The Hα luminosity function of the galaxy cluster A521 at \( z = 0.25 \)

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ABSTRACT

We present an optical multicolor-imaging study of the galaxy cluster A521 at \( z = 0.25 \), using Suprime-Cam on the Subaru Telescope, covering an area of \( 32' \times 20' \) (\( 9.4 \times 5.8 \) \( \text{Mpc}^2 \) at \( z = 0.25 \)). Our imaging data taken with both a narrowband filter, NB816 (\( \lambda_0 = 8150 \, \text{Å} \) and \( \Delta \lambda = 120 \, \text{Å} \)), and broadband filters, \( B, V, R_C, i', \) and \( z' \), allow us to find 165 Hα emitters. We obtain the Hα luminosity function (LF) for the cluster galaxies within 2 Mpc; the Schechter parameters are \( \alpha = -0.75 \pm 0.23, \phi' = 10^{-0.05} \text{ to } 10^{-0.05} \, \text{Mpc}^{-3}, \) and \( L^* = 10^{41.86} \) to \( 10^{42.2} \, \text{ergs} \, \text{s}^{-1}. \) Although the faint-end slope \( \alpha \) is consistent with that of the local cluster Hα LFs, the characteristic luminosity \( L^* \) is about 6 times (or \( \approx 2 \) mag) brighter. This strong evolution implies that A521 contains more active star-forming galaxies than the local clusters, being consistent with the observed Butcher-Oemler effect. However, the bright \( L^* \) of A521 may be, at least in part, due to the dynamical condition of this cluster.

Subject headings: galaxies: clusters: individual (A521) — galaxies: evolution — galaxies: luminosity function, mass function

1. INTRODUCTION

Recent observations of clusters of galaxies at intermediate redshift (0.1 \( \leq z \leq 0.5 \)) have demonstrated that environmental processes play an important role in both the star formation activity and the morphology of galaxies (e.g., Dressler et al. 1997; Balogh et al. 1998; Poggianti et al. 1999; Moss & Whittle 2000). The galaxy evolution in such clusters may be explained as the result of the increased activity of the field galaxies at more distant redshifts (Lilly et al. 1996), modulated by changing the infall rate onto the clusters (Bower 1991). However, little information on the global star formation history in such intermediate-redshift clusters has been obtained even to date.

In many previous spectroscopic studies, such as the Canadian Network for Observational Cosmology (CNOC) and MORPHS surveys (e.g., Abraham et al. 1996; Poggianti et al. 1999), the [O ii] \( \lambda 3727 \) emission line has often been used to investigate the star formation activity in cluster galaxies. However, the Hα emission line provides a more reliable indicator of star formation because it is less sensitive both to dust extinction and to metallicity effects (Kennicutt 1998). Recently, an Hα survey has been made for the nearby clusters of galaxies A1367 and Coma (Eliasias-Paramo et al. 2002). These data are utilized to derive the Hα luminosity function (LF) of the cluster member galaxies. Optical spectroscopic surveys are also useful in studying Hα emission-line properties of cluster member galaxies (Balogh et al. 2002; Couch et al. 2001). However, such spectroscopic samples are selected by using optical broadband color properties, being independent of their Hα emission-line properties. Therefore, these data sets may miss a part of Hα-emitting galaxies that are too faint to be selected in a continuum-magnitude-limited sample. In order to determine the shape of the Hα LF unambiguously, carrying out a deeper Hα imaging survey is required.

Motivated by this, we performed our deep Hα imaging survey of the cluster of galaxies A521 at \( z = 0.25 \), which is a relatively rich (richness class 1) cluster; note that its Bautz-Morgan type is III (Abell, Corwin, & Olowin 1989). Recent studies of this cluster have shown that the projected galaxy density distribution in the central region has a very anisotropic morphology, since it exhibits two high-density filaments crossing in an X-shaped structure at the barycenter of the cluster (Arnaud et al. 2000; Maurogordato et al. 2000; Ferrari et al. 2003). The observed high velocity dispersion of the cluster (\( \approx 1325 \, \text{km s}^{-1} \)) may be attributed to the presence of these substructures. Since this velocity dispersion is also high compared to that expected from the temperature of the X-ray gas (\( kT = 6.3 \, \text{keV}; \) Arnaud et al. 2000), it has been suggested that this cluster is undergoing strong dynamical evolution driven by mergers among substructures. In this paper we present observational properties of Hα-emitting galaxies in A521 and then derive the Hα LF for the first time. Throughout this paper, magnitudes are given in the AB system (Fukugita, Shimasaku, & Ichikawa 1995). We adopt an \( H_0 = 50 \, \text{km s}^{-1} \text{Mpc}^{-1}, q_0 = 0.5, \) and \( \Lambda = 0 \) cosmology for comparison with previous results in the literature.

