scale structures using the photometric redshift technique. F. Nakata et al. (2011, in preparation) performed a wide-field spectroscopic follow-up observation and confirmed that these huge structures are really at the same redshift as the main cluster. Fortunately, the Hα line from A851 shifts to \(\approx 9220 \\AA\), which is between the night sky emission lines. We utilize a narrow-band filter NB921 (\(\lambda_c = 9180 \\AA, \Delta \lambda = 133 \\AA\)) installed on the Suprime-Cam and using this filter we conduct a wide-field Hα emitter survey for this cluster. The transmission curve of the NB921 filter is shown in Figure 1 with the velocity distribution of spectroscopically confirmed cluster member galaxies taken from Oemler et al. (2009; solid-line histogram). We also show the velocity distribution of member galaxies in the filamentary structures located far from the cluster center, taken from F. Nakata et al. (2011, in preparation, dashed-line histogram). No significant difference can be seen between the two distributions, supporting that our narrow-band survey is uniformly sensitive throughout the field. We also note that the peak of the velocity distribution and that of the filter transmission are slightly different. We can still detect Hα emission from cluster member galaxies with the line-of-sight velocities of \(-3500 \text{ km s}^{-1} \lesssim \Delta v \lesssim +1000 \text{ km s}^{-1}\), although we need to be careful when deriving physical quantities such as SFRs. Nevertheless, this filter is sensitive to \(\geq 70\%\) of Hα emission lines of member galaxies.

![Figure 1](image-url)
galaxies throughout the field, and this provides us with an opportunity to conduct a wide-field Hα emitter survey in and around the A851 cluster.

On top of the Suprime-Cam BVRI imaging data and photometric redshifts (phot-z) of the A851 cluster field taken from Kodama et al. (2001), we have also collected z′-band and NB921 data using Suprime-Cam covering the same area as the existing BVRI imaging data (i.e., 27′ × 27′). The data are reduced in a standard manner using the Suprime-Cam data reduction pipeline (Yagi et al. 2002; Ouchi et al. 2004) in the way described in Kodama et al. (2001). All the images are smoothed to ∼1″1 seeing size, which is the worst among our data (the B-band data). The exposure times are 30 minutes and 180 minutes for the z′-band and NB921, respectively, and the 5σ limiting magnitudes are 24.0 mag and 24.4 mag, respectively (measured from the deviation of randomly distributed 3″ apertures in each image). Photometry of sources is performed at the position of I-band-detected objects with I ≤ 24.0 mag (−M_i^o + 4) using SExtractor software (Bertin & Arnouts 1996), and we use 3″ aperture photometry throughout the paper.

3. ANALYSIS

3.1. Hα Emitter Selection

We first identify narrow-band excess galaxies using the z′−NB921 colors. We plot in Figure 2 the z′−NB921 colors of all galaxies within the observed field against their NB921 magnitudes. The curves show ±3σ color excesses. We define the NB921 emitters as those satisfying z′−NB921 > 0.2 and z′−NB921 > 3σ (see the magenta crosses above the z′−NB921 = 0.2 line and z′−NB921 = +3σ curve in Figure 2). We detect 724 NB921 emitters in total, but some of these emitters are not necessarily Hα emitters at z = 0.4 since Hβ/[O iii] emitters at z ∼ 0.8 and [O ii] emitters at z ∼ 1.45 can also be detected as NB921 emitters. However, these contaminations can be eliminated relatively easily based on their broad-band colors. In Figure 3, we show the B−R versus R−z′ color–color diagram. We here plot galaxies with 0.30 < z_phot < 0.45 (gray dots) and all the NB921 emitters selected above (magenta crosses). We also show the model prediction of colors for galaxies at z = 0.4, 0.8, and 1.45 from Kodama et al. (1999). This color combination clearly separates the Hα emitters at z ∼ 0.4 from other major line emitters at other redshifts; in fact, these colors are also used in Kodama et al. (2004) in order to identify Hα emitters at a similar redshift (z = 0.39). We define the NB921 emitters distributed in the closed box in Figure 3 as Hα emitters at z = 0.4. We note that this boundary is set by eye, and we may miss a small fraction of real members near the boundary. However, a small change of this boundary does not change our results at all (see a similar selection method in Kodama et al. 2004 and Koyama et al. 2010). This color selection can be applied only for the galaxies that are detected in all BRz′ bands. Therefore, we do not include any Hα emitter if it is not detected in any of these bands. However, the quantitative analyses presented in this paper are mainly based on bright galaxies with z′ < 23 mag and are not affected by the faint undetected objects. After application of all these color cuts, we left with 445 Hα emitters in and around the A851 cluster throughout the observed field. This is one of the largest samples of Hα emitters currently available for distant clusters.

3.2. Necessity of Narrow-Band Imaging

We here briefly describe the powerful nature of the narrow-band survey. We show a plot showing z_spec versus z_phot in Figure 4. The spectroscopic catalog of the A851 field is taken from Oemler et al. (2009). The photometric redshifts are not...
always perfect, especially for blue star-forming galaxies due to the lack of significant features such as a 4000 Å break in their spectral energy distribution (SED; e.g., Kodama et al. 1999). In the lack of significant features such as a 4000 Å break in their always perfect, especially for blue star-forming galaxies due to their colors, through the narrow-band survey (see the discussion in Kodama et al. 2004). The selection criteria of Hα emitters shown in Section 3.1 correspond to EWR(Hα+[N II]) ≳ 20 Å and SFR(Hα) ≳ 0.3 M⊙ yr−1, and the typical uncertainty in the SFR(Hα) from photometric error is ≈ 0.1 M⊙ yr−1. We should note that the assumptions for [N II] contamination and dust extinction adopted above are somewhat uncertain. It is reported that the contribution of [N II] emission to the Hα+[N II] line flux depends on EW(Hα+[N II]) (e.g., Villar et al. 2008) or B-band luminosity (Kennicutt et al. 2008). Also, the strength of dust extinction can vary considerably (e.g., depending on the morphological type of galaxies; Boselli et al. 2001). In extreme cases, it may become A(Hα) ≳ 3 mag (e.g., Poggianti & Wu 2000), although the assumption of ∼ 1 mag extinction adopted here seems to be valid on average in the distant universe as well, and the level of dust extinction at a given SFR does not change strongly with redshift (e.g., Garn et al. 2010; Moore et al. 2010).

