

MORPHOLOGICAL DEPENDENCE OF STAR FORMATION PROPERTIES FOR THE GALAXIES IN THE MERGING GALAXY CLUSTER A2255

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ABSTRACT

The merging cluster of galaxies A2255 is covered by the Sloan Digital Sky Survey (SDSS) survey. The physical parameters of 184 bright member galaxies derived from the SDSS data analyses by Brinchmann et al. allow a detailed study of the star formation properties of galaxies within a merging cluster at intermediate redshift. In this paper we perform a morphological classification on the basis of the SDSS imaging and spectral data and investigate the morphological dependence of the star formation rates (SFRs) for these member galaxies. As we expect, a tight correlation between the SFR normalized by stellar mass (SFR/M_*) and the $H\alpha$ equivalent width is found for the late-type galaxies in A2255. The correlation of SFR/M_* with the continuum break strength at 4000 \AA is also confirmed. A SFR/M_*-M_* correlation is found for both early- and late-type galaxies, indicating that the star formation activity tends to be suppressed when the assembled stellar mass (M_*) increases, and this correlation is tighter and steeper for the late-type cluster galaxies. Compared with the mass range of field spiral galaxies, only two massive late-type galaxies with $M_* > 10^{11} M_\odot$ have survived in A2255, suggesting that the gas disks of massive spiral galaxies could have been tidally stripped during cluster formation. In addition, the SFR variation with the projected radial distance is found to be heavily dependent on galaxy morphology: the early-type galaxies have a very weak inner decrease in SFR/M_* , while the inner late-type galaxies tend to have higher SFR/M_* values than the outer late-type galaxies. This may suggest that the galaxy-scale turbulence stimulated by the merging of subclusters might have played different roles in early- and late-type galaxies, which leads to a suppression of the star formation activity for E/S0 galaxies and an SFR enhancement for spiral and irregular galaxies.

Key words: galaxies: clusters: individual (Abell 2255) — galaxies: evolution — stars: formation

Online material: color figures

1. INTRODUCTION

To study the star formation history of the universe is one of the major tasks of extragalactic astronomy. The current star formation rates (SFRs) of galaxies and the variation with morphology, environment, and some galactic physical properties are crucial in our understanding of the evolution of galaxies (Kennicutt 1998; Brinchmann et al. 2004b). Some studies show that galaxy-scale turbulence plays a key role in star formation of galaxies (e.g., Mac Low & Klessen 2004 and references therein). However, the origin and consequence of this turbulence are still unclear; it is reasonable to expect that the star formation activity should be a function of many variables. A large number of investigations focus on finding the possible correlations of the SFRs of galaxies with some global quantities, such as stellar mass (Kauffman et al. 2003a, 2003b), morphological classification (Kennicutt et al. 1994; Kennicutt 1983, 1998), metallicity (Brinchmann et al. 2004b; Tremonti et al. 2004), luminosity (e.g., Bell 2003), and redshift (Butcher & Oemler 1984; Finn et al. 2004).

It is widely accepted that the above-mentioned physical properties of galaxies are fundamentally linked with their gravitational environment (e.g., Dressler 1980; Butcher & Oemler 1984). Of great concern is whether the star formation properties of cluster galaxies are similar to those of field galaxies. The star formation rates (SFRs) for nearby galaxies ($z < 0.3$) are estimated by many investigators with traditional $H\alpha$ spectroscopy (Kennicutt 1983). The main advantages of this approach are direct measurements of the ionizing flux from young stars and a greater insen-

sitivity to extinction than for $[O \text{ II}]$ measurements. Based on the $H\alpha$ data, Kennicutt (1983) and Kennicutt et al. (1984) study four nearby clusters and find that cluster and field spiral galaxies with the same morphological type have similar SFRs in three of four clusters. However, a difference between field and cluster spiral galaxies is found by Moss & Whittle (1993), and such a difference is likely to depend on morphology (Moss & Whittle 2000).

The SFRs in late-type galaxies are found to be closely related to their gas content (Kennicutt 1998). To look at which environmental processes have actually affected the gas content of the spiral galaxies within a nearby cluster, Koopmann & Kenney (2004) compare the $H\alpha$ morphologies of the spiral galaxies in the Virgo Cluster with those of isolated field spiral galaxies and find that about half the Virgo spiral galaxies have truncated $H\alpha$ disks. Considering that the truncated $H\alpha$ disks are relatively rare in isolated spiral galaxies, this result suggests that many Virgo spiral galaxies could have experienced intracluster medium (ICM)–interstellar medium (ISM) stripping and significant tidal effects. Gavazzi et al. (2002) investigate the star formation properties as a function of the clustercentric projected distance for 369 late-type galaxies in the Virgo, Coma, and Abell 1367 clusters, and they find that the bright spiral galaxies in the Virgo Cluster tend to have their SFRs decreasing inward and that the fainter late-type galaxies show no, or the opposite, trend. In addition, convincing evidence of the star formation suppression of the cluster galaxies has been found in some rich clusters with higher redshifts (Couch et al. 2001; Balogh & Morris 2000; Balogh et al. 2002; Finn et al. 2004).

This paper explores the properties of star formation for the merging cluster of galaxies A2255, which is covered by the Sloan Digital Sky Survey (SDSS) and the Beijing-Arizona-Taiwan-Connecticut (BATC) multicolor photometric survey. There are

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132 early-type and 52 late-type galaxies in this cluster with absolute magnitudes in the SDSS r band (M_r) brighter than -20.0 , which provides a good sample for studying the SFR variation of cluster galaxies with morphology and projected radial distance. Another main motivation of this study is to find possible links among the physical properties of cluster galaxies. For a better understanding of the environmental effects of the star formation properties of galaxies at different evolutionary stages, it is illuminating to compare our results with those of field galaxies and high- z cluster galaxies.