2. OBSERVATIONS AND DATA REDUCTION

The imaging data of A521 were obtained with Suprime-Cam (Miyazaki et al. 2002) on the 8.2 m Subaru Telescope atop Mauna Kea during two runs (2001 October and 2002 February). We used the narrowband filter, NB816 (\( \lambda_0 = 8150 \, \text{Å} \) and \( \Delta \lambda = 120 \, \text{Å} \)); the central wavelength corresponds to a redshift of \( \approx 0.24 \) for Hα emission. We also used broadband filters, \( B, V, R_C, i', \) and \( z' \). A journal of our observations is summarized in Table 1.
We used IRAF and the mosaic-CCD data reduction software NEKOOSFT (Yagi et al. 2002) to reduce and combine the individual CCD data. Photometric and spectrophotometric standard stars used for the flux calibration are as follows: SA 98 (Landolt 1992) for the B data, SA 95 and SA 98 (Landolt 1992) for the V data, SA 95, SA 113, and PG 0231 (Landolt 1992) for the R_C data, GD 50 (Oke 1990) for the i' data, and GD 50, GD 108, and PG 1034+001 (Stone 1996) for the NB816 data. Since the zero point of Landolt (1992) is based on Vega, we convert the B, V, and R_C magnitudes to the AB system assuming monochromatic colors of B(Vega) = B(AB) = 0.140, V(Vega) - V(AB) = 0.019, and R_C(Vega) - R_C(AB) = -0.169 (Fukugita et al. 1995). For i' and NB816, we multiplied the atmospheric, instrumental, and filter transmittance, mirror reflectivity, and CCD quantum efficiency with the spectral energy distribution (SED) of standard stars to calculate absolute flux. The z' data were calibrated by using the magnitude of the quasar SDSSp J104433.04-012502.2 (Fan et al. 2000), which were obtained in the same observing night (see Fujita et al. 2003). Since any quasar is a potentially variable object, the photometric calibration of the z' data may be more unreliable than those of the other band data. In order to estimate the uncertainty, we compared the colors of stars in our area with Galactic stars given by Gunn & Stryker and applied the correction to our z' data. The combined images for the individual bands were aligned and smoothed with Gaussian kernels to match the point-spread function (1'1'). The final images cover an area of 32' x 20', which corresponds to 9.4 x 5.8 Mpc^2 at z = 0.25.

Source detection and photometry were performed by using SExtractor, version 2.2.2 (Bertin & Arnouts 1996). The NB816 image was used as a reference image for detection, and photometry was performed for each band image. We used a criterion that a source have at least a 13 pixel connection at the 2σ level. For each object, we measured the magnitude within a fixed aperture of 3'' (≈15 kpc at z = 0.25) diameter for colors and magnitudes in all six band images. However, we used an adaptive aperture of diameter 2.5r_K for measurement of total magnitudes, where r_K is the Kron radius (Kron 1980). Our 3σrms within a 3'' aperture in each band is given in Table 1.

In order to correct for the Galactic extinction, we calculated the extinction at each band (Cardelli, Clayton, & Mathis 1989), assuming that A_J = 0.324 (Schlegel, Finkbeiner, & Davis 1998; NED). The extinction at each band, A_i', is given in Table 1.

### Table 1

| Filter    | Observation Date | Total Exposure (s) | A_i' | Limiting Magnitude^b |
|-----------|------------------|--------------------|------|----------------------|
| B         | 2002 Feb 15      | 480                | 0.324| 25.3                 |
| V         | 2001 Oct 14, 15  | 2250               | 0.245| 25.5                 |
| R_C       | 2001 Oct 14      | 1620               | 0.203| 25.5                 |
| i'        | 2001 Oct 14      | 1320               | 0.157| 25.4                 |
| NB816     | 2002 Feb 14      | 3600               | 0.139| 24.6                 |
| z'        | 2002 Feb 15      | 840                | 0.113| 24.2                 |

a Galactic extinctions are applied to our imaging data (Cardelli et al. 1989; Schlegel et al. 1998).

b The limiting AB magnitude (3σ) within a 3'' aperture.

