ANOMALOUS STAR FORMATION ACTIVITY OF LESS-LUMINOUS GALAXIES IN A CLUSTER ENVIRONMENT

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ABSTRACT

We discuss a correlation between the star formation activity (SFA) and the luminosity of star-forming galaxies at intermediate redshifts of $0.2 \leq z \leq 0.6$ in both cluster and field environments. The equivalent width (EW) of $[\text{O II}]$ is used for the measurement of SFA, and the $R$-band absolute magnitude, $M_R$, is used for the measurement of luminosity. In less-luminous ($M_R \approx -20.7$) galaxies, we find (1) the mean EW ($[\text{O II}]$) of cluster galaxies is smaller than that of field galaxies but that (2) some cluster galaxies have as large EWs ($[\text{O II}]$) as that of actively star-forming field galaxies. Based on both of these results, we discuss a new possible mechanism for the Butcher-Oemler (BO) effect, assuming that the luminosity of a galaxy is proportional to its dynamical mass. Our proposal is that BO galaxies are less-massive cluster galaxies with smaller peculiar velocities. They are then stable against Kelvin-Helmholtz instability (KHI) and are not affected by the tidal interaction between clusters and themselves. Their interstellar medium (ISM) would hardly be stripped, and their SFA would be little suppressed. Hence, as long as such galaxies keep up their SFA, the fraction of blue galaxies in a cluster does not decrease. As a cluster becomes virialized, however, such galaxies become more accelerated, the ISM available for SFA is stripped by KHI, and their color evolves redward, which produces the BO effect.

Subject headings: galaxies: clusters: general — stars: formation

1. INTRODUCTION

The Butcher-Oemler (BO) effect is the first observational evidence of the evolution of galaxy populations. It shows that clusters at redshifts higher than 0.2 have a higher fraction of blue galaxies than that of local clusters (Butcher & Oemler 1978, 1984). In the last decade, Hubble Space Telescope images have revealed that such blue galaxies, which are recognized as BO galaxies, are predominantly normal late-type spiral galaxies (e.g., Dressler et al. 1994; Couch et al. 1994, 1998).

According to numerical and analytical studies, a dynamical interaction between a cluster and its galaxies has been proposed as a mechanism for the BO effect. Because of this interaction, late-type spiral galaxies lose and/or consume their interstellar medium (ISM), and then their star formation activity (SFA) is suppressed during their infall into the higher density regions of a cluster. Their color evolves redward, and the fraction of BO galaxies in the cluster decreases (e.g., Gunn & Gott 1972; Sarazin 1986; Kodama & Bower 2001; Abadi, Moore, & Bower 1999; Quilis, Moore, & Bower 2000; Mori & Burkert 2000; Balogh, Navarro, & Morris 2000). Indeed, many observations have revealed that BO galaxies lie preferentially in the lower density regions of clusters (Butcher & Oemler 1984; van Dokkum et al. 2000; Balogh et al. 1999). Thus, observational results seem consistent with the current theoretical picture.

The above studies predict that there should be a difference between the mean SFA of clusters and that of field galaxies at intermediate redshifts of $0.2 \leq z \leq 0.6$. Furthermore, such a difference should be more evident in less-luminous (i.e., less-massive) galaxies, which have shallower gravitational potential wells and are more environmentally affected. This trend, however, has not been observationally confirmed since previous papers focused primarily on the morphology of galaxies at the redshifts. In this Letter, we present a statistical investigation of the environmental effects on SFA for less-luminous galaxies at intermediate redshifts.

In addition to the dynamical interaction that is mentioned above, other effects of the BO phenomenon are also expected. The first one is the decrease of the infall rate of galaxies into clusters with time (e.g., Kodama & Bower 2001). As a second one, we propose in this Letter a further possible kinematic origin for the BO effect from our new findings in observational data.

This Letter is organized as follows: In § 2 we present the results of our statistical analysis of a correlation between the equivalent width (EW) ($[\text{O II}]$) and the luminosity of cluster and field galaxies at intermediate redshifts. In § 3 we discuss SFA in less-luminous cluster galaxies and propose an alternative cause for the BO effect. In § 4 we give our conclusions. We assume a spatially flat universe with $\Omega_m = 0.3$, $\Lambda_m = 0.7$, and $H_0 = 70$ km $s^{-1}$ Mpc$^{-1}$.

