Evolution of the Blue Luminosity-to-Baryon Mass Ratio of Clusters of Galaxies

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Abstract

We derive the ratio of the total blue luminosity to the total baryon mass, $L_B/M_b$, for massive ($M_{gas}$ at the Abell radius is $\geq 1 \times 10^{13}h^{-2.5}M_\odot$) clusters of galaxies up to $z \approx 1$ from the literature. Twenty-two clusters in our sample are at $z > 0.1$. Assuming that the relative mix of hot gas and galaxies in clusters does not change during cluster evolution, we use $L_B/M_b$ to probe the star-formation history of the galaxy population as a whole in clusters. We find that $L_B/M_b$ of clusters increases with redshift from $L_B/M_b = 0.024(L_B/M_b)_0$ at $z = 0$ to $\approx 0.06(L_B/M_b)_0$ at $z = 1$, indicating a factor of 2-3 brightening (we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$). This amount of brightening is almost identical to the brightening of the $M/L_B$ ratio of early-type galaxies in clusters at $0.02 \leq z \leq 0.33$ reported by van Dokkum et al. (1998, AAA 70.160.065). We compare the observed brightening of $L_B/M_b$ with luminosity evolution models for the galaxy population as a whole, changing the e-folding time of star formation, $\tau$, by $0.1 \leq \tau \leq 5$ Gyr and the formation redshift, $z_F$, by $2 \leq z_F < \infty$. We find that $\tau = 0.1$ Gyr for 'single burst' models with $z_F \geq 3$ and $\tau = 5$ Gyr for 'disk' models with arbitrary $z_F$ are consistent with the observed brightening, while models with $\tau = 1-2$ Gyr tend to predict brightening that is too steep. We also derive the ratio of the blue luminosity density to the baryon density for field galaxies, adopting $\Omega_b h^2 = 0.02$, and find that the blue luminosity per unit baryon is similar in clusters and in fields up to $z \approx 1$ within the observational uncertainties.

Key words: galaxies: clusters: general — galaxies: evolution — galaxies: photometry

1. Introduction

Clusters of galaxies are suitable objects for studying the evolution of galaxies in dense environments. Recent observations based on large telescopes including Hubble Space Telescope (HST) have been revealing the morphology-dependent evolution of galaxies in clusters up to $z \approx 1$. The evolution of elliptical and S0 galaxies has been found to be reproduced well by the so-called single-burst model (e.g., Schade et al. 1997; Ellis et al. 1997; Kodama et al. 1998; van Dokkum et al. 1998). Schade et al. (1996) found that spiral galaxies in clusters brighten by $\sim 1$ mag with the redshift up to $z \approx 0.5$, and that this brightening is similar to that of field spiral galaxies in the same redshift range [see, however, Vogt et al. (1997) and Lilly et al. (1998) for the evolution of field spiral galaxies]. Morphological studies based on HST imaging suggest that a transition from spiral galaxies to S0 galaxies may have occurred in clusters since $z \approx 0.5$ (Dressler et al. 1997). An attempt to measure the star-formation rate of individual galaxies has also started (e.g., Balogh et al. 1998; Poggianti et al. 1999).

In this paper, we discuss the global (or average) star-formation history of the galaxy population as a whole in clusters of galaxies. To do so, we derive the ratio of the total blue luminosity ($L_B$) to the total baryon mass ($M_b$) for clusters of galaxies up to $z \approx 1$. The quantity $L_B/M_b$, including its evolution, should reflect when (and what fraction of) baryons (= primordial gas) in clusters are converted into stars. Similar studies have been done for field galaxies. The global luminosity density, $l/[L_B Mpc^{-3}]$, in various wavelengths has been measured by many workers on the basis of observations of field galaxies (e.g., Lilly et al. 1996; Madau et al. 1998). If the density parameter of baryons ($\Omega_b$) is given, one can compute from $l$ the mean luminosity per unit baryon mass in fields ($l/p_b$). We derive $B$-band $l/p_b$ in fields up to $z \approx 1$ and compare it with $L_B/M_b$ of clusters.