We start in § 2 with describing the relevant physical parameters for the galaxies in A2255. The star formation properties for these cluster galaxies, as a function of other physical parameters, are shown in § 3. We then compare the properties with nearby field galaxies and high- z cluster galaxies and discuss the implications in § 4. Finally, the conclusions are given in § 5. A Friedmann-Robertson-Walker cosmology with $(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is assumed throughout this paper.

2. PHYSICAL PARAMETERS FOR CLUSTER GALAXIES

A2255 is a cluster of galaxies with an intermediate redshift of $z = 0.0806$ (Struble & Rood 1999, giving a distance modulus of 37.8), and richness class 2 (Abell 1958). Using the data from the SDSS Data Release 2 (DR2) and the BATC multicolor photometric survey, we have explored the color-magnitude relation, luminosity function, and dynamics of the member galaxies, and direct dynamical evidence for an ongoing merger has been found for this cluster (Yuan et al. 2003).

The SDSS aims at targeting 10^6 galaxies with r -band magnitude $r < 17.77$ for spectroscopy (Strauss et al. 2002). Based on a large sample of spectroscopically confirmed galaxies provided by the SDSS DR2 (Abazajian et al. 2004) and the new models of stellar population synthesis (Bruzual & Charlot 2003; Charlot et al. 2002; Charlot & Longhetti 2001), Brinchmann et al. (2004a) have derived and compiled the physical quantities concerning the star formation properties for more than 2×10^5 galaxies, including stellar mass, current SFRs, gas-phase metallicity, absorption-line indices, and emission-line measurements.

The parameters relevant to this work are estimated mainly by the following investigations: (1) Kauffmann et al. (2003a, 2003b) developed a method to constrain the star formation history, dust attenuation, and stellar mass (M_*) of the specified galaxy on the basis on the continuum break at 4000 \AA (D_n) and the $H\delta$ absorption line. The strength of the continuum break at 4000 \AA is a prominent feature in galaxy spectra, resulting from a large number of metal lines. This can be treated as a powerful age estimator since the young and hot stellar populations show a very weak 4000 \AA break. The strength of the continuum break is also defined in Tremonti et al. (2004). (2) Brinchmann et al. (2004b) make use of the methodology in Charlot et al. (2002) and the emission-line models in Charlot & Longhetti (2001) to derive the SFRs inside the fiber aperture. The total SFRs in the galaxies are then derived by the aperture correction.

We select all the SDSS galaxies with $14.5 < r < 17.77$ in the BATC-targeting sky region of $59' \times 59'$, defined by a right ascension range from $17^{\text{h}}08^{\text{m}}03^{\text{s}}.7$ to $17^{\text{h}}16^{\text{m}}58^{\text{s}}.6$, and a declination range from $63^\circ 36' 31''.5$ to $64^\circ 35' 28''.8$ (J2000.0) (Yuan et al. 2003). As a result, we obtain 184 spectroscopically confirmed member galaxies with $0.070 < z < 0.097$, of which the physical properties are publicly released by Brinchmann et al. (2004a).³ The completeness of this sample reaches at least 90% down to an

r -band absolute magnitude (M_r) of ~ -20.0 . This should be an ideal sample for investigating the star formation properties of the galaxies within a merging cluster at intermediate redshift.

3. RESULTS

3.1. Morphological Classification

In order to classify the cluster galaxies into early- and late-type galaxies, we have collected their SDSS imaging and spectral data, as well as some photometric parameters relevant to the morphology, such as the likelihoods for radial profile fitting with the de Vaucouleurs (1948) $r^{1/4}$ model (L_{dev}) and the exponential model (L_{exp}); the concentration index characterized by the ratio between two galaxy radii that contain 90% and 50% of the Petrosian flux, respectively ($R_{p,90}/R_{p,50}$); the color index ($u-r$); and the continuum break strength at 4000 \AA (D_n).

Although the concentration index and fitting likelihoods parameterize the light profiles of galaxies, visual inspection should be the most straightforward way for finding some morphological characteristics (e.g., spiral arms, bars, rings, and dust lanes). For a secure morphological classification, it is important to directly inspect the SDSS images of galaxies. For about half the galaxies in A2255, visual classification is quite accurate. It can be understood that the regular elliptical galaxies have $L_{\text{dev}} \gg L_{\text{exp}}$ and/or $R_{p,90}/R_{p,50} > 2.6$, while the disk-dominated spiral galaxies have $L_{\text{exp}} \gg L_{\text{dev}}$ and/or $R_{p,90}/R_{p,50} < 2.5$. For the galaxies with a significant likelihood difference (i.e., $|\ln L_{\text{dev}} - \ln L_{\text{exp}}| > 150$) and with one of the profile-fitting likelihoods greater than e^{-75} , it is completely unambiguous to classify the galaxies with larger L_{dev} as early-type galaxies and those with larger L_{exp} as late-type galaxies.