3. SELECTION OF H_α EMISSORS

We defined the off-band continuum flux of objects as i'z' = 0.6i' + 0.4z', which was computed from a linear interpolation between the effective frequencies of the i' and z' bands. Taking the scatter in the i'z' - NB816 color into account, emission-line objects were selected with the following criteria:

i'z' - NB816 > max (0.1, 3σ error of i'z' - NB816),

(1)

i'z' < 24.9.

(2)

The color of i'z' - NB816 = 0.1 corresponds to an equivalent width of ≈12 Å in the rest frame at z = 0.247. The magnitude limit corresponds to the 3σrms of the i'z' band. These criteria are shown by the solid, dashed, and dotted lines in Figure 1. Then we found 324 objects that satisfy the above criteria; note that they are brighter than the limiting magnitude at each band.

Narrowband imaging can potentially detect galaxies with different emission lines at different redshifts. Emission lines detected in our narrowband imaging survey are, for example, H_α (z ≈ 0.24), [O ii] λ4959, 5007 (z ≈ 0.63), H_β (z ≈ 0.68), and [O iii] λ3727 (z ≈ 1.18). In order to distinguish H_α emitters at z ≈ 0.24 from other emission-line objects, we investigate their broadband color properties. In Figure 2 we show the diagram between B - V and V - i' for the 324 emission-line objects. We also show the model galaxy colors that were estimated by using the population synthesis model GISSEL96.
shown by filled triangles, and those with
respectively. We select the objects above the dashed line as H\(z\) galaxies at (filled squares)
colors. Colors of model galaxies (for SB, Irr, Scd, Sbc, and E) from objects with
images. We prepared model galaxies with broadband colors of
emitters, we performed a detection test on simulated artificial
(Bruzual & Charlot 1993). The star formation rate of model
galaxies is taken at the position of the main X-ray cluster (Arnaud et al.
the distance of 2 Mpc from the center of A521; note that the center
the cluster members is clearly seen in the area within a radial
criterion. In Figure 3 the excess of surface number density by
distribution of the galaxies that are selected by the above color
criterion because they have neighboring galaxies, causing large photo-
remaining two objects were rejected in our selection procedure
objects satisfy the color criterion based on our photometry. The
These members are identified in our catalog. We found that 123
in this cluster (Ferrari et al. 2003; Maurogordato et al. 2000).
previous spectroscopic surveys identified 125 member galaxies
spectroscopically confirmed member galaxies in A521. The
well more quantitatively, we investigate color properties of the
obtain a sample of 165 H\(z\) emitters from other emitters at different redshifts. We then
find that H\(z\) emitters at \(z \approx 0.24\) can be selected by adopting the following color criterion:
\[
B - V > 0.75(V - i') + 0.25. \tag{3}
\]
As shown in Figure 2, this criterion appears to isolate H\(z\) emitters from other emitters at different redshifts. We then obtain a sample of 165 H\(z\) emitters.

In order to examine whether or not this color criterion works well more quantitatively, we investigate color properties of the spectroscopically confirmed member galaxies in A521. The previous spectroscopic surveys identified 125 member galaxies in this cluster (Ferrari et al. 2003; Maurogordato et al. 2000). These members are identified in our catalog. We found that 123 objects satisfy the color criterion based on our photometry. The remaining two objects were rejected in our selection procedure because they have neighboring galaxies, causing large photometric errors. As a further check, we examined the spatial distribution of the galaxies that are selected by the above color criterion. In Figure 3 the excess of surface number density by the cluster members is clearly seen in the area within a radial distance of 2 Mpc from the center of A521; note that the center is taken at the position of the main X-ray cluster (Arnaud et al. 2000).