The structure of this paper is as follows. In section 2, we present the data of nearby and distant clusters used to derive $L_B/M_b$. We compare $L_B/M_b$ with predictions of simple luminosity evolution models in section 3. A comparison with $l/p_b$ in fields is also given in section 3. We summarize our conclusions in section 4.

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We adopt $h = 0.7$, $\Omega_0 = 0.2$, and $\lambda_0 = 0$ throughout this paper, unless otherwise stated, where $h$ is the Hubble constant in units of $100 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_0$ is the density parameter, and $\lambda_0$ is the cosmological constant. Under this assumption, the present age of the universe is 11.8 Gyr. The value $h = 0.7$ is taken from recent determinations of $H_0$ (e.g., Freedman 1999). Adopting different values for $\Omega_0$ and $\lambda_0$ in the observationally reasonable ranges of $0.2 \leq \Omega_0 \leq 1$ and $0 \leq \lambda_0 \leq 0.8$ does not significantly change our results.

2. Data

We divide clusters of galaxies into nearby clusters ($z \leq 0.1$) and distant clusters ($z > 0.1$). We assume that evolutionary effects are negligible for $z \leq 0.1$ clusters and regard their properties as those of the present-day clusters.

We adopt the $B$ band to measure the luminosity of galaxies, and think that it is the best compromise. Cluster luminosities have been measured mainly in optical bandpasses such as $B$, $V$, or $R$. Among the optical bandpasses, $B$ is most sensitive to the luminosity evolution of galaxies. Though ultraviolet wavelengths, such as $U$, are much better for measuring star formation, data in such wavelengths are very few. As for field galaxies, there are many measurements of the luminosity density of field galaxies in the $B$ band, which enables us to compare $L_B/M_b$ with $l_B/p_b$.

2.1. Nearby Clusters

We use the sample of nearby clusters given in Arnaud et al. (1992) to derive $L_B/M_b$ of the present-day clusters. Arnaud et al. (1992) compiled a sample of 27 clusters of galaxies, where the total $V$-band luminosity ($L_V$), morphological-type mix of galaxies (E, S0, and S), and gas mass within a radius of $1.5 h^{-1} \text{Mpc}$ (the Abell radius) are given. Morphological-type mix is available for 18 clusters.

Arnaud et al. (1992) found in their clusters a strong dependence of $L_V/M_{\text{gas}}$ on $L_V$: $L_V/M_{\text{gas}} \propto L_V^{-0.9}$. If such a strong dependence holds in the whole mass range of clusters, it would very much complicate a comparison of $L_B/M_b$ among clusters having different masses. Thus, we first examine for what clusters such a strong dependence exists. Figure 1 plots $L_V$ against $M_{\text{gas}}$ for all clusters in Arnaud et al. (1992). The dependence found in Arnaud et al. (1992) is shown as the dashed line. The solid line, on the other hand, is a regression line between $L_V$ and $M_{\text{gas}}$ for $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$ clusters, $L_V \propto M_{\text{gas}}^{0.8}$. This is close to a linear regression, i.e., a constant $L_V/M_{\text{gas}}$, indicated as the dotted line. Thus, the strong dependence of $L_V/M_{\text{gas}}$ on $L_V$ (or equivalently on $M_{\text{gas}}$) found by Arnaud et al. (1992) is probably due to the inclusion of less massive clusters.

Figure 2 shows $L_V/M_{\text{gas}}$ as a function of the fraction of luminosity emitted from elliptical and S0 galaxies to the total luminosity for 18 clusters with the type-mix data. It is found that $L_V/M_{\text{gas}}$ is constant for $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$ clusters irrespective of the type mix. This implies that $L_V/M_{\text{gas}}$ is not sensitive to a change in the populations of galaxies for massive clusters.

Figures 1 and 2 demonstrate that the dependence of $L_V/M_{\text{gas}}$ on $L_V$ (or on $M_{\text{gas}}$) is much weak for massive clusters. This is also supported by Renzini (1997), who found that rich clusters have a fairly constant $M_{\text{gas}}$ to $B$-band luminosity ratio. The reason why poor clusters have a relatively higher $L_V/M_{\text{gas}}$ value is not clear, but a possible explanation is that a significant fraction of hot gas in poor clusters escaped from the clusters during cluster evolution, owing to their shallow gravitational potentials, resulting in a higher $L_V/M_{\text{gas}}$ value (e.g., Renzini 1997).