Nevertheless, the spatial resolution ($0''.396 \text{ pixel}^{-1}$) of the SDSS images is not high enough for a secure classification of some faint galaxies. Furthermore, some late-type bulge-dominated (Sa–Sb) galaxies are likely to be misclassified because their light profiles cannot be distinguished from those of early-type galaxies (Scodreggio et al. 2002). The template spectra of nearby normal galaxies (Kennicutt 1992) show that the Sa–Sb spiral galaxies usually have a weak $H\alpha$ emission feature, which should be present in their SDSS spectra ($R = 1800$). Therefore, it is necessary to inspect the spectral feature for further classification, particularly for the galaxies with low fitting likelihoods for both profile models. For easy comparison with the spectrophotometric atlas of nearby normal and peculiar galaxies with known morphologies (Kennicutt 1992), we transform the SDSS spectra to the rest frame defined by the given redshifts and then normalize the spectra by the flux at rest-frame wavelength 5500 \AA . For the majority of cluster galaxies, the spectral classification into early- and late-type galaxies is unambiguous, and their images and relevant morphological parameters (i.e., L_{exp} , L_{dev} , and $R_{p,90}/R_{p,50}$) are consistent with each other. For a small number of ambiguous cases in the S0/Sa separation, we classify the galaxies with $H\alpha$ equivalent widths (EWs) greater than 1.0 \AA as late-type galaxies.

Finally, we obtain 132 early-type galaxies and 52 late-type galaxies in A2255. It should be noted that there are five early-type galaxies with strong emission lines [i.e., $\text{EW}(H\alpha) > 5 \text{ \AA}$] in our sample. Their morphologically relevant parameters are given in Table 1. According to the diagnostics of the emission lines in the spectra (Baldwin et al. 1981), four of these five early-type galaxies are found to be active galactic nuclei (AGNs), and one is a star-forming (SF) galaxy.

The criterion of $R_{p,90}/R_{p,50} > 2.6$ is adopted by many investigators (e.g., Shimasaku et al. 2001; Padmanabhan et al. 2004) for selecting elliptical galaxies. In addition, Kauffmann et al.

³ See <http://www.mpa-garching.mpg.de/SDSS>.

TABLE 1
FIVE EARLY-TYPE GALAXIES WITH STRONG EMISSION LINES

Object Name	r	$\ln L_{\text{dev}}$	$\ln L_{\text{exp}}$	$R_{p,90}/R_{p,50}$	D_n	Remarks ^a
SDSS J171315.45+642418.3.....	17.0	-10.744	-263.037	2.573	1.4729	SF Galaxy
SDSS J171429.16+641656.3.....	16.6	-71.789	-369.118	2.367	1.4852	BLAGN
SDSS J171221.14+643418.1.....	17.2	-0.666	-188.854	2.498	1.4749	NLAGN
SDSS J171302.13+634758.8.....	17.3	-0.038	-223.167	2.842	1.6238	NLAGN
SDSS J171052.51+633917.2.....	16.3	-74.485	-1529.74	2.872	1.6591	AGN (LINER)

NOTE.—EW(H α) > 5 Å.

^a SF = star-forming; BLAGN = broad-line AGN; NLAGN = narrow-line AGN; LINER = low-ionization nuclear emission-line region.

(2003a) use a cut of $D_n > 1.6$ to pick up elliptical galaxies. It is interesting to check the efficiency of these morphology classification criteria. Figure 1 shows the continuum break strengths (D_n) of the galaxies in A2255 as a function of the radius ratios ($R_{p,90}/R_{p,50}$). The early-type galaxies are denoted with filled circles, while the late-type galaxies are shown by open circles. Two criteria used in the literature are also marked in Figure 1. It can be easily seen that D_n is a better morphology indicator for the nearby cluster galaxies. With the criterion $D_n > 1.6$, we can pick up 128 (~97% of 132) early-type galaxies, and 12 late-type galaxies are misclassified as early types. However, if we simply adopt $R_{p,90}/R_{p,50} > 2.6$ to construct a sample of the early-type galaxies in A2255, nearly 30% of the early-type galaxies will be lost.

It should be pointed out that the $R_{p,90}/R_{p,50}$ - D_n relation is heavily dependent on the gravitational environment. The slope at which D_n increases with $R_{p,90}/R_{p,50}$ tends to be flat for the galaxies in low-density regions (see Fig. 7 in Kauffmann et al. 2004). Therefore, for selecting the field elliptical galaxies, the concentration parameter $R_{p,90}/R_{p,50}$ becomes more effective than the continuum break strength D_n . Both criteria are used by Shimasaku et al. (2001) to ensure their sampling of elliptical galaxies from the SDSS galaxies.

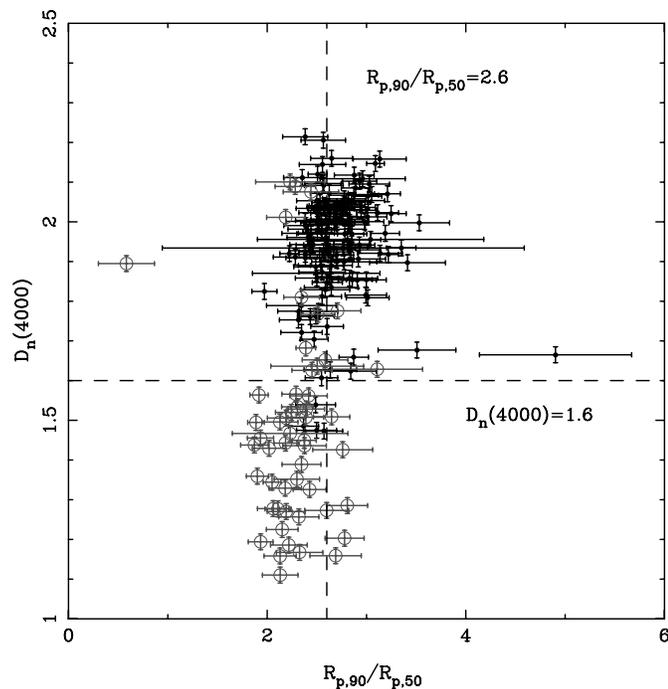


FIG. 1.—Continuum break strengths (D_n) at 4000 Å as a function of the radius ratios ($R_{p,90}/R_{p,50}$) for 132 early-type galaxies (filled circles) and 52 late-type galaxies (open circles) in A2255. [See the electronic edition of the Journal for a color version of this figure.]