In order to investigate the detection completeness of H\(z\) emitters, we performed a detection test on simulated artificial images. We prepared model galaxies with broadband colors of late-type galaxies (SB, Irr, Scd, and Sbc) at \(z = 0.24\) generated by the GISSEL96 model. Since the equivalent width of H\(z\) emission is generally different from galaxy to galaxy, we put the excess of NB816 to \(i'z'\) continuum as a parameter. We studied a color range of \(0.1 < i'z' - NB816 < 1.1\) with five bins of \(\Delta(i'z' - NB816) = 0.2\). Since the total magnitude of NB816 is another parameter, we studied a magnitude range of \(18.0 < NB816 < 24.0\) with twelve bins of \(\Delta(NB816) = 0.5\). We prepared 500 model galaxies in each set of NB816 and \(i'z' - NB816\). The light distribution of model galaxies is generated as an exponential law by IRAF ARTDATA. Their sky positions, half-light radii (1–7 kpc), and ellipticities (0.3–1.0) were randomly set and put into the CCD data together with Poisson noises. After smoothing model-galaxy images to match to the seeing size, we tried to detect them using SExtractor and to select them as H\(z\) emitters with the same procedure as used for the observed data. The detectability of the model emitters is shown in Figure 4 as a function of NB816 magnitude. We found that the detectability is higher than 80% for objects with NB816 < 22.0 but lower than 30% for objects with 23.0 < NB816 < 24.0.

Next, we examined contamination by emission-line objects at other redshifts (e.g., [O \(iii\)] \(\lambda\lambda 4959, 5007\) at \(z \approx 0.63\) in the same manner as that for the detection completeness estimate. We found the contamination to be only less than 5% even for the faint objects with 23.0 < NB816 < 24.0. In conclusion, our color criterion allows us to select reliable H\(z\) emitters at \(z \approx 0.24\) for sources with NB816 < 23.0.

4. H\(z\) LUMINOSITY FUNCTION

4.1. Emission-Line Equivalent Width

At first we derive the emission-line equivalent width of the individual H\(z\) emitters. Since the passband of our narrowband filter is too wide to separate [N \(ii\)] \(\lambda\lambda 6548, 6584\) from H\(z\), the equivalent width derived here is that contributed from the three emission lines. We adopt the same method as that used by Pascual et al. (2001) to calculate the H\(z\) + [N \(ii\)] \(\lambda\lambda 6548, 6584\)
(hereafter the \( \text{H} \alpha + [\text{N} \, \text{ii}] \)) equivalent width. The flux density in each filter can be expressed as the sum of the line flux and the continuum density (the line is covered by both filters),

\[
\begin{align*}
\text{\( f_{\text{NB}} \) } & = f_c + (F_L/\Delta \text{NB}), \\
\text{\( f_{\text{NB}} \) } & = f_c + 0.6(F_L/\Delta i'),
\end{align*}
\]

where \( f_c \) is the continuum density, \( F_L \) is the line flux, \( \Delta \text{NB} \) and \( \Delta i' \) are the NB816- and \( i' \)-band filter effective widths, respectively, and \( f_{\text{NB}} \) and \( f_{i'} \) are the flux densities in each filter. Then the equivalent width can be expressed as follows:

\[
\text{EW}_{\text{obs}}(\text{H} \alpha + [\text{N} \, \text{ii}]) = \frac{F_L}{f_c} = \Delta \text{NB} \left[ \frac{f_{\text{NB}} - f_{i'}}{f_{i'} - 0.6f_{\text{NB}}(\Delta \text{NB}/\Delta i')} \right],
\]

where \( \Delta i' = 1535 \, \text{Å} \) for the \( i' \) band and \( \Delta \text{NB} = 120 \, \text{Å} \) for the NB816 band.

### 4.2. \text{H} \alpha Luminosity

In order to obtain the \text{H} \alpha luminosity, we have to correct for the flux contribution from the [\text{N} \, \text{ii}] doublet. We also have to apply correction for internal extinction. For the two corrections, we adopt the flux ratio of \( \text{H} \alpha/[\text{N} \, \text{ii}] = 2.3 \) (Kennicutt 1992) and \( A_{\text{H} \alpha} = 1 \, \text{mag} \) as a typical internal extinction at \( z \sim 0.2 \) (Tresse & Maddox 1998). Applying these corrections, we estimate the \text{H} \alpha luminosity \( L(\text{H} \alpha) \) from the total magnitude for each object. We then obtain the star formation rate SFR using the following relation (Kennicutt 1998):

\[
\text{SFR} \left( M_\odot \, \text{yr}^{-1} \right) = 7.9 \times 10^{-42}L(\text{H} \alpha) \left( \text{ergs s}^{-1} \right).
\]