In any case, in what follows we assume that $L_B/M_b$ is constant for $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$ clusters and use them to derive the average $L_B/M_b$ of nearby clusters. We show in the next subsection that all of the distant clusters adopted in this paper have $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$. This promises a fair comparison of $L_B/M_b$ between nearby...
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Fig. 2. $L_v/M_{\text{gas}}$ plotted against the fraction of luminosity emitted from elliptical and S0 galaxies to the total luminosity $L_v(E/S0)/L_v$ for Arnaud et al.'s (1992) clusters having type-mix data. The filled and open circles indicate $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$ and $M_{\text{gas}} < 1 \times 10^{13} h^{-2.5} M_\odot$ clusters, respectively.

Fig. 3. $L_B/M_b$ as a function of $M_{\text{gas}}$ for Arnaud et al.'s (1992) clusters. The filled and open circles indicate clusters with and without type-mix data, respectively.

and distant clusters.

For Arnaud et al.'s (1992) clusters which have a morphological type mix, we compute the total B-band luminosity ($L_B$) from $L_v$ using $B - V = 0.96$ (E), 0.85 (SO), and 0.68 (S) (see Fukugita et al. 1995). For clusters without type-mix data, we adopt $B - V = 0.85 \pm 0.2$ as the average color of galaxies. We compute the baryon mass $M_b$ from the gas mass $M_{\text{gas}}$ using

$$M_b = M_{\text{gas}} + (M/L_B)_* L_B,$$

where $(M/L_B)_*$ is the mean mass-to-luminosity ratio of the stellar population in galaxies. We neglect the atomic and molecular gas in galaxies. We adopt $(M/L_B)_* = (6 \pm 3) h (M/L_B)_\odot$, which roughly covers the mass-to-luminosity ratio of elliptical galaxies (van der Marel 1991; Pizzella et al. 1997) and of spiral disks (Bahcall 1984; Broeils, Courteau 1997). The errors in $L_B/M_b$ contain (i) errors in $L_B$ which are given in Arnaud et al. (1992), (ii) errors in the mean $B - V$ (only for clusters without type mix data), and (iii) errors in $(M/L_B)_*$ in equation (1). Since most of the baryons in clusters are in form of hot gas, the error in $M_b$ due to (iii) is only about 5%.

Figure 3 presents $L_B/M_b$ as a function of $M_{\text{gas}}$. The filled and open circles indicate Arnaud et al.'s (1992) clusters with and without type-mix data, respectively. As shown in figure 1, a clear trend is seen in figure 3 that clusters with $M_{\text{gas}} \leq 1 \times 10^{13} h^{-2.5} M_\odot$ have a systematically higher $L_B/M_b$. To derive $L_B/M_b$ of nearby clusters, we not only remove clusters with $M_{\text{gas}} < 1 \times 10^{13} h^{-2.5} M_\odot$, but also remove clusters without type-mix data because the uncertainties in $L_B$ of these clusters are on the average larger than those for clusters having type mix (to include the clusters without type-mix data hardly changes the result, though).

Twelve out of the 21 clusters with $M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$ have type-mix data, and their mean $L_B/M_b$ for $h = 0.7$ is

$$L_B/M_b = (0.024 \pm 0.004) (L_B/M_b)_\odot,$$

which we regard as the representative value for the present-day clusters. The contribution from elliptical and SO galaxies to total B luminosity is on the average (69 \pm 13)% for the 12 clusters, implying that these clusters are dominated by early-type galaxies (see figure 2). Clusters which have $M_{\text{gas}} < 1 \times 10^{13} h^{-2.5} M_\odot$ tend to be less dominated by early-type galaxies. For example, the Virgo cluster, which has $M_{\text{gas}} = 0.44 \times 10^{13} h^{-2.5} M_\odot$, has $L_B(E + S0)/L_B(\text{tot}) = 45\%$.