4. WIDE-FIELD MAPPING OF Hα EMITTERS

4.1. Panoramic Hα View of the A851 Cluster

We show in Figure 5 the spatial distribution of the Hα emitters selected in the previous section. The coordinates are shown with respect to the peak of the diffuse X-ray emission from the intracluster medium (ICM; α = 09h42m58.0s and δ = +46°59′01″), which is the same definition as in Oemler et al. (2009). We plot all the cluster member candidates (0.30 ≤ zphot ≤ 0.45; see the horizontal dotted lines in Figure 4) with gray dots. The Hα emitters are shown by colored symbols in Figure 5. Larger blue squares indicate larger SFRs, and green squares indicate the galaxies with weak Hα lines (SFR(Hα) < 0.75 M⊙ yr−1). Red squares indicate Hα emitters with B − I > 2.0 (hereafter red Hα emitters). Our survey reveals the entire distribution of star-forming galaxies around the A851 cluster across the ∼30′ field for the first time. It is evident that the Hα emitters are widely distributed throughout the field, which strongly supports the existence of real structures at z = 0.41 associated with the central cluster A851. In fact, most of the structures have been spectroscopically confirmed to be physically associated with the cluster based on our intensive spectroscopic follow-up (F. Nakata et al. 2011, in preparation).

We here define the galaxy environments used in this paper as shown in Figure 5, and summarize them in Table 1. The cluster core and two outskirt regions (1 and 2) correspond to r < 0.5 Mpc (which includes the two X-ray emission peaks; see Oemler et al. 2009), 0.5 Mpc < r < 1.0 Mpc, and 1.0 Mpc < r < 1.5 Mpc from the cluster center, respectively (all in the physical scale). We also define the west clump (the richest group in the observed field) and Groups 1, 2, 3, and 4 to pick out galaxies concentrated in groups relatively far out from the cluster core. Note that the west clump, Groups 2 and 3 are large clumps spectroscopically confirmed by F. Nakata et al.
Figure 5. Spatial distribution of the phot-$z$ members with $0.30 < z_{\text{phot}} < 0.45$ (gray dots) and H$\alpha$ emitters (open colored squares). Blue squares indicate H$\alpha$ emitters with SFR$_{H\alpha} > 0.75$ $M_\odot$ yr$^{-1}$, and larger symbols indicate galaxies with larger SFRs. Green squares show weak H$\alpha$ emitters with SFR$_{H\alpha} < 0.75$ $M_\odot$ yr$^{-1}$. Red squares represent the red H$\alpha$ emitters with $B - I > 2.0$. Contours show 3$, 5$, 7$, 10$, and 15$σ$ significance of galaxy overdensity calculated using all the member galaxies (all the phot-$z$ members and/or H$\alpha$ emitters). Solid-line circles and dashed-line rectangles show the areas where we define different environments to study environmental effects (see the text and Table 1).

(A color version of this figure is available in the online journal.)

(2011, in preparation), while the Group 1 region was not well covered by their spectroscopic observation. Group 4 is also a spectroscopically confirmed infalling group, identical to the NW group in Oemler et al. (2009). It is interesting to note that in addition to these known structures (the west clump and Groups 2, 3, and 4), H$\alpha$ emitters are concentrated in the northern part (i.e., Group 1), where we did not identify a prominent overdensity of phot-$z$ selected galaxies in Kodama et al. (2001). Therefore, our wide-field emission-line survey suggests the existence of a prominent structure traced by star-forming galaxies in the north direction of A851. This new group (Group 1) is defined as a circle in Figure 5. Finally, as a comparison, we define the three “Field” regions as indicated in Figure 5, in which we avoid any prominent structures.

4.2. H$\alpha$ Fraction

We here calculate the fraction of H$\alpha$ emitters for each environment defined above (see the labels in Figure 6). We statistically subtract the expected contaminations in our phot-$z$-based membership using the surface number density of the “Field” regions, $\rho_{\text{cont}} = 2.06$ arcmin$^{-2}$. We calculate the H$\alpha$
fractions in each environment using the following equation:

\[ f(H\alpha) = \frac{N_{H\alpha}}{N_{\text{member}} - N_{\text{cont}}}, \tag{4} \]