The net \text{H} \alpha flux depends on the source redshift because of the fixed transmittance of our NB816 filter. In order to correct for this effect, we adopt the following assumptions: (1) The velocity (redshift) distribution of the cluster galaxies is a Gaussian probability density function \( P(z) \) around a mean velocity of 74,019 km s\(^{-1}\) with a dispersion of 1325 km s\(^{-1}\) (Ferrari et al. 2003). (2) The equivalent width distribution of the \text{H} \alpha emitters in the rest frame is expressed as the following exponential functional form:

\[
Q(\text{EW}) = A \exp\left(-\text{EW}/B\right),
\]

where \( A \) and \( B \) are free parameters. Then the rest-frame equivalent width probability of the \text{H} \alpha emitters at redshift \( z \) can be expressed as \( P(z) \times Q(\text{EW}) \). The best-fit parameters are obtained so as to fit the distribution of \( \text{EW} - \text{NB}816 \).

We apply the correction for the incomplete velocity coverage of the NB816 filter. Since the number of the \text{H} \alpha emitters excluded from the filter can be calculated from the value of the equivalent width, we correct the equivalent width distribution function that derived above. Therefore, using the equivalent width distribution function, we obtain the corrected \text{H} \alpha luminosity distribution.

### 4.3. Statistical Weights

Since the excess of surface galaxy density by the cluster member is clearly seen in the area within 2 Mpc radius (see Fig. 3), it seems safe to use the \text{H} \alpha emitters located in the region; note that there are 53 \text{H} \alpha emitters in this region. Although the NB816 filter corresponds to the redshifted \text{H} \alpha emission line at \( z = 0.242 \pm 0.009 \), the mean redshift of the cluster is \( z = 0.247 \). Therefore, our \text{H} \alpha emitter sample may suffer contamination from field \text{H} \alpha emitters, in particular from field galaxies in the foreground. In order to correct for this effect, we estimate the field contamination by the following method.

In order to obtain a sample of field galaxies, we use an area of 3 Mpc outside from the cluster center, taking account that the virial radius is estimated to be 2.74 Mpc (Girardi & Mezzetti 2001). However, since a subclump is seen to the northeast at about 4.5 Mpc from the cluster center, we exclude this area from our analysis. The remaining sky area is used to estimate the surface number density of field galaxies as a function of NB816 magnitude. Since A521 shows elongated galaxy distribution (Ferrari et al. 2003), we use the local surface number density, which is calculated from 10 nearest neighbors, rather than the radial surface number density distribution. In this way, all \text{H} \alpha emitters in the cluster region are weighted by the luminosity-dependent factor \( w_l \) and the density-dependent factor \( w_d \), after renormalizing \( w_d \) so that the sum of the total galaxy weights \( w_l \times w_d \) is equal to the sum of \( w_l \).

### 4.4. \text{H} \alpha Luminosity Function

We derive the \text{H} \alpha LF for the cluster region. In order to normalize the \text{H} \alpha LF to a proper volume, we use the sphere volume within a 2 Mpc radius. The \text{H} \alpha LF for our sample is well fitted by the Schechter (1976) function:

\[
\phi(L)\,dL = \phi^* (L/L^*)^{\alpha} \exp\left(-L/L^*\right) d(L/L^*). \tag{8}
\]

The size of the bins is taken to be \( \Delta \log L(\text{H} \alpha) = 0.5 \). The number counts in the individual bins are given in Table 2, and Figure 5 shows the \text{H} \alpha LF for A521 and its Schechter fit. After correcting for the detection completeness (see \S 3), we obtain the best-fit parameters for the cluster membership within a 2 Mpc radius as

\[
\begin{align*}
\alpha &= -0.75 \pm 0.23, \\
\phi^* &= 10^{-0.45} \text{ to } 10^{-0.05} \, \text{Mpc}^{-3}, \\
L^* &= 10^{41.86} \text{ to } 10^{42.2} \, \text{ergs s}^{-1}.
\end{align*}
\]
The inset panel in Figure 5 shows the $\chi^2$ error contours corresponding to the 1 and 2 $\sigma$ levels. It can be seen that the $\alpha$ and $L^*$ values are highly correlated.