2. ENVIRONMENTAL EFFECTS ON SFA

Environmental effects on the SFA of galaxies can be statistically investigated with archival data. As a measure of SFA, we adopt the EW of $[\text{O II}] \lambda 3727$. The $[\text{O II}]$ emission is utilized because it is correlated to Balmer line emission that can trace current SFA (Gallagher, Bushouse, & Hunter 1989). EW is used because the aperture effect can be neglected and because it is line luminosity that is normalized by the luminosity of whole a galaxy. This measure permits us to discuss the specific SFA of each galaxy.

The following cluster galaxies are utilized: nine MORPHS clusters ($0.37 < z < 0.56$, $r \leq 22$; Dressler et al. 1999); Cl 1358+62 ($z = 0.33$, $r \leq 21$; Fisher et al. 1998); AC 103, AC 114, and AC 118 ($z = 0.31$, $r \leq 22$; Couch et al. 1998); Abell 2390 ($z = 0.23$, $r \leq 21.0$; Abraham et al. 1996); and CNOC (0.18 < $z < 0.56$, $M_R \leq -19.6$; Yee et al. 1996a, 1998; Yee, Ellington, & Carlberg 1996b; Ellington et al. 1997, 1998; Abraham et al. 1998; Balogh et al. 1999), where $M_R$ and $r$ are the absolute magnitude and apparent magnitude in the $R$ band, respectively. For field galaxies, we use CNOC.
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Fig. 1.—$R$-band magnitude and EW ([O\emissionline{ii}]) of (a) cluster galaxies and (b) field galaxies; filled squares indicate CNOC (Balogh et al. 1999), circles indicate MORPHS (Dressler et al. 1999), diamonds indicate Cl 1358 (Fisher et al. 1998), triangles indicate AC 103, AC 114, and AC 118 (Couch et al. 1998), and open squares indicate Abell 2390 (Abraham et al. 1996).

Fig. 2.—Mean EW ([O\emissionline{ii}]) of (a) cluster galaxies and (b) field galaxies in each $R$-band magnitude bin. An error bar designates the standard deviation of each value.

TABLE 1

| $M_R$   | $N_d$ | $N_f$ | $t$   | Sig. ($t$) | $u^b$ | Sig. ($U$) |
|---------|-------|-------|-------|------------|-------|------------|
| 22.3    | 7     | 10    | -0.91 | 9.90E-01   | 31    | 6.96E-01   |
| -21.9   | 23    | 30    | -0.50 | 6.17E-01   | 318   | 6.28E-01   |
| -21.6   | 50    | 67    | -2.05 | 4.29E-02   | 1310  | 4.43E-02   |
| -21.2   | 106   | 65    | -3.89 | 1.80E-04   | 1935  | 1.55E-06   |
| -20.8   | 95    | 95    | -0.53 | 5.96E-01   | 3765  | 4.86E-02   |
| -20.5   | 153   | 116   | -3.96 | 1.02E-04   | 6167  | 1.84E-05   |
| -20.1   | 130   | 96    | -2.30 | 2.22E-02   | 3873  | 1.10E-06   |
| -19.7   | 78    | 80    | -2.58 | 1.10E-02   | 1926  | 3.26E-05   |

Note.—Tests are for all galaxies in each magnitude bin (left set) and for those galaxies with EW less than 100 Å (right set).

(a) cluster

(b) field

In Figure 1, we present the EW ([O\emissionline{ii}]) and the $R$-band absolute magnitudes for the galaxies. In Figure 1a, cluster galaxies are plotted, while in Figure 1b field galaxies are plotted. In Figures 2a and 2b, using the same sample as Figure 1, we depict the mean EW of galaxies in each magnitude bin in each environment. From these figures, we can examine the environmental effects on the mean SFA. The results are more convincingly revealed in Table 1 by means of Welch's $t$-test (Press et al. 1988). Even when variances are not the same between two sample groups, this test can be applied to answer the ques-



Note.—Tests are for all galaxies in each magnitude bin (left set) and for those galaxies with EW less than 100 Å (right set).

$a$ Sig. ($t$) means the significance level of each value of $t$. When Sig. ($t$) is less than 0.05, the averages of two groups are significantly different.

$b$ $u$ means the rank sum of one group that has fewer samples.