where \( N_{H\alpha} \), \( N_{\text{member}} \), and \( N_{\text{cont}} \) represent the number of H\(\alpha\) emitters, all member galaxies (phot-z members or H\(\alpha\) emitters), and the expected contaminations (i.e., \( N_{\text{cont}} = \rho_{\text{cont}} \times S \), where \( S \) is the surface area of each environment), respectively. In this calculation, we limit our sample to the galaxies with \( z' < 23 \) mag, since the selection of H\(\alpha\) emitters becomes incomplete below this magnitude, as can be seen in Figure 3. In Figure 6, filled circles with error bars indicate the values after the statistical subtraction, while open triangles show those before subtraction. It can be seen that the H\(\alpha\) fractions are almost unchanged after statistical subtraction in the dense cluster central region, while the contribution of contaminant galaxies gets larger in poorer environments. Note that, since we cannot calculate the H\(\alpha\) fraction for the field environment by definition (see Equation (4)), we present instead the blue galaxy fraction calculated based on the phot-z selected galaxies in the field environment as a rough estimate of the fraction of star-forming galaxies. This assumption is reasonable because we find that the fraction of H\(\alpha\) emitters among blue galaxies is \( \sim 1 \) at all environments after statistical correction. However, as will be discussed in the following section, there must be H\(\alpha\) emitters with red colors as well. Therefore, the blue galaxy fraction shown here for “Field” environments may be a lower limit of the H\(\alpha\) fraction. We also note that, although our “Field” environments avoid any prominent structures, it is still located near the rich cluster. This may lead to an overestimation of contaminant galaxies in the above calculation. However, our results including the “relative” trends seen in Figure 6 would not change even if we do not apply any correction for the contamination.

In Figure 6, it is evident that the H\(\alpha\) emitter fraction sharply declines toward the higher-density environment (only \( \sim 10% \) in the core and Outskirt 1, in contrast to \( \geq 50% \) in the west clump and groups), suggesting the clear environmental dependence of star-forming activity at \( z \sim 0.4 \). We also show the fraction of red galaxies with \( B - I > 2 \) in the top panel of Figure 6 (again, open triangles and filled circles indicate before and after statistical subtraction). The trend of an increasing fraction of red galaxies toward the cluster center is consistent with our result obtained from the analysis on the H\(\alpha\) fraction (i.e., the bottom panel of Figure 6).

It is now clear that the fraction of star-forming galaxies is significantly lower in the cluster central regions than in the other surrounding environments (see also Sato & Martin 2006b for the measurements of [O ii] emitter fraction within \( \sim 3 \) Mpc from the cluster), although some H\(\alpha\) emitters are found in the core of A851 (see Figure 5 and Oemler et al. 2009). Such H\(\alpha\) emitters found in the cluster central region are not distributed uniformly over the cluster environment but are concentrated along the north–south direction near the core. In particular, we find a strong concentration of H\(\alpha\) emitters at \( \sim 1.5 \) north from the cluster center. This position coincides with the “north group” noted by Oemler et al. (2009), where they also found a large number of star-forming galaxies. Therefore, it may be possible that some of the star-forming galaxies found in the cluster central region belong to a group moving near the cluster central region in projection.

5. RED STAR-FORMING GALAXIES

We have mapped out the spatial distribution of the H\(\alpha\) emitters across the \( \sim 30' \) field around A851. The majority of the H\(\alpha\) emitters have blue colors with \( B - I \leq 2 \). This is a natural consequence of young stellar populations in active star-forming galaxies. On the other hand, we have also identified a large number of red H\(\alpha\) emitters throughout the field (red squares in Figure 5). We here focus on the environment and nature of such red H\(\alpha\) emitters because they may be transitional galaxies migrating from the blue cloud to the red sequence.

5.1. Environment of Red H\(\alpha\) Emitters

To examine the colors of the H\(\alpha\) emitters and their environmental dependence in detail, we construct color–magnitude diagrams in Figure 7. We divide the sample into five environmental bins as defined in the previous section; namely, cluster core, two cluster outskirts, west clump, and groups (Groups 1,
dusty star-forming activities are triggered in such environments and in the groups show red colors, which probably suggests that emitters in each environment (see Figure 8). This plot clearly identifies this, we calculate the fraction of red galaxies among all Hα emitters in the west clump and in the groups. To quantify this, we calculate the fraction of red Hα emitters in the central cluster regions (i.e., in the cluster core and the two outskirt regions). In contrast, we see a large number of red emitters in the west clump and in the groups. To quantify this, we calculate the fraction of red galaxies among all Hα emitters in each environment (see Figure 8). This plot clearly shows that the red Hα emitters are seen exclusively in the relatively low-density environments. We find that a surprisingly high fraction (≥20%–30%) of Hα emitters in the west clump and in the groups show red colors, which probably suggests that dusty star-forming activities are triggered in such environments (see also the discussion in Section 5.3).

Note that the definition of “red galaxies” here includes not only the galaxies on the red sequence but also those in the “green valley.” Our result is not affected even if we select only the red-sequence galaxies, although the number of red Hα emitters becomes smaller in this case. We combined the four groups to obtain a composite value for the group environment so that we can achieve better statistics, although we find that the fraction is nearly constant at ∼30% in all the groups. It is also interesting to note that we find three red Hα emitters in the Outskirt 2 region (see the middle panel of Figure 7), but they are all located in the southern filament connecting the cluster core and Group 2 (see Figure 5). This may suggest that the galaxies falling into the cluster along the filamentary structure are experiencing somewhat different environmental effects than those for galaxies falling directly into the cluster from other various directions.

It is clear that the red Hα emitters are absent in the cluster central region. We note that this deficit of red Hα emitters does not simply reflect the environmental dependence of the color distribution of overall galaxy populations. As shown in the top panel of Figure 6, the fraction of red galaxies monotonically decreases toward the cluster center (equally, those Hα emitters near the cluster core are almost exclusively blue). Therefore, the environmental trend of the red galaxies and that of the red Hα emitters are clearly different, and so there is a clear difference in star-forming activity between cluster and group/filament environments.