For the 12 clusters, we estimate the ratio of the stellar mass to the baryon mass to be $M_*/M_b = 0.10 \pm 0.05$ ($h = 0.7$) using $(M/L_B)_* = (6 \pm 3) h (M/L_B)_\odot$. This means that only ~10% of baryons have been used to form stars to date in rich clusters.
Table 1. Distant clusters.

<table>
<thead>
<tr>
<th>Name</th>
<th>$z$</th>
<th>$L_B/M_b^*$</th>
<th>$L_B^+$</th>
<th>$M_{gas}^+$</th>
<th>Radius</th>
<th>Error</th>
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<td>1.08</td>
<td>1.81</td>
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<td>3.0</td>
<td>0.74</td>
<td>0.26</td>
<td>48</td>
</tr>
<tr>
<td>MS 0302+16</td>
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<td>0.044</td>
<td>50.6</td>
<td>10.4</td>
<td>1.67</td>
<td>—</td>
</tr>
<tr>
<td>CL 0939+47</td>
<td>0.41</td>
<td>0.089</td>
<td>1.8</td>
<td>0.18</td>
<td>0.14</td>
<td>—</td>
</tr>
<tr>
<td>RX J1347.5-1145</td>
<td>0.45</td>
<td>0.053</td>
<td>65.7</td>
<td>11.3</td>
<td>1.09</td>
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<tr>
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<td>3.0</td>
<td>0.74</td>
<td>0.26</td>
<td>48</td>
</tr>
<tr>
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<td>0.027</td>
<td>2.5</td>
<td>0.84</td>
<td>0.60</td>
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<tr>
<td>Abell 2218</td>
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<td>0.021</td>
<td>6.3</td>
<td>2.7</td>
<td>0.60</td>
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<tr>
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<td>2.7</td>
<td>0.60</td>
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<tr>
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<td>0.021</td>
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<td>2.7</td>
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<td>2.1</td>
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<td>0.028</td>
<td>4.2</td>
<td>1.4</td>
<td>0.60</td>
<td>—</td>
</tr>
</tbody>
</table>

*In units of $h^{0.5}(L_B/M_b)^*$.
1In units of $h^{-2} \times 10^{11} L_b$.
2In units of $h^{-2} \times 10^{11} M_b$.
3Radius in units of $h^{-1}$ Mpc adopted to measure $L_B$ and $M_{gas}$.
4Relative error (%).

2.2. Distant Clusters

Searching for the total luminosity and gas mass data of distant clusters in the literature, we take 22 clusters, among which thirteen are from the CNOC cluster sample (Carlberg et al. 1996; Lewis et al. 1999). We do not apply any selection criterion to compile our sample. Data of these clusters are given in Table 1. All of the clusters have rest-frame luminosity (either B, V, or r band) and gas mass measurements. For a cluster whose rest-frame luminosity is in the $V$ or $r$ band, we use an observed or assumed color to convert the luminosity to the rest-frame $B$-band luminosity.

When computing $M_b$ from $M_{gas}$ by $M_b = M_{gas} + M_{*,v}$, we use $M_{*,v} = 0.10 (h = 0.7)$, which is the value for the nearby clusters. Although distant clusters may have lower $M_{*,v}/M_b$ values than the nearby clusters, the uncertainties in $L_B/M_b$ due to this effect are at most $\approx 10\%$, which is negligible for our discussion. Below are references to the nine clusters and the CNOC clusters. (i) Abell 1413 ($z = 0.14$) and Abell 1689 ($z = 0.18$) These two clusters are taken from Cirimele, Neschi, and Trèvese's (1997) sample. This sample consists of 12 clusters with $z < 0.2$ for which $M_{gas}$ and $L_V$ within a radius of $0.75 h^{-1}$ Mpc are given. We calculate $L_B$ assuming rest-frame $B - V = 0.85 \pm 0.2$.
(ii) Abell 2218 ($z = 0.18$) We adopt $M_{gas}$ and $L_B$ from Squires et al. (1996).
(iii) Abell 2163 ($z = 0.20$) $M_{gas}$ and $L_V$ are given in Squires et al. (1997). $L_B$ is computed assuming rest-frame $B - V = 0.8 \pm 0.2$.
(iv) CL 0500-24 ($z = 0.32$) $M_{gas}$ is taken from Schindler and Wambsganss (1997). $L_V$ is given in Infante et al. (1994), and $L_B$ is computed using rest-frame $B - V = 0.85$. [The mean apparent color of this cluster, $V - I = 1.8$, reported by Infante et al. (1994) corresponds to $B - V = 0.85$ in the rest frame.]
(v) CL 0939+47 ($z = 0.41$) Schindler et al. (1998) found two substructures in this cluster, implying that this cluster has not yet been virialized. $M_{gas}$ and $L_B$ adopted here are the sum of the values for the two substructures given in Schindler et al. (1998). Dressler et al. (1997) reported the fraction in number of elliptical and S0 galaxies to be 55%.
(vi) RX J1347.5-1145 ($z = 0.45$)
$M_{\text{gas}}$ is taken from Sahu et al. (1998) and $L_B$ is computed from $M_{\text{tot}}$ and $M_{\text{tot}}/L_B$ given in Fischer and Tyson (1997), where $M_{\text{tot}}$ is the total mass of a cluster.