$c$ Sig. ($U$) means the significance level of each value of $U$. When Sig. ($U$) is less than 0.05, the representative statistical values of two groups are significantly different.
tion of whether their averages are the same or not, using the $t$-value that is estimated as

$$
t(M_{b_i}) = \frac{E_W(M_{b_i}) - E_W(M_{b_j})}{\left[ \text{Var}(E_W(M_{b_i}))/N_{b_i}(M_{b_i}) + \text{Var}(E_W(M_{b_j}))/N_{b_j}(M_{b_j}) \right]^{1/2}}.
$$

(1)

Here $E_W(M_{b_i})$ is the equivalent width of cluster galaxies in the $i$th magnitude bin, while $E_W(M_{b_j})$ is that of the field galaxies, $\text{Var}(E_W)$ is the variance of each value, $N_{b_i}(M_{b_i})$ is the number of cluster galaxies in the $i$th magnitude bin, and $N_{b_j}(M_{b_j})$ is that of the field galaxies. In Table 1, we also give a nonparametric test, Mann-Whitney’s $U$-test (Pitman 1948), to answer whether or not the statistically representative values of two sample groups are the same. The $U$-test is performed since our sample may not be normally distributed because of the bias of selection criterion (iv). Table 1 contains the results of the $t$-test and the $U$-test for all galaxies in the sample and also for galaxies with EWs smaller than 100 Å. The subscript “i” runs from the bins of more-luminous galaxies to those of less-luminous galaxies, and its maximum is adopted to be 8.\(^2\)

Adopting a significance level of 0.05, we first conclude that for less-luminous galaxies with magnitudes of $M_r \gtrsim -20.7$, the mean SFA of cluster galaxies is always smaller than that of field galaxies. Even when we omit several galaxies whose EWs are larger than 100 Å, our conclusion is not altered. On the assumption that the luminosity is proportional to the dynamical mass of a galaxy, this result statistically confirms the expectation of almost all theoretical studies that the SFA of less-luminous cluster galaxies should suffer more suppression because of their shallower gravitational potential well (e.g., Henriksen & Byrd 1996; Abadi et al. 1999; Quilis et al. 2000; Mori & Burkert 2000; Balogh et al. 2000).

As a second conclusion, while there is no theoretical prediction that less-luminous cluster galaxies continue their SFA, we discover the following: there are some less-luminous cluster galaxies with exceptionally large SFA (EW $\gtrsim 90$ Å, i.e., larger than the mean EW in less-luminous, $M_r \gtrsim -20.7$, field galaxies), which is as large as that of less-luminous but actively star-forming field galaxies. The existence of such cluster galaxies is consistent with the observational fact that BO galaxies are mostly less luminous (Dressler et al. 1994). Therefore, to argue the possibility of such exceptions, in the next section we reexamine the dynamical effects on their ISM.

3. DISCUSSION

As long as less-luminous cluster galaxies are assumed to be less-massive, their ISM should be easily stripped by environmental effects, and then their SFA must be suppressed. In this section, we inversely examine which environmental effect is inactive in stripping the ISM in less-luminous cluster galaxies. The typical effects are the following: (1) tidal interaction between a cluster and its galaxies, (2) ram pressure owing to the intracluster medium (ICM), and (3) Kelvin-Helmholtz instability (KHI) via disturbances on the boundary of the ISM and ICM (e.g., Henriksen & Byrd 1996). Since we focus on less-luminous galaxies, we assume that the luminosity of a galaxy is proportional to its dynamical mass and adopt the density profile of Burkert (1995), which well explains the density profile of less-massive galaxies. In that profile, the radius of a galaxy ($R_{gal}$) is related to its dynamical mass ($M_{gal}$) by $R_{gal} = 6.9 \times 10^{-3}(M_{gal})^{3/7}$.

We first consider the tidal effect between a cluster and its galaxy, comparing with the self-gravity of its galaxy. The tidal force ($F_{tid}$) and the gravitational force ($F_{grav}$) are given as $F_{tid} = 2G\rho_{gal} R_{gal} / R_{cl}$ and $F_{grav} = G M_{gal} / R_{gal}^2$, respectively. Here $G$ is the gravitational constant, $M_{cl}$ is the mass of a galaxy cluster, and $R_{cl}$ is the radius of a galaxy cluster. From the equilibrium of the two forces, we obtain a critical mass of

$$
M_{tid} = 3 \times 10^{11}(R_{gal}/500 \text{ kpc})^{2/7}(M_{gal}/10^{14} M_\odot)^{-7/2} M_\odot.
$$

(2)

This means that the tidal force is not effective for less-luminous galaxies when their mass is smaller than $M_{tid}$, although it does not prove anything for massive galaxies to which the Burkert profile may not apply.