One may claim that the definitions of the groups and the west clump are somewhat arbitrarily chosen. In order to assess the effect of the uncertainty in the definition of environments, we apply another definition based on the local density of galaxies (i.e., Σ* using all the phot-z members). We then investigate the dependence of colors of Hα emitters on the local density. The trends seen in Figures 7 and 8 are still visible, but weaker. In fact, we find that the local densities of the Outskirt 2 region and the groups are similar, but the occurrence of the red Hα emitters is different (∼twice larger in the groups than in Outskirt 2, although the error bars are large). This may suggest that the star-forming activity is determined not solely by local environment but also by global environment.

We should note that the preferred environment of the red Hα emitters may change with redshift. In fact, we have shown in Koyama et al. (2010) that red Hα emitters are located immediately outside of the cluster core at z 0. However, our current analysis on A851 suggests that at z ∼ 0.4 red Hα emitters are found in group environments relatively far away from the cluster, and that such galaxies are very rare even in the cluster outskirts. This may support the “propagation scenario” of star formation in clusters; that is, the site of the red star-forming galaxies (probably the transition objects) shifts from cluster cores to outer regions from z ∼ 1.5 to the present-day universe (see also Hayashi et al. 2010). However, the situation might be more complicated, given that there exist heavily obscured MIR bright galaxies as well. A more detailed discussion including such MIR sources is in the following sections.
Dressler et al. (2009) also noted that a significant fraction of "red star-forming" galaxies there.

It is naturally expected that star-forming galaxies show blue colors because young, massive, hot stars dominate their total light. Therefore, the interpretation for the red galaxies with emission lines is not straightforward. The most likely interpretation for the red Hα emitters is that they are dusty red galaxies (e.g., Wolf et al. 2005, 2009). If a star-forming galaxy contains a significant amount of dust, it appears red due to the selective extinction of bluer light, and in some cases, it becomes difficult to be distinguished from passively evolving red galaxies. Furthermore, in the extremely dusty cases, even the Hα lines are heavily attenuated by dust, and large corrections are required to obtain true SFRs from the observed post-starburst galaxies, are detected in MIR (see also Smail et al. 1999 for the radio continuum detection with VLA from k+a galaxies in A851). In the spectroscopic catalog of A851 in Oemler et al. (2009), 22 galaxies with $Q \lesssim 3$ are detected with MIPS (i.e., $f_{34 \mu m} \gtrsim 80 \mu Jy$ or SFR$_{IR} \gtrsim 3 M_{\odot}$ yr$^{-1}$). We find that 6 of these 22 sources have redshifts slightly outside of our Hα survey (their Hα lines fall outside of the FWHM of the NB filter), but we can expect to detect Hα emission from the remaining 16 sources. However, we find that only eight galaxies (50%) satisfy our Hα emitter selection criteria, while the remaining eight galaxies (50%) are not detected in Hα (see Table 2). These galaxies are likely to be heavily attenuated by dust, so that even the Hα emission cannot come through. Furthermore, we find a systematic difference in spectral types between Hα-detected and Hα-undetected MIPS sources (again, see Table 2). All the Hα-detected MIPS sources show "e(a,b,c,n)" spectra (i.e., [O II] emission lines are present in their spectra), while many of the Hα-undetected MIPS sources show "k+a/a+k" spectra (or "k"-type in two cases) without [O II] emission lines. We can also confirm in Table 2 that the Hα-undetected MIPS sources have systematically redder colors than the Hα-detected ones ($(B - I) = 1.48$ and 2.48 for Hα-detected and Hα-undetected objects, respectively). These results suggest that some red galaxies do not show Hα or [O II] emission lines in spite of their significant amount of hidden star formation activities.

5.3. What are the Red Hα Emitters?

5.2. Mid-infrared Sources

The central $\sim 5' \times 5'$ region of A851 was observed with Spitzer MIPS (24 μm) by Dressler et al. (2009). They reported that some galaxies in the core of A851 are detected in MIR. Here, we show in Figure 9 the spatial distribution of such MIPS sources taken from the catalog in Oemler et al. (2009), overlaid on the distribution of our Hα emitters. We only show the cluster central region due to the small coverage of the MIPS data. The MIPS sources are shown by orange circles. It is apparent that the spatial distribution of the Hα emitters and the MIPS sources are qualitatively similar, and they are both concentrated in the north–south direction. In fact, some sources are directly overlapping each other. We also construct a color–magnitude diagram for the central region with $R_c < 1$ Mpc (Figure 10). The MIPS sources are again shown by orange circles in Figure 10. They are located on the slightly bluer side of the red sequence and also at the bright end of the "blue cloud" and the "green valley." Some of the MIR galaxies are overlapping with Hα emitters. Interestingly, most of the red MIR galaxies with $B - I > 2$ are not detected in Hα, although these MIPS sources are all spectroscopically confirmed members and many of them should have been detected as Hα emitters judging from their spectroscopic redshifts (see below). Therefore, we should keep in mind that the lack of red Hα emitters in the cluster central region does not necessarily indicate a lack of "red star-forming" galaxies there.

Dressler et al. (2009) examined the spectral type of MIPS-detected sources and found that many of the MIPS sources in A851 have "e(a)-type" spectra (strong Balmer absorption and [O II] emission lines), which are interpreted as ongoing dusty starbursts (e.g., Poggianti et al. 1999; Poggianti & Wu 2000). Dressler et al. (2009) also noted that a significant fraction (≈30%) of "k+a" or "a+k" galaxies (strong Balmer absorption without [O II] emission lines), which are often interpreted as...
Hζ intensities (e.g., Poggianti & Wu 2000). This may explain the fact, presented in the previous subsection, that optically red MIPS-detected galaxies in A851 do not show significant Hα emissions.