3.2. The SFR Tracers

There are different indicators of galaxy SFR at different wavelengths. In the optical band, the traditional SFR calibration uses the H α emission-line luminosity. The [O II] emission is also an important tool for estimating current SFRs for galaxies with $z > 0.5$ (Kennicutt 1998), which is based on the fact that there is a good correlation between observed [O II] line fluxes and observed H α fluxes (i.e., prior to any obscuration corrections). Kennicutt (1992) sets up the SFR calibration with the [O II] fluxes by using a sample of 90 nearby ($z < 0.03$) galaxies and obtains the empirical ratio EW([O II])/EW(H α + [N II]) = 0.4.

To avoid the additional uncertainties produced by the aperture corrections of the emission-line fluxes, we sketchily observe the correlation between the EWs of these two lines. For comparison, we give the plot of the [O II] EWs versus the composite EWs of H α + [N II] for 184 member galaxies in Figure 2. Kennicutt's relation (solid line, Fig. 2) can be used to fit the EW correlation for 184 A2255 galaxies very well. Jansen et al. (2001) point out that the flux ratio [O II]/H α should be luminosity and metallicity dependent. Therefore, the appropriate flux ratio should be influenced by the selection effects of the various samples of galaxies.

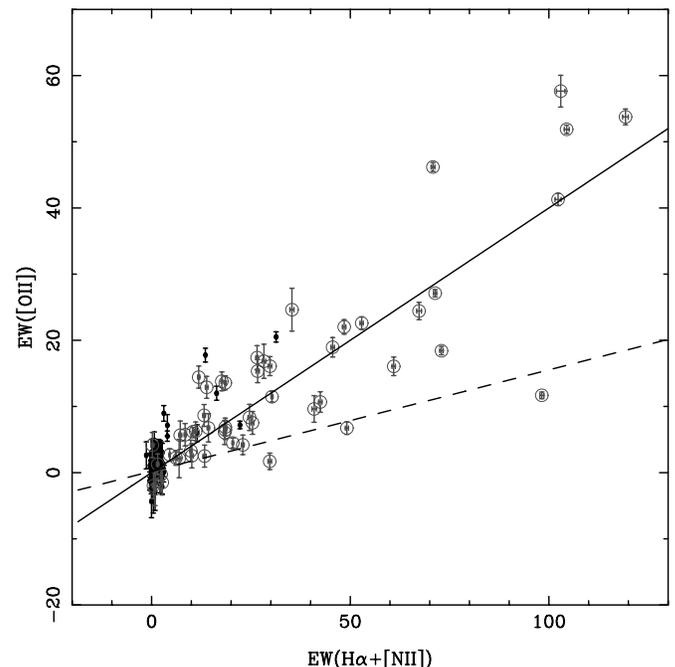


FIG. 2.—Correlation between the EWs of the composite line H α + [N II] and the [O II] line. Symbols are the same as in Fig. 1. The solid line corresponds to the observed ratio EW([O II])/EW(H α + [N II]) = 0.4 (from Kennicutt 1992), and the dashed line represents the line flux ratio [O II]/H α = 0.23 (from Hopkins et al. 2003), if we assume [N II]/H α = 0.5 (Kennicutt 1992). [See the electronic edition of the Journal for a color version of this figure.]

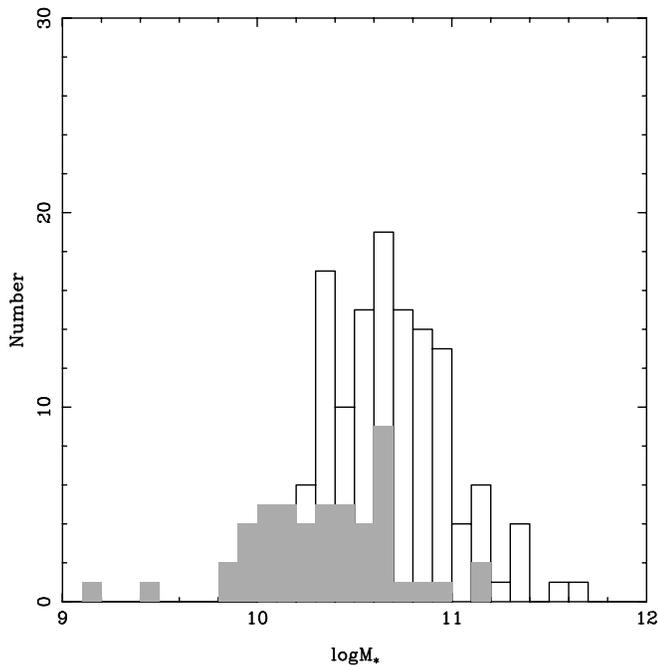


FIG. 3.—Distribution of the stellar masses for 132 early-type galaxies (*open histogram*) and 52 late-type galaxies (*filled histogram*).

The median flux ratio $[\text{O II}]/\text{H}\alpha = 0.23$ is derived by Hopkins et al. (2003) with a sample of 752 SDSS SF galaxies. Our result does not coincide with this flux ratio, denoted with a dashed line in Figure 2, when $[\text{N II}]/\text{H}\alpha = 0.5$ (Kennicutt 1992) is assumed. This is probably because our sample only contains the cluster galaxies that are predominately early-type galaxies.