Second, we take the ram pressure ($P_{ram}$) due to the ICM and compare it with the gravity ($P_{grav}$) of a galaxy in the same dimension of the pressure. These are expressed as $P_{ram} = \rho_{ICM} \sigma_{gal}^2$ and $P_{grav} = 2G\rho_{gal}^2 \Sigma_{ISM} = 2GM_{gal}^2 F/\pi R_{gal}^3$, respectively. Here $\rho_{ICM}$ is the mass density of the ICM, $\sigma_{gal}$ is the velocity of a galaxy, $\Sigma_{ISM}$ is the surface density of a galaxy, $\Sigma_{ISM}$ is the surface density of the ISM, and $F$ is the ratio of gas mass to dynamical mass. Therefore, less-massive (i.e., less-luminous) galaxies than a critical mass of

$$
M_{ram} = 1 \times 10^{-7} (F/0.1)^{-7/2} (\rho_{ICM}/10^{-4} m_H)^{7/2} \times (\sigma_{gal}/500 \text{ km s}^{-1})^7 M_\odot
$$

(3)

are affected by ram pressure stripping effects.

Third, we take up the KHI that is ineffective in a condition of

$$
k = \frac{\pi}{R_{gal}} \leq \frac{GM_{gal} \rho_{ICM} - \rho_{ISM}^3}{R_{gal}^2 \rho_{ICM}^2 (R_{gal}^3)^{2/3}} \approx \frac{GM_{gal}^2 F}{\pi R_{gal}^3 \rho_{ICM}^2 \sigma_{gal}^2},
$$

(4)

where $k$ is the wavenumber (Chandrasekhar 1961) and $\rho_{ISM}$ is the mass density of the ISM. Thus, we find that more-massive galaxies than a critical mass of

$$
M_{KHI} = 1 \times 10^{10} (F/0.1)^{-7/2} (\rho_{ICM}/10^{-4} m_H)^{7/2} \times (\sigma_{gal}/500 \text{ km s}^{-1})^7 M_\odot
$$

(5)

are difficult to strip by KHI. Since the timescale of KHI stripping is longer than that of ram pressure stripping (Mori & Burkert 2000), there remains a chance for galaxies that suffer KHI to contribute to the BO effect temporarily, before the virialization of their cluster.

Here we propose an alternative scenario for the BO effect, supposing that the blueness of galaxies reflects large SFA. From equations (2), (3), and (5) we find that when the mass of a galaxy is within the range of

$$
M_{KHI} < M_{gal} < M_{tid},
$$

(6)

such less-luminous galaxies are not affected by either tidal interaction, ram pressure, or KHI. For such galaxies it is possible to retain their ISM and SFA without the ISM being stripped, and hence they contribute to BO galaxies.

\(^2\) Since the number of bins generally affects statistical tests, we have checked that the general trend of the results is not altered if the maximum bin number is 7, 9, or 10.
Finally, we consider the evolution of clusters from the viewpoint of their galaxies. In unvirialized clusters, their galaxies are expected to move relatively slowly, and thus $M_{h}$ becomes small, the range of equation (6) gets wide, and the fraction of blue galaxies is high. On the contrary, in virialized clusters the opposite situation is expected. Thus, the fraction of blue galaxies becomes larger in clusters at higher redshift, according to their degree of virialization. Our scenario is consistent with the observational fact that the fraction of blue galaxies is larger in irregular (i.e., unvirialized) clusters whose $\sigma_{gal}$ (velocity dispersion among member galaxies) is smaller than those of regular clusters (Andreon & Ettori 1999; Margoniner et al. 2001).

The consistency of our scenario with numerical simulations (Andreon & Ettori 1999; Margoniner et al. 2001). The observational fact that the fraction of blue galaxies is larger in clusters at higher redshift, according to their degree of virialization. Our scenario is consistent with the numerical simulations of irregular clusters (Andreon & Ettori 1999; Margoniner et al. 2001).

4. CONCLUSION

We have investigated environmental effects on the SFA of star-forming cluster galaxies within the magnitude range of $-22.5 \leq M_{r} \leq -19.6$ at intermediate redshifts of $0.2 < z < 0.6$. The SFA is estimated from EW ([O ii]). In less-luminous ($M_{r} \geq -20.7$) galaxies, we first find that the mean SFA of cluster galaxies is smaller than that of field galaxies. Second, we find that some of the cluster galaxies have as large EWs ([O ii]) as those of the actively star-forming field galaxies. Such actively star-forming less-luminous cluster galaxies have never been predicted before. To explain this new finding, we propose a possible alternative scenario for the origin of BO galaxies. We propose that BO galaxies are stable against KHI and are not affected by the tidal effects of a galaxy cluster. Thus, their ISM is not easily stripped, and they keep up their SFA. In younger clusters, such BO galaxies are more likely. As clusters become virialized, however, member galaxies become more accelerated, $M_{h}$ increases, and fewer galaxies are stable against KHI. Hence, the fractions of blue galaxies decrease, which produces the BO effect.

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