An important point here is that, in contrast to the fact that the optically red MIPS sources in the cluster core are not detected in Hα, we do find many red Hα emitters in the group environments. If there are similar MIR-bright dusty red sources in groups, they should not have been detected in Hα in the groups, either. Why do only the red star-forming galaxies in groups have detectable Hα emissions? A possible answer is that the SFRs of these galaxies in groups are significantly higher and have stronger intrinsic Hα intensities, and/or the mode of star formation in these systems is different from the MIPS sources in the cluster core (e.g., the location of star formation within galaxies and/or the geometry of dust extinction is different).

### 5.3.1. Strong Starbursts or Moderate Star Formation?

It has been reported that there is an excess of IR luminous star-forming galaxies in group-like environments in the distant universe. For example, Tran et al. (2009) studied a supergroup environment at \( z \sim 0.4 \) in the MIR and showed an excess at the bright end of the IR luminosity function in group environments compared to cluster/field environments. Also, Poggianti et al. (2009a) studied the spectra of galaxies in the EDisCS clusters at \( z = 0.4−0.8 \) and showed that the “{e(a)}-type” galaxies (those having a signature of dusty starbursts in their optical spectra) are most numerous in group environments. This excess in star-forming activity of group galaxies may suggest that galaxy transition is actively taking place in group environments, and some galaxies with exceptionally high SFR may be detected in Hα. Also, recent MIR studies of distant clusters at \( z \gtrsim 0.5 \) found a large number of luminous infrared galaxies (LIRGs) in the outskirts of clusters (e.g., Marcillac et al. 2007; Koyama et al. 2008), and so it is likely that such dusty starburst galaxies are included in our red Hα emitter sample. In fact, Koyama et al. (2010) discovered some red Hα emitters in the outskirts of a \( z = 0.81 \) cluster and found that most of these red Hα emitters are indeed MIR-detected LIRGs with significant extinction at Hα \((A_{H\alpha} \gtrsim 3 \text{ mag})\). Geach et al. (2009) conducted MIR spectroscopy for some LIRGs in the outskirts of the CL0024 cluster at \( z = 0.4 \) that was reported in Geach et al. (2006). They identified clear polycyclic aromatic hydrocarbon (PAH) emission features from the majority of their targets, suggesting that these LIRGs are really dusty starbursts (active galactic nucleus (AGN) contribution is small). Their MIR spectra resemble those of nuclear starbursts rather than normal star formation in disks, and they proposed that such dusty starbursts seen in the outskirts of distant clusters are progenitors of the present-day cluster S0 galaxies (see also the discussion in Section 5.3.2).

However, such extremely active galaxies tend to be more dusty, and it might be difficult to detect their Hα emission. Also, the timescale of dusty starbursts is not long, typically \(<1 \text{ Gyr}\). In our sample, we detect Hα emission for \( \sim 20\%−30\% \) of the red galaxies in the west clump and in the groups. This fraction may be too large if we assume that they are all short-lived dusty starbursts. It is more likely that a gentle mechanism that produces relatively long-lived red star-forming galaxies is also at work in the group environment around the A851 cluster. Wolf et al. (2009) studied dusty red galaxies in the complex structure of the A901/902 clusters at \( z = 0.17 \) with UV+MIR photometry and found that their specific SFRs are systematically lower than blue star-forming galaxies (see also Wolf et al. 2005 and Gallazzi et al. 2009 for their identification of dusty red galaxies). They concluded that the dusty red galaxies in A901/902 are “semi-passive” rather than intense starbursts. They also proposed that the origin of such red star-forming galaxies is similar to that of “passive spirals” (galaxies with spiral morphology but without

### Table 2

Properties of Spectroscopically Confirmed MIPS Sources in A851

| Redshift | Spectral Type | \( B−f \) (mag) | \( EW_{H\alpha+[N\text{II}]} \) (Å) | SFR(Hα) \((M_{\odot} \text{ yr}^{-1})\) | \( f_{24} \) \(\mu\text{m} \) \((\text{ly})\) | SFR(IR) \((M_{\odot} \text{ yr}^{-1})\) | Hα Emitter (Yes/No) |
|----------|--------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.4084   | e(a)         | 1.11           | 34.52          | 3.51           | 3.05 \times 10^{-4} | 10.2        | Yes            |
| 0.4059   | e(a)         | 1.78           | 29.04          | 1.98           | 1.63 \times 10^{-4} | 5.0         | Yes            |
| 0.3972   | e(a)         | 0.75           | 147.31         | 22.93          | 7.96 \times 10^{-4} | 30.1        | Yes            |
| 0.4010   | e(a)         | 1.92           | 30.84          | 1.48           | 1.30 \times 10^{-4} | 3.8         | Yes            |
| 0.3958   | e(b)         | 0.91           | 145.75         | 27.45          | 1.04 \times 10^{-3} | 40.3        | Yes            |
| 0.3932   | e(a)         | 1.64           | 28.90          | 3.35           | 2.12 \times 10^{-4} | 6.8         | No             |
| 0.4061   | e(a)         | 1.72           | 69.79          | 19.24          | 3.98 \times 10^{-3} | 165.5       | Yes            |
| 0.3937   | e(a)         | 1.97           | 38.64          | 4.02           | 4.82 \times 10^{-4} | 17.2        | Yes            |
| 0.4007   | k+a          | 2.70           | 8.66           | 4.44           | 5.21 \times 10^{-4} | 18.7        | No             |
| 0.4060   | k+a          | 2.36           | 3.59           | 1.82           | 3.14 \times 10^{-4} | 10.6        | No             |
| 0.4075   | a+k          | 2.30           | −2.57          | −0.37          | 1.12 \times 10^{-4} | 3.2         | No             |
| 0.4076   | e(a)         | 1.65           | 21.00          | 0.59           | 8.13 \times 10^{-5} | 2.2         | No             |
| 0.3938   | k+a          | 2.30           | 14.27          | 3.69           | 5.78 \times 10^{-4} | 21.1        | No             |
| 0.4083   | k+a          | 2.50           | 0.91           | 0.10           | 1.49 \times 10^{-4} | 4.5         | No             |
| 0.3960   | k            | 2.84           | 0.40           | 0.07           | 7.32 \times 10^{-4} | 27.4        | No             |
| 0.4017   | k            | 3.17           | −0.50          | −0.04          | 1.01 \times 10^{-4} | 2.9         | Yes            |