3.3. The SFR Variation with Morphology

Figure 3 shows the distributions of the stellar masses (M_*) for the early-type galaxies (*open histogram*) and the late-type galaxies (*filled histogram*). The early-type galaxies occupy a broader range (i.e., more than 2 orders of magnitude) in stellar mass, while the late-type galaxies cover a range of about 1 order of magnitude. We can find a significant trend toward old stellar populations for the galaxies with larger stellar masses. The typical stellar mass of the late-type galaxies is ~ 0.4 dex lower than that of the early-type galaxies. This histogram supports the finding by Kauffmann et al. (2003b) that there is a rapidly increasing fraction of galaxies with old stellar populations for the massive galaxies with $M_* > 3 \times 10^{10} M_\odot$. In our sample there are only two late-type cluster galaxies with stellar masses larger than $10^{11} M_\odot$.

The *specific SFR*, defined as SFR/M_* , is a key parameter for measuring the rate at which new stars add to the assembled mass of a galaxy. It is common to use this SFR normalized by stellar mass to investigate the relationship between the star formation activity and the physical properties (e.g., Brinchmann & Ellis 2000). Brinchmann et al. (2004b) find a strong correlation between the SFR and stellar mass over a significant range in M_* , from 3×10^6 to $10^{10} M_\odot$ (see Fig. 17 therein). Figure 3 shows that a vast majority of the galaxies in A2255 have stellar masses larger than $10^{10} M_\odot$, so the SFR- M_* correlation breaks down for our sample.

Since the EW is defined as the emission-line luminosity normalized to the adjacent continuum flux, the EW of the $\text{H}\alpha$ emission line is also a direct measure of the SFR per unit red luminosity (Kennicutt 1998). It can be expected that there should be a tight correlation between the $\text{H}\alpha$ EW and SFR/M_* , when a fixed mass-

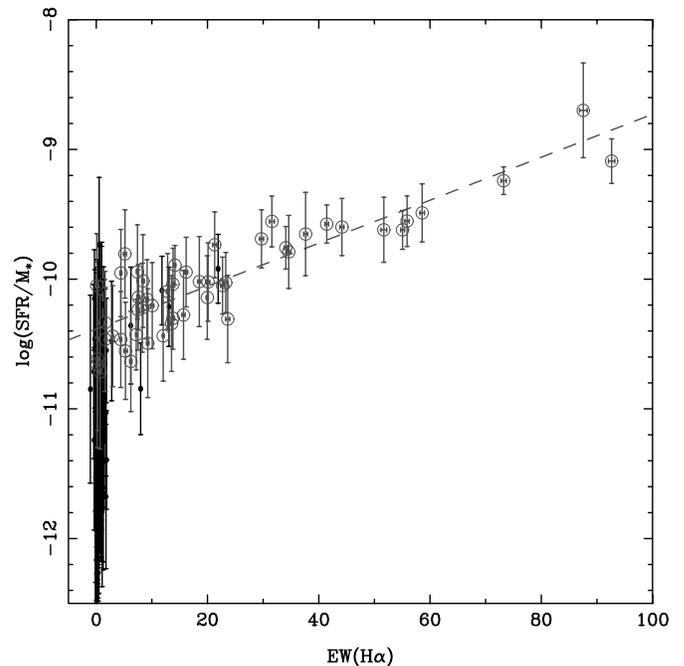


FIG. 4.—Relation between the specific SFR (SFR/M_*) and the EW of the $\text{H}\alpha$ emission line for 132 early-type galaxies (*filled circles*) and 52 late-type galaxies (*open circles*) in A2255. The dashed line represents a linear fit for the late-type galaxies only. [See the electronic edition of the Journal for a color version of this figure.]

to-luminosity ratio is assumed for the late-type galaxies. This SFR/M_* - $\text{EW}(\text{H}\alpha)$ correlation is evident in Figure 4. A linear fitting is performed for the late-type galaxies with a wide range of $\text{H}\alpha$ EWs, and we obtain $\log(\text{SFR}/M_*) = (0.017 \pm 0.001) \text{EW}(\text{H}\alpha) - 10.385 \pm 0.041$. This correlation is so tight that its correlation coefficient reaches 0.877, and the rms dispersion in $\log(\text{SFR}/M_*)$ is 0.20. Meanwhile, this correlation demonstrates the reliability of the specific SFRs derived by Brinchmann et al. (2004b) and Kauffmann et al. (2003a, 2003b).

Figure 5 shows the relation between the *specific SFR* and the stellar mass for the galaxies in A2255. The late-type galaxies tend to have higher SFR/M_* values than the early-type galaxies. Most of the early-type galaxies have a lower fraction of newly formed stellar mass, with respect to their large assembled masses. The early-type galaxies in A2255 cover a range from 10^{-12} to 10^{-10} in the SFR/M_* domain, and the specific SFRs decline slightly when their stellar masses grow. The weak SFR/M_* - M_* correlation can be expressed by a linear fit of $\log(\text{SFR}/M_*) = (-0.23 \pm 0.15) \log M_* - 8.61 \pm 1.59$, which is shown in Figure 5 with the dotted line. The correlation coefficient is only -0.135 , and the rms dispersion of $\log(\text{SFR}/M_*)$ is 0.52. For the late-type galaxies, however, one can see a clear trend that the star formation activity decreases when the stellar mass increases (*dashed line*), with a linear fit of $\log(\text{SFR}/M_*) = (-0.71 \pm 0.12) \log M_* - 2.65 \pm 1.27$. The correlation coefficient is -0.639 , and the rms dispersion is 0.33. Note that there is a significant difference between the slopes of these two relations, and its implication is addressed in § 4.