5. DISCUSSION

In Figure 5 we also show the H$\alpha$ LFs of field galaxies in the local universe (Gallego et al. 1995), at $z \sim 0.2$ (Tresse & Maddox 1998), and at $z \approx 0.24$ (Fujita et al. 2003) and those of the nearby clusters of galaxies (Iglesias-Páramo et al. 2002). As for the nearby clusters of galaxies, Iglesias-Páramo et al. (2002) derived the H$\alpha$ LFs for A1367 and Coma (richness class 2). The physical areas analyzed by them are nearly the same as those of the field H$\alpha$ LFs (Tresse & Maddox 1998), and at local universe (Gallego et al. 1995), at different extinction correction, same as that of A521. Although they applied a slightly different extinction correction, $A_{H\alpha} = 1.1$ mag for type Scd or earlier and $A_{H\alpha} = 0.6$ for type Sd or later (Boselli et al. 2001), they obtained $\alpha \approx -0.7$ and $L^* \approx 10^{41.25}$ ergs s$^{-1}$ for these clusters. The inset panel in this figure shows the best-fit parameters of A521 and the others. There is a significant difference in H$\alpha$ LFs between the clusters and the fields. It is found that the faint-end slope $\alpha$ of the H$\alpha$ LF of A521 is flatter than that of the field H$\alpha$ LFs at the same redshift. Therefore, although the sample analyzed here is not so large, it appears that the fainter faint-end slope of the H$\alpha$ LF is commonly seen in the clusters of galaxies between $z \approx 0$ and $z \approx 0.2$.

The most important finding in this study is that the characteristic luminosity $L^*$ of A521 is $\approx 6$ times (or $\approx 2$ mag) brighter than those of the local cluster H$\alpha$ LFs, and nearly the same as those of the field H$\alpha$ LFs. The evolution of the field H$\alpha$ LF from $z \approx 0.2$ to $z \approx 0$ appears closely related to the $\phi^*$ parameter rather than to the $L^*$ and $\alpha$ parameters. However, as for the cluster H$\alpha$ LFs, the $L^*$ parameter appears to evolve strongly from $z \approx 0.2$ to $z \approx 0$. Furthermore, we investigate the following galaxy clusters for which spectroscopic H$\alpha$ emitter surveys were already made: A1689 at $z = 0.18$ (Balogh et al. 2002) and AC 114 at $z = 0.31$ (Couch et al. 2001). Since their observations are based on spectroscopy, they are difficult to compare with our H$\alpha$ LF straightforwardly. Therefore, we compare the H$\alpha$ LF of A521 with the other clusters using only the H$\alpha$-luminous galaxies ($L^* \approx 10^{41.5}$ ergs s$^{-1}$). It should be noted that the same dust extinction correction (i.e., $A_{H\alpha} = 1$ mag) is applied for these clusters, and the H$\alpha$ luminosity from spectroscopy may be underestimated due to aperture bias.

Figure 6 shows the surface density of the H$\alpha$ luminosity distribution of each cluster; note that the surface density is used instead of the volume density that is used in Figure 5, to compare simply with previous results. Although there are some galaxies whose SFRs exceed SFR $\sim 4 M_\odot$ yr$^{-1}$ in A521 and A1689, no such galaxies are found in A1367 and Coma. This SFR is about the same level as that observed in the Milky Way (Rana 1991). This result implies that A521 and A1689 contain more active star-forming galaxies than the nearby clusters. However, AC 114 has nearly the same property in the H$\alpha$ LF as those of the nearby clusters in spite of its higher redshift.

This evolution may simply reflect the Butcher-Oemler (BO) effect, which is the increase in the fraction of blue galaxies, presumably star-forming galaxies, in clusters with increasing redshift (Butcher & Oemler 1984). In fact, the fraction of blue galaxies in our H$\alpha$ emitters by the definition of Butcher & Oemler (1984) is $\approx 85\%$. The blue fraction $f_B$ in A1689 is comparable to that of A521 ($f_B \approx 0.17$; see the Appendix for details) and much higher than those in the nearby rich clusters such as Coma ($f_B = 0.03$). However, AC 114 and A1367 also have a large fraction of blue galaxies ($f_B \approx 0.20$). Therefore, the star formation activity in clusters of galaxies may not be understood solely by the BO effect.