Notes. All the galaxies listed here are spectroscopically confirmed MIPS-detected members at 0.389 \( \lesssim \z_{\text{spec}} \lesssim 0.409 \) (i.e., Hα lines of these sources fall within the FWHM of the NB921 filter), with spectral quality \( Q \lesssim 3 \) in Oemler et al. (2009). Remarkably, the MIPS sources without Hα emissions (lower side) tend to be redder and to have spectral types without emission lines (i.e., k/k+a/a+k) compared to those with Hα detections (upper side). Redshifts, spectral types, and \( f_{24} \) \(\mu\text{m} \) are taken from Oemler et al. (2009). In deriving SFR(IR), we first estimate \( L_{\text{IR}} \) by using the SED templates of starburst galaxies in Lagache et al. (2004) and then convert it to SFR(IR) based on the Kennicutt (1998) calibration. Two sources have negative values of \( EW(H\alpha+[N\text{II}]) \) and SFR(Hα) due to their negative (but almost \( \sim 0 \)) \( H\alpha \) colors.
ongoing star formation activity; e.g., Poggianti et al. 1999; Goto et al. 2003). Although a direct comparison of their results with ours is difficult, a fraction of the red Hα emitters identified in our survey could be similar to the dusty red galaxies discussed in Wolf et al. (2009), which are not strongly starbursting galaxies but moderately star-forming dusty galaxies.

5.3.2. Progenitors of the Cluster S0 Galaxies?

The existence of a large number of red star-forming galaxies and their locations (i.e., preferably in groups) may indicate that such populations are highly related to the transformation of galaxies due to environmental effects, as there is a hint that the group environment is a key place for galaxy truncation and the formation of S0 galaxies (see, e.g., Wilman et al. 2008, 2009). It has been reported that the fraction of S0 galaxies in cluster cores dramatically increases from $z \sim 0.5$ to $z \sim 0$ (e.g., Dressler et al. 1997; Desai et al. 2007; Poggianti et al. 2009b; Just et al. 2010), and it has been widely discussed in terms of the transformation from infalling field spirals to cluster S0s as they assemble to clusters (e.g., Poggianti et al. 1999; Kodama & Smail 2001). To reconstruct the S0 fraction in the nearby clusters, it may be required that galaxies are “pre-processed” in group environments (e.g., Fujita 2004), and late-type spirals (Scdm) may be transformed into bulge-strong early spirals such as Sab in the group environment (Kodama & Smail 2001). Moreover, considering the high bulge-to-disk ratios of S0 galaxies, just a simple fading of spiral disks may not be sufficient to produce S0 galaxies (Christlein & Zabludoff 2004). The physical processes that can move the gas toward the galaxy center and can grow bulges through new star formation activity would be preferable. The galaxy–galaxy interactions or harassment expected in groups are the best candidates (see also the discussion in Moran et al. 2007). In this context, many of the red Hα emitters reported in this paper may be in the phase of growing bulges with significant star formation in the galactic central regions with moderate dust extinction. However, the star formation activity is not as strong as a starburst, and their Hα emission is still visible through moderate dust extinction.

Moran et al. (2007) studied passive spirals and young S0 galaxies in two clusters at $z = 0.4$ and 0.5. They found that these transitional objects are preferentially seen in the infalling groups, and they also found that some of them are detected in UV. Such galaxies are probably similar populations to our red Hα emitters. Moran et al. (2007) also examined the UV/optical colors of these objects and proposed that they are likely to be truncated with a long timescale ($\gtrsim 1$ Gyr), qualitatively consistent with our suggestion of long timescales of the red Hα emitters in group environments. On the other hand, Moran et al. (2007) found that the star formation is more rapidly truncated in the cluster core environment (especially for more massive clusters with strong ICs). In our analysis, we did not find red Hα emitters in the cluster central region. This may be because the A851 cluster is also a very rich cluster, and it is possible that red Hα emitters cannot survive in the strong ICM in the cluster core (maybe their star formation is immediately shut off after entering the cluster core). In contrast, the MIPS-detected galaxies found in the cluster central region would be more intense short-lived starbursts with stronger extinction, probably triggered by galaxy mergers as suggested by Oemler et al. (2009).

Unfortunately, we do not have MIR data (which are essential to identifying obscured starbursts) and high-resolution HST data (which are essential to resolving galaxy morphology, mergers and localized star formation) for the group environments where we find a large number of red Hα emitters. This information would be extremely helpful in understanding the physical origin of the pre-processing working in the group environments, which may be closely related to the formation of cluster S0 galaxies. Combining these data with our wide-field Hα imaging data will clearly be an important future work.