(vi) CL 0016+16 ($z = 0.55$)

$M_{\text{gas}}$ is taken from Neumann and Böhringer (1997) and $L_B$ is computed from the $r$-band total luminosity given in Carlberg et al. (1996) using rest-frame $B - r = 0.97$, which corresponds to the observed $g - r$ color of 1.455 (Carlberg et al. 1996). Dressler et al. (1997) reported the fraction in number of elliptical and S0 galaxies to be 73%.

(vii) AX J2019+1127 ($z = 1.01$)

$M_{\text{gas}}$ is taken from Hattori et al. (1997), and $L_B$ is computed from $L_V$ (Benitez et al. 1998) assuming a rest-frame $B - V = 0.7 \pm 0.3$, which roughly covers the expected colors of elliptical and spiral galaxies at $z = 1$.

CNO clusters

Carlberg et al. (1996) give rest-frame $r$-band luminosity at the virial radius for 16 clusters at $0.17 < z < 0.55$. Out of them, 14 clusters have gas mass measurements (figure 4 of Lewis et al. 1999). Since the maximum radius at which gas mass is plotted, $r = 600 \, h^{-1}$ kpc for all the clusters, is smaller than the virial radii, we derive for each cluster the $r$-band luminosity at $600 \, h^{-1}$ kpc from the value at the virial radius assuming that luminosity is proportional to radius. The ratio of $600 \, h^{-1}$ kpc to the virial radii of 14 clusters is on the average 0.48, implying that a large factor of conversion is necessary. For each cluster, we then transform the rest-frame $r$-band luminosity into the rest-frame $B$-band luminosity on the basis of the observed $g - r$ color given in figure 4 of Carlberg et al. (1996). CL 0016+16 is among the 14 clusters. As seen in (vii), we have adopted for gas mass of this cluster the measurement given in Neumann and Böhringer (1997) because their value is at $r = 1.67h^{-1}$ Mpc, which is very close to the virial radius where $r$-band luminosity is measured. The number of the CNO clusters adopted here is thus 13.

The radii used for measuring $L_B/M_b$ differ among the clusters, and most of them are smaller than the Abell radius (see table 1). Unfortunately, it is not clear whether $L_B/M_b$ measured at these small radii represent global values, i.e., values at the Abell radius, though there is a study showing that the $L_B/M_b$ of the Coma cluster is nearly constant between a radius of $\approx 0.4 \, h^{-1}$ Mpc and the Abell radius (Taguchi et al., in preparation). In this paper, we assume that the values of $L_B/M_b$ derived here represent the global values of individual clusters. (For CL 0939+47, see, however, the next section.)