These results suggest that some physical processes work in their star formation activity, independent of the blue fraction of each cluster. We investigated which cluster parameter is correlated with the existence of high-SFR galaxies. One possible parameter is the dynamical status, as pointed out by Balogh et al. (2002). Although A1689 appears to show a round shape in X-rays, the observed radial velocity distributions of the cluster show substructures. On the other hand, AC 114 appears to be relaxed dynamically, although the cluster member galaxies show an elongated morphology (Balogh et al. 2002). Therefore, it seems important to investigate the radial velocity distributions of the H$\alpha$ emitters of each cluster (Fig. 7). In Figure 7 we use the relative radial
velocity $\Delta v_r$ to the systemic velocity $v_{r,0}$ of each cluster, and $v_{r,0}$ is shown in the left corner of each figure. For A521, A1367, and Coma, the redshifts are unknown from the imaging survey, since the $H\alpha$ emitters are detected using the narrowband filters. Therefore, their distributions are shown using available spectroscopic data in the literature (Ferrari et al. 2003; Iglesias-Páramo et al. 2002; Cortese et al. 2003). The vertical dashed lines in this figure show the velocity coverage corresponding to the FWHM of the narrowband filters. For A521 in particular, since some $H\alpha$ emitters with $\Delta v_r > 0$ km s$^{-1}$ may be excluded from the filter transmittance, we also show the velocity distribution of galaxies identified with other emission lines ([O ii] or H$\beta$) taken from Ferrari et al. (2003). It is found that this radial velocity distribution is consistent with that of the $H\alpha$ emitters with $\Delta v_r < 0$ km s$^{-1}$. Therefore, we expect that it also traces that of the $H\alpha$ emitters with $\Delta v_r > 0$ km s$^{-1}$. In this figure, the radial velocity distribution for the $H\alpha$ emitters in A521 is inconsistent with a Gaussian distribution that we assumed in § 4.1. However, since the spectroscopic sample is rather small, it is dangerous to apply this distribution to our sample. Even if this distribution is valid, it does not change the result that $L^*$ of A521 is much brighter than those of the nearby clusters.

In Figure 7 the radial velocity distributions in A1367 and Coma tend to be concentrated around $\Delta v_r \approx 0$ km s$^{-1}$. Therefore, it is suggested that these galaxies are associated with a galaxy population in the cluster core, probably a virialized system. For AC 114, the radial velocity distribution suggests that the most $H\alpha$ emitters are associated with the structure centered at $\Delta v_r \approx \pm 2000$ km s$^{-1}$. Even if they comprise a substructure infalling onto the cluster center, the star-forming activity seems to have already been ceasing because of the environment effect (Kodama et al. 2001; Gómez et al. 2003). For A521 and A1689, the radial velocity distributions show several peaks in a wide velocity range and there are few $H\alpha$ emitters at the mean cluster redshifts. And for A521, they are not thought to be field contamination but to be associated with the cluster, since their number density is high at the center of the cluster (Fig. 3). The $H\alpha$ emitters in the two clusters are likely to be in the process of accretion of the field population. If this is the case, it may explain why their star-forming activities are higher than those of the other clusters. It is thus suggested that the star formation activity in clusters seems to be strongly related to the dynamical status of the clusters.

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In order to derive the fraction of blue galaxies $f_B$ in A521, we followed the procedure of Butcher & Oemler (1984). We calculated the fraction of galaxies that are 0.2 mag bluer than the color-magnitude sequence of early-type galaxies in the rest-frame $B-V$ color within a magnitude limit $M_V = -20$ and that are enclosed within $R_{30}$, the radius that contains 30% of the cluster population.

The blue fraction $f_B$ was calculated by subtracting the number count expected for the field from that obtained for the cluster sample. In order to obtain the value of $f_B$, we used the $V-R_C$ color index, which is very close to $B-V$ rest frame at the cluster redshift. The magnitude limit $M_V = -20$ in the rest frame corresponds to $R_C \approx 20.8$ at cluster redshift, and a difference of $\Delta (B-V) = 0.2$ mag is $\Delta (V-R_C) \approx 0.17$ mag. The value of $R_{30}$ is determined from the surface number density profile (Fig. 3). We found $R_{30} = 3.1$ (≈0.9 Mpc), being very similar to the typical radius of $R_{30} \sim 1$ Mpc for a sample of rich clusters at $0.2 \leq z \leq 0.4$ (Kodama & Bower 2001). As a result, we obtain $f_B = 0.17 \pm 0.03$.

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