5.3.3. Summary

In summary, the red Hα emitters are most commonly seen in galaxy groups around A851. They are probably related to the physics of the “pre-processing” in group environments, forming cluster S0 galaxies prior to entering the cluster core. The physical mechanisms primarily responsible for these populations are likely to be group-specific slow processes such as strangulation (e.g., Larson et al. 1980; Bekki et al. 2002; Kawata & Mulchaey 2008) or harassment-like mechanisms (e.g., Moore et al. 1999; Moran et al. 2007). The latter might be more preferred if they are in the process of morphological change toward the more bulge-dominated early spirals at the same time. Strong dusty starbursts triggered by, e.g., galaxy–galaxy interactions or mergers may also be included in our red Hα emitter sample, as we actually found such a population in the study of the $z \sim 0.8$ cluster (see Koyama et al. 2010). However, it is currently difficult to quantify their relative contribution or its redshift evolution. The most demanding and promising next step is a wide-field observation of the infalling groups in the MIR/FIR with the future space IR missions. Dusty starbursts should be bright in IR, while gradually fading star-forming galaxies would not be as bright in IR. Such surveys will give us information critical to identifying the key process for the evolution of cluster galaxies.

6. CLUSTER TOTAL STAR FORMATION RATE

Our narrow-band Hα line survey is also useful for studying total SFR in clusters. The advantage of the narrow-band survey is that we can trace star-forming activity throughout the observed field, and that we do not suffer from a sample selection bias or a completeness correction, which is inevitable for slit spectroscopy. The wavelength range of the narrow-band filter used in this study is slightly offset from the actual redshift distribution of the cluster member galaxies in Hα (see Figure 1). We correct for it in a statistical manner. We use the velocity distribution of the spectroscopic members within $0.5 \times R_{200}$ from Oemler et al. (2009), and estimate the fraction of Hα emission from the A851 cluster that can be recovered by our NB921 filter. The resultant correction factor to get the total SFR turns out to be $1.54^{+0.08}_{-0.06}$ (the uncertainty is given as a 1σ deviation derived from a bootstrap resampling of the spectroscopic members).

Following the procedure in Finn et al. (2005) and Koyama et al. (2010), we sum up the SFRs of Hα emitters within $0.5 \times R_{200}$ from the cluster center to derive $\Sigma SFR_{H\alpha}$, where $R_{200}$ is the radius within which the mean density is 200 times larger than the critical density of the universe (Carlberg et al. 1997). This allows us to directly compare our data with previous Hα-based cluster studies over a wide range in redshift, which have been compiled by Finn et al. (2005). We also calculate the cluster mass, $M_{200}$, as in Koyama et al. (2010) and derive the cluster mass-normalized SFR (i.e., $\Sigma SFR_{H\alpha}/M_{200}$). The $R_{200}$ and $M_{200}$ are calculated in the following equations:

$$R_{200} = 2.47 \times \frac{\sigma}{1000 \text{ km s}^{-1}} \frac{1}{\sqrt{\Omega_{\Lambda} + \Omega_{M}(1 + z)^3}} \text{ Mpc}$$

(5)
We plot in Figure 11 the values derived above and compare them with those for other clusters in the literature, all based on Hα (see Koyama et al. 2010 and references therein). This plot clearly shows that the mass-normalized SFR of A851 is located on the general evolutionary trend with redshift, following approximately $\propto (1+z)^6$. The lower limit in SFR that is used to calculate $\Sigma SFR$ is slightly different from cluster to cluster, but is within the range of 0.1–1 $M_\odot$ yr$^{-1}$ (dust-free).

Since the integrated SFRs are dominated by galaxies with strong star formation, we do not correct for this effect (see also Finn et al. 2004; Kodama et al. 2004). The strong evolution of star-forming activity in the clusters presented above is consistent with our previous study in Koyama et al. (2010), and this trend is much more significant than the trend of a decrease in the specific SFRs of individual galaxies, $\propto (1+z)^3$, shown by, e.g., Yoshida et al. (2006) and Zheng et al. (2007); see also the Hα-based studies of cosmic star formation history by, e.g., Sobral et al. 2009; Westra et al. 2010; Dale et al. 2010). Therefore, our result also suggests that cluster environment does indeed accelerate the quenching of activities in galaxies. We note that this redshift dependence of the cluster mass-normalized SFRs (or its scatter) may be related to the cluster mass growth (e.g., Finn et al. 2005; Koyama et al. 2010). As presented in Koyama et al. (2010), more massive clusters exhibit lower $\Sigma SFR_{H\alpha}/M_{200}$ (see also Homeier et al. 2005; Bai et al. 2009). This may also be related to the fact that the fraction of star-forming galaxies is a decreasing function of cluster mass (e.g., Poggianti et al. 2006, but see a different result by Haines et al. 2009b). In fact, a large scatter between clusters is clearly visible, even at a fixed redshift, in the top panel of Figure 11. In particular, the value of A851 presented in this paper is significantly different from that of the CL0024 cluster at a similar redshift (see Figure 11). However, A851 is $\sim$1 order of magnitude more massive than CL0024, and both clusters still lie along the general trend of decreasing $\Sigma SFR_{H\alpha}/M_{200}$ with increasing cluster mass (Figure 12). Furthermore, we also

$$M_{200} = 1.71 \times 10^{15} \left(\frac{\sigma}{1000 \text{ km s}^{-1}}\right)^3 \frac{1}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} M_\odot,$$

where $\sigma$ is the velocity dispersion of the cluster. Using the velocity dispersion of the cluster core galaxies ($\sigma = 1071$ km s$^{-1}$; Oemler et al. 2009) and the cosmological parameters adopted in this paper, we derived $R_{200} = 2.13$ Mpc and $M_{200} = 1.70 \times 10^{15} M_\odot$. Then, using all galaxies with $z' - \text{NB921} > 3\sigma$, we derived $\Sigma SFR_{H\alpha} = 208 \pm 10 M_\odot$ yr$^{-1}$ and the mass-normalized SFR of $\Sigma SFR_{H\alpha}/M_{200} = 12.2 \pm 0.6 M_\odot$ yr$^{-1}/10^{14} M_\odot$. These values include the correction for the filter transmission curve as described above (i.e., a factor of $\sim 1.5$), and the error bars are given as a composite of the photometric errors and the uncertainty of the correction factor.