Figure 4 plots $L_B$ against $M_{\text{gas}}$ for the 12 nearby clusters and the 22 distant clusters. Both $L_B$ and $M_{\text{gas}}$ are values at $r = 1.5 \, h^{-1}$ Mpc, which are derived from raw values on the assumption that $L_B(r)$ and $M_{\text{gas}}(r)$ are proportional to radius $r$. The thick solid line indicates the best fit of a linear law, $L_B \propto M_{\text{gas}}$, to the nearby clusters. The thin solid line and the dotted line correspond to a similar fit to distant clusters at $0.1 < z < 0.4$ and $0.4 < z < 0.7$, respectively. It is found that the average $B$ luminosity at a given gas mass increases with redshift. This should reflect some evolution of $L_B/M_{\text{gas}}$. Note that the range of the gas mass is similar between the nearby and distant clusters: there is no distant cluster in our sample whose gas mass at $r = 1.5 \, h^{-1}$ Mpc is less than $1 \times 10^{13} h^{-2.5} M_\odot$. Also note that no clear dependence of $L_B/M_{\text{gas}}$ on $M_{\text{gas}}$ is seen either in the nearby cluster sample or in the distant cluster sample.

We mention here the effects of changing $\Omega_0$ and $\lambda_0$ on estimates of $L_B/M_b$ for distant clusters. Let $d_L(z)$ and $d_A(z)$ be the luminosity distance and the angular diameter distance to a cluster at $z$, respectively. The ratio $L_B/M_{\text{gas}}$ is proportional to $d_L^{-0.9}(z)$, because of $L_B \propto d_L^2(z)$, $M_{\text{gas}} \propto d_A^2(z)$, and $d_L(z) = (1+z)^2 d_A(z)$. Thus, $L_B/M_{\text{gas}}$ depends on $\Omega_0$ and $\lambda_0$ through $d_L^{-0.9}(z)$. Since $M_b$ is dominated by $M_{\text{gas}}$, the dependence of $L_B/M_b$ on $\Omega_0$ and $\lambda_0$ is very close to that of $L_B/M_{\text{gas}}$. Figure 5 shows the ratio of $L_B/M_{\text{gas}}$ ($\Omega_0, \lambda_0$) to $L_B/M_{\text{gas}}$ ($\Omega_0 = 0.2, \lambda_0 = 0$) as a function of redshift for two sets of ($\Omega_0, \lambda_0$). Since $d_L(z)$ is a decreasing function of $\Omega_0$ and an increasing function of $\lambda_0$ up to at least $z = 1$, we find...
from this figure that the change in $L_B/M_B$ due to the change in $\Omega_0$ and $\lambda_0$ in the ranges $0.2 \leq \Omega_0 \leq 1$ and $0 \leq \lambda_0 \leq 0.8$ is less than $\pm 10\%$ for $z < 1$ clusters, which is negligible for our discussion below.

3. Results and Discussion

Figure 6 shows $L_B/M_B$ of clusters as a function of redshift. The filled circles present the distant clusters and the filled square indicates the average $L_B/M_B$ of nearby clusters. Clusters without errors (but for CL 0939+47 and CL 0016+16) are the CNOC clusters. The lines indicate model predictions, which are discussed in the next subsection. It is found that $L_B/M_B$ increases with $z$, from $L_B/M_B = 0.024(L_B/M)_0$ at $z = 0$ to $\simeq 0.06(L_B/M)_0$ at $z = 1$, though the error in each distant cluster is fairly large. CL 0939+47 deviates largely from this trend. We suspect, however, that the observed $L_B/M_B$ of this cluster does not represent the real, global value, because the observed $L_B/M_B$ is the value for two substructures whose radii are only $r = 0.14 h^{-1}$ Mpc.

The CNOC clusters seem to have a larger scatter in $L_B/M_B$. This may reflect uncertainties due to a large factor of the conversion of optical luminosity from the value at the virial radius to that at $r = 600 h^{-1}$ kpc.

There are two opposite explanations for the increase in $L_B/M_B$ with redshift. One is a brightening of $L_B$ due to the luminosity evolution of the galaxy population as a whole. Note that galaxy mergings, even if they occur, do not change the total mass of the galaxy population, and that star formation which could be triggered by merging can be treated in the framework of the 'pure' luminosity evolution of the galaxy population. The other explanation is that the mass of baryons ($\sim$ hot gas) per galaxy decreases with redshift. However, this explanation seems to be less plausible, because no significant evolution has been observationally found for the global properties of clusters at $z \lesssim 1$ (e.g., Schindler 1999). (This result is, however, mainly for X-ray properties, and the evolution of the galaxy distribution in clusters is not well known.)