Brinchmann et al. (2004b) find a tight correlation between the specific SFR (SFR/M_*) and the 4000 Å break strength (D_n) for the SDSS SF galaxies with signal-to-noise ratio $\text{S/N} > 3$ in the emission lines $\text{H}\alpha$, $\text{H}\beta$, $[\text{O III}]$, and $[\text{N II}]$. Because the SF galaxies with strong emission lines become rare in the rich clusters, this correlation has been extended to the non-SF galaxies for estimating the specific SFRs. We plot the relation between SFR/M_*

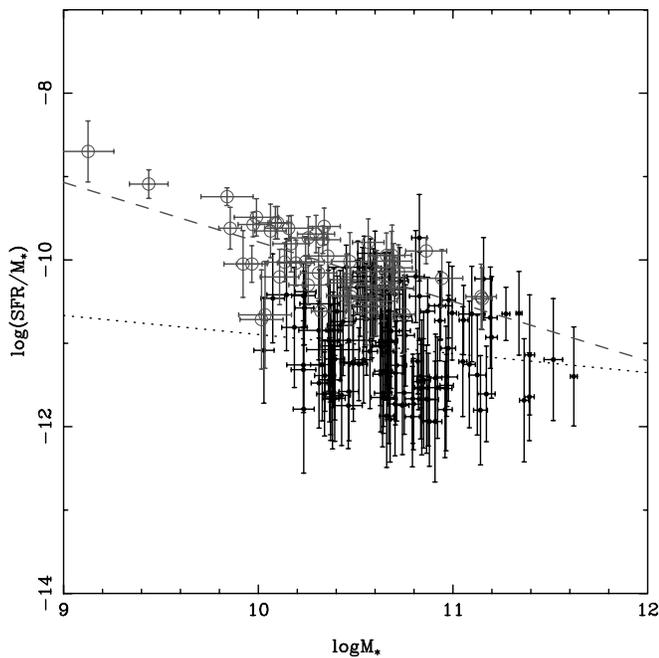


FIG. 5.—Relation between the specific SFR (SFR/M_*) and the stellar masses (M_*) for 132 early-type galaxies (*filled circles*) and 52 late-type galaxies (*open circles*) in A2255. [See the electronic edition of the *Journal* for a color version of this figure.]

and D_n for the galaxies in A2255 in Figure 6. A very tight correlation can be easily found for the late-type galaxies (*open circles*) with smaller continuum break strengths. A linear fitting is given for the late-type galaxies, with an expression of $\log(SFR/M_*) = (-1.59 \pm 0.16) \log M_* - 7.70 \pm 0.23$ (*dashed line*). The correlation coefficient is -0.825 , and the rms dispersion is 0.24.

The SFR/M_*-D_n correlation is weak for the early-type galaxies, with a larger rms dispersion of 0.49 and a similar slope of -1.24 ± 0.30 . The continuum break strengths for the majority

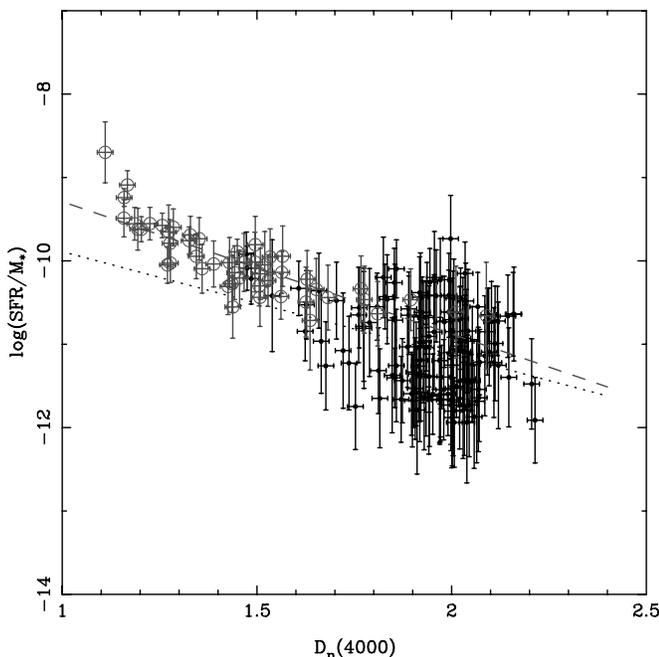


FIG. 6.—Relation between the specific SFR (SFR/M_*) and the continuum break strength (D_n) at 4000 Å. Notation is the same as in Fig. 1. [See the electronic edition of the *Journal* for a color version of this figure.]

of early-type galaxies are greater than 1.6. The distribution in the SFR/M_*-D_n space for the early-type galaxies in A2255 is in good accordance with the contour map shown in Figure 11 of Brinchmann et al. (2004b), suggesting that the majority of the SDSS SF galaxies with a strong continuum break at 4000 Å are early-type galaxies within a dense environment.

3.4. The Radial Distribution of SFR/M_*

The star formation properties are fundamentally related to the local environment. It is interesting to observe how the star formation activities of the galaxies in a cluster vary with the distances to the cluster center. Figure 7 shows the SFR normalized by stellar mass as a function of projected distance (R) to the cluster center. We adopt the center of A2255 as $17^h 12^m 31^s, +64^\circ 05' 33''$ (J2000.0), which is given by the NASA/IPAC Extragalactic Database (NED).