Note that we include all galaxies with $z' - \text{NB921} > 3\sigma$ that satisfy the same color selection criteria as in Figure 3. If we use only the secure Hα emitters as defined in this study (i.e., $z' - \text{NB921} > 3\sigma$ and $z' - \text{NB921} > 0.2$), these values would become smaller by a factor of $\sim 2$ (lower limit), and if we use all galaxies with $z' - \text{NB921} > 0$, these values would increase by $\sim 25\%$ (upper limit). Although this uncertainty is large, this does not affect our main conclusion. We expect that the uncertainty regarding the dust extinction may also be very large. In fact, we derive $\Sigma SFR(\text{IR}) \sim 370 M_\odot$ yr$^{-1}$ by just summing up the IR-derived SFRs of the 16 MIPS-detected spec-$z$ members listed in Table 2, which is clearly larger than $\Sigma SFR(H\alpha)$ as derived above. Although we use a constant 1 mag extinction correction in this paper to make a fair comparison with the values in other works in the literature, it is also essential to study such obscured/hidden activities in more detail with the MIR–FIR observations (see some examples of such IR studies of the global evolution of star-forming activities in clusters by, e.g., Geach et al. 2006; Bai et al. 2007; Koyama et al. 2010; Haines et al. 2009a; Chung et al. 2010).
calculated these values for the west clump of A851 in the same way as for the main cluster, adopting the $R_{200}$ and $M_{200}$ taken from the preliminary result of the optical spectroscopy by F. Nakata et al. (2011, in preparation). We plotted these values for the west clump in Figures 11 and 12. Interestingly, the west clump of A851 is more massive than the CL0024 cluster and has a lower value of $\Sigma_{\text{SFR}}/M_{200}$, indicating the importance of the mass of the structure in determining the star-forming activity in the system.

We should comment that this simultaneous trend of SFR versus cluster mass and SFR versus redshift makes it difficult to derive any evolutionary trend in star formation activities in clusters. Our fitting of a form $\Sigma_{\text{SFR}}c (1+z)^{n} \times M_{cl}^{m}$ to the data shown in Figures 11 and 12 yielded $m = 1.2 \pm 2.0$ and $n = -0.75 \pm 0.2$. However, these numbers should be taken as very preliminary because they are based on a small sample. It should also be noted that, as shown in Figure 12, the low-$z$ clusters (open symbols) studied so far tend to be more massive, while the high-$z$ clusters (filled symbols) tend to be less massive. This may have led to an apparently stronger evolutionary trend than the actual one. It is thus critically important to collect a large number of distant clusters covering various masses and redshifts with future large cluster surveys.

7. SUMMARY AND CONCLUSIONS

We performed a panoramic narrow-band Hα emitter survey for the intermediate redshift cluster A851 at $z = 0.41$ with Suprime-Cam on the Subaru Telescope. This is one of the most distant wide-field Hα emitter surveys ever made for clusters. After selecting the Hα emitters with color excess in $c' \sim NB921$ and the broad-band color information, we first mapped out the spatial distribution of the Hα emitters around A851. The Hα emitters are found throughout the observed $27' \times 27'$ field, suggesting that the large-scale structures identified by our previous optical imaging survey are really located at the cluster redshift and are physically associated with the main cluster. The fraction of Hα emitters is a strong function of environment and shows a clear decline toward the cluster central region.

The most important result of this study is the color variation of Hα emitters and their clear environmental dependence. The majority of the Hα emitters are blue galaxies with $B-I < 2$, but we find that $\sim 15\%$ of the Hα emitters have red colors. Such red Hα emitters are preferentially found in the group environment, relatively far away from the cluster core. Our survey shows that $\sim 20\%$–$30\%$ of Hα emitters in the west clump and the groups have red colors with $B-I > 2$, while such red emitters are very rare in and immediately outside of the cluster core ($\lesssim 5\%$). Some of the red Hα emitters might be dusty starbursts with significant star formation produced via, e.g., galaxy–galaxy interactions or mergers. However, it would be unlikely that all the red Hα emitters are dusty starbursts, because most of the optically red MIR-detected galaxies found in the cluster central region are not detected in Hα (and also because the number of red Hα emitters is apparently too large for their short expected lifetime). Therefore, it would be reasonable to interpret that the red Hα emitters in group environments are generated by relatively gentle and slow processes, which are different from those producing MIR sources in the core of A851. Also, a large number of the red Hα emitters found in the groups might be closely related to the “pre-processing” contributing to the formation of bulge-dominated cluster S0 galaxies before entering the cluster core region.

We also derived the cluster total SFR and the cluster mass-normalized SFR by summing up the SFRs of individual galaxies within $0.5 \times R_{200}$ of the main cluster and the west clump. We confirmed a general trend that the mass-normalized SFRs increase sharply toward distant clusters following approximately $\propto (1+z)^{6}$, which turned out to be remarkably consistent with our previous studies, although there is a large scatter between clusters. This scatter may be related to the variation of the cluster mass at each epoch. More massive clusters have lower star formation activity inside them, suggesting that the cluster mass growth is related to the suppression of the star formation activity in galaxies.

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The Astrophysical Journal, 734:66 (13pp), 2011 June 10
Koyama et al.