At first glance, the striking feature in Figure 7 is that the cluster galaxies with various morphologies have significantly different tendencies about how the specific SFRs vary with the locations. For the early-type galaxies, there is a very weak trend that the inner galaxies have lower SFR/M_* values, with a linear fit of $\log(SFR/M_*) = (0.05 \pm 0.07)R(\text{Mpc}) - 11.10 \pm 0.09$. The corresponding correlation coefficient is 0.058, and the rms dispersion of $\log(SFR/M_*)$ is 0.522. This trend suggests a slight suppression of the star formation activity when these cluster galaxies become massive and concentrated. The inner early-type galaxies might have a higher probability to be near the endpoint of their star formation activities when the internal gas reservoir has run out.

As a sharp contrast, the late-type galaxies follow a clear trend that the inner galaxies have a higher rate of mass supplemented from new stars (relative to the assembled stellar mass). The correlation between SFR/M_* and the projected radial distance R is more significant for the late-type galaxies. We obtain a linear fit of $\log(SFR/M_*) = (-0.17 \pm 0.07)R(\text{Mpc}) - 9.79 \pm 0.12$.

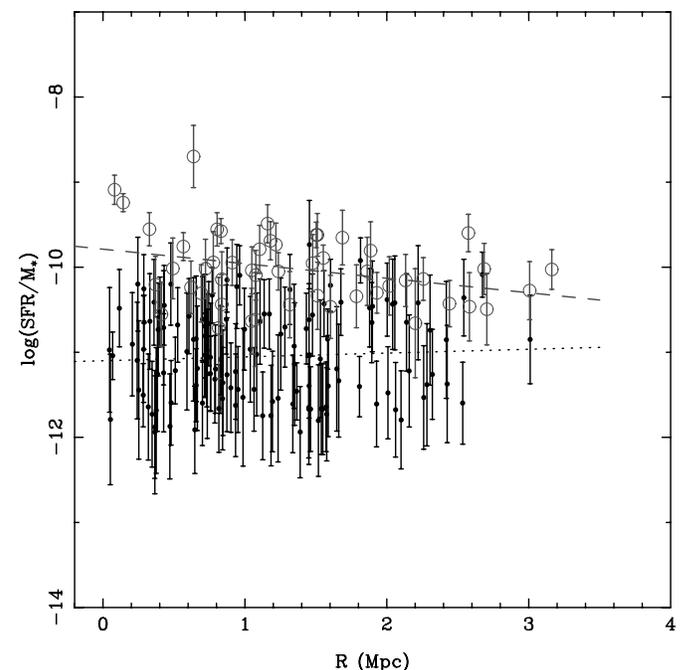


FIG. 7.—Specific SFR (SFR/M_*) as a function of the distance to the cluster center for the early-type galaxies (*filled circles*) and the late-type galaxies (*open circles*) in A2255. [See the electronic edition of the *Journal* for a color version of this figure.]

Its correlation coefficient is -0.492 , and the rms dispersion in $\log(\text{SFR}/M_*)$ is 0.392 . The different behaviors in radial distribution of the specific SFRs between the early- and late-type galaxies in A2255 might indicate that the galaxy-scale turbulence has played different roles on the star formation process for different types of galaxies, which leads to a suppression of the star formation activity for E/S0 galaxies and a SFR enhancement for spiral and irregular galaxies.

4. DISCUSSION

A2255 is a merging cluster with an intermediate redshift ($z = 0.0806$), which provides an ideal laboratory for studying the SFR variation of the galaxies within a merging cluster with morphology and projected radial distance. There are 52 late-type cluster galaxies with r -band absolute magnitude brighter than -20.0 . On the one hand, the rich clusters with smaller redshifts are expected to have a smaller number of blue late-type member galaxies in the cluster cores (Butcher & Oemler 1984). On the other hand, for the rich clusters with higher redshifts, many late-type member galaxies will be fainter than $r = 17.77$ and thus beyond the limit of SDSS spectroscopy.

According to the hierarchical model of large-scale structure formation in the cold dark matter scenario, clusters grow in mass by accreting galaxies from the surrounding field. After the galaxies are integrated into a dense environment (e.g., a cluster of galaxies), further star formation activity within the galaxies is expected to be suppressed by some important processes, such as tidal stripping and “harassment” (Moore et al. 1996), ram pressure stripping of the gas disk (Abadi et al. 1999; Quilis et al. 2000), and removal of the gas reservoir surrounding each galaxy (Balogh et al. 2002). These galaxies then evolve to be early-type galaxies, with red color and little gas. This hierarchical model can be used to interpret why a higher fraction of the early-type galaxies appear in nearby galaxy clusters rather than in the high- z clusters and in the field (Dressler 1980; Whitmore et al. 1993).

The correlation between SFR/M_* and stellar mass (M_*) has been found for both the early- and late-type galaxies in A2255, with a trend that the star formation activity declines as the assembled stellar mass increases. Brinchmann & Ellis (2000) constructed a sample of 321 field galaxies with known morphologies in a large redshift range of $0 < z < 1$ and found the same trend for both E/S0 and spiral disk galaxies. This SFR/M_*-M_* correlation can be extended to some *dwarf* early-type galaxies in the field (with $M_* < 3 \times 10^9 M_\odot$), and the slope for early-type *disk* galaxies (-1.19) is much steeper than that for the E/S0 galaxies in A2255 (-0.23 ± 0.15). The late-type galaxies in a cluster seem to have a similar behavior in the SFR/M_*-M_* relation as compared with the field spiral and peculiar galaxies. It should be noted that only two massive late-type galaxies (i.e., $M_* > 10^{11} M_\odot$) survived in A2255, which might indicate that the massive late-type galaxies have a greater probability for colliding with other galaxies as they are falling into a cluster and that their gas disks could be tidally stripped. Considering the fact that about half the spiral galaxies in the Virgo Cluster show truncated $H\alpha$ disks (Koopmann & Kenney 2004), a certain fraction of the late-type galaxies in A2255 might have also experienced ICM-ISM stripping and strong tidal interaction. As a result, some massive spiral galaxies have ended their star formation activity and then evolved into early-type galaxies.

The correlation between the SFR/M_* and the projected radial distance R is found marginally for the early-type galaxies in A2255. This slight trend of an inner decrease in their specific SFRs can be easily interpreted with the hierarchical model: once the galaxies enter the denser environment (i.e., the core region of

a cluster), their star formation activities are reduced by the above-mentioned physical processes, and their appearances tend to become more concentrated. However, some spiral/irregular galaxies in A2255 have survived those processes, which means that the overall cluster tidal field or high-speed “harassment” interaction between galaxies should have not stripped their gas disks during the formation of this cluster (via accreting and merging of subunits). Of great interest is that these late-type galaxies are found to possess a contrary trend in that the inner late-type galaxies are likely to have more violent star formation activities.

Is the morphological dependence of the SFR/M_*-R relation universal for galaxies in rich clusters? This tendency has also been found in some nearby and high- z clusters of galaxies. Moss & Whittle (2000) use an objective-prism technique to survey the $H\alpha$ emission from late-type galaxies in the regions of eight nearby Abell clusters ($z < 0.024$), and they find that the frequency of starburst emission in spiral galaxies increases from the regions of lower to higher local galaxy density. For the nearby galaxy cluster A1367 at $z = 0.0214$, a much larger fraction of spiral galaxies are detected with compact $H\alpha$ emission in the cluster core region (Moss et al. 1998). A similar radial distribution of the SFRs is found for the high- z galaxy cluster CLJ 0023+0423B ($z = 0.84$); a high fraction of late-type galaxies (characterized by the small index given by Sérsic profile fittings) with strong $H\alpha$ emission are found in the cluster core (Finn et al. 2004). The radial trend of the SFR distribution for late-type galaxies in the Virgo, Coma, and A1367 clusters is studied by Gavazzi et al. (2002), and no clear trend is found for these three local clusters. Only the sample of bright Virgo galaxies shows an inner decrease in SFR, which is inconsistent with our finding for the late-type galaxies in A2255.

What physical processes may lead to an enhancement of star formation activity for the inner late-type galaxies? This question is important for understanding the evolution of cluster galaxies. Lavery & Henry (1994) first proposed that the star formation can be triggered by galaxy-galaxy interactions in clusters with intermediate redshifts, which could be used to explain why the fraction of blue galaxies in cluster cores increases with redshift (Butcher & Oemler 1984). Numerical simulations by Gnedin (1999) have shown that a time-varying cluster potential could cause a sequence of strong tidal shocks on individual galaxies. The shocks would probably take place over a wide region of the cluster and enhance the galaxy-galaxy merger rates. The tidal perturbation in a short range may lead to a triggering of star formation.

Recent observations from the radio (e.g., Feretti et al. 1997; Miller & Owen 2003) and X-ray bands (Burns et al. 1995; Davis & White 1998) show some features indicative of an ongoing merger event in A2255. Based on dynamical analysis of the member galaxies, we also find direct evidence that A2255 possesses a cluster/group merger (Yuan et al. 2003). An ordered magnetic field on large scales was recently detected in A2255 by Govoni et al. (2005), which strongly supports the merging scenario. We would like to point out that the subcluster mergers might be the main mechanism for driving a time-varying cluster potential and an accelerated rate of galaxy-galaxy mergers, which may have played different roles in the star formation activities for present-day early- and late-type galaxies in A2255. It is worthwhile to carry out similar studies to check this effect with large and complete samples of galaxies in clusters at different stages of dynamical evolution.

5. CONCLUSION

On the basis of the physical parameters derived by Brinchmann et al. (2004a) for the SDSS galaxies, this paper explores the star formation properties of the galaxies in A2255, a merging cluster

of galaxies with the intermediate redshift of 0.0806. The main conclusions can be summarized as follows:

1. The continuum break strength at 4000 Å (D_n) is a better morphology indicator for the *cluster* galaxies. For selecting the early-type galaxies in high-density regions, the criterion $D_n > 1.6$ is more effective than the concentration parameter $R_{p,90}/R_{p,50}$.
2. For the late-type galaxies in A2255, a strong correlation between the EW of the H α emission line and the SFR normalized by stellar mass is confirmed. This correlation demonstrates the reliability of the SFRs and stellar mass estimates derived from the SDSS spectral data.
3. We have investigated the specific SFRs for the early- and late-type galaxies in A2255 as a function of stellar mass (M_*) and continuum break strength at 4000 Å (D_n). Generally speaking, the early-type member galaxies have lower SFRs per unit stellar mass than the late-type galaxies do. Only two massive late-type galaxies (with $M_* > 10^{11} M_\odot$) are found in A2255. The late-type galaxies possess tighter correlations of SFR/ M_* with the assembled stellar mass (M_*) and the continuum break strength (D_n).

4. We have observed the morphological dependence in radial distribution of the specific SFRs. The E/S0 galaxies are likely to have an inner decrease in their star formation activities. On the contrary, the inner late-type galaxies tend to have more violent star formation activities. The merging scenario might be the main mechanism for leading to different influences on the star formation activities of present-day early- and late-type galaxies in A2255.

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