In what follows, we take the former explanation as our hypothesis, i.e., we assume that the increase in $L_B/M_B$ found here is due to pure brightening of the galaxy population as a whole. Then, the increase found here corresponds to brightening by $\sim 1$ mag of the galaxy population.

In the next subsection, we compare the observed brightening with predictions of simple luminosity evolution models of galaxies.

3.1. Comparison with Luminosity Evolution Models

We characterize the evolution of $L_B$, the $B$-band luminosity summed over all galaxies in a cluster, by two parameters: the star formation timescale $\tau$ and the formation redshift $z_F$. In other words, we assume that all galaxies are formed at the same redshift, $z_F$, and that the e-folding time of star formation summed over all galaxies is $\tau$ (Gyr). We compute the $B$-band luminosity using the population synthesis code developed by Kodama and Arimoto (1997). The values of $\tau$ and $z_F$ examined here are $\tau = 0.1, 1, 2, 3$, and $5$ Gyr and $z_F = 2.3, 3, 5$, and $\infty$. Models with $\tau = 0.1$ Gyr correspond to elliptical galaxies and models with $\tau = 5$ Gyr are for spiral disks, like that of our Galaxy. We do not examine $\tau > 5$ Gyr, since to take $\tau > 5$ Gyr leads to too blue colors at $z = 0$, which are inconsistent with the observed colors of galaxies in nearby clusters. The mean $B - R_C$ of the Virgo and Coma cluster galaxies is 1.2 and 1.8, respectively [Andreon (1996) for Coma and Young and Currie (1998) for Virgo], while the models with $\tau = 0.1$ and $\tau = 5$ Gyr give $B - R_C = 1.6$ and $B - R_C = 1.1$, respectively, at an age of 12 Gyr. We also set the lower limit of $z_F$ to be 2 following the traditional pure luminosity evolution models which assume that elliptical/S0 galaxies and spiral galaxies are formed at high redshifts ($z \gtrsim 2$) and which broadly succeed in reproducing the observed properties of these galaxies (e.g., Kodama et al. 1998; Shimasaku, Fukugita 1998).

Figure 6 compares the observed $L_B/M_B$ with the predictions. The predicted values of $L_B/M_B$ are normalized to match the observed value at $z = 0$. In other words, models are used to predict relative brightening (or fading) of $L_B$ as a function of $z$. Panels (a), (b), and (c) are for $z_F = \infty, 3$, and 2, respectively. From panel (a),
we find that all the models reproduce the observation. If, however, $z_p = 3$ is adopted [panel (b)], models with $\tau = 1$ and 2 Gyr give too steep brightening compared with the observation. This trend is strengthened for the $z_p = 2$ case [panel (c)]: the $\tau = 0.1$ Gyr model also becomes inconsistent with the observation, though the discrepancy is at less than 2$\sigma$ levels. The allowed range for $\tau$ is dependent on $z_p$, and we cannot rule out any value of $\tau$ on the basis of the current data if we permit $z_p = \infty$, though 'single burst' models with $\tau = 0.1$ Gyr and 'disk' models with $\tau = 5$ (and $\tau = 3$ Gyr models) match the observation for a wider range of $z_p$ toward lower redshifts than the other ($\tau = 1, 2$ Gyr) models.

It is interesting that 'single burst' ($\tau = 0.1$ Gyr) models and 'disk' ($\tau = 5$ Gyr) models are consistent with the observation. In this paragraph, we concentrate on these models, and examine which are more consistent with the observed luminosity evolution of individual galaxies in clusters. Various observations suggest that elliptical and S0 galaxies in clusters brighten by $\sim 1$ mag from $z = 0$ to $z = 1$, which is consistent with the single-burst model (e.g., Schade et al. 1997; Ellis et al. 1997; Kodama et al. 1998; van Dokkum et al. 1998). Spiral galaxies have also been found to brighten by $\sim 1$ mag (e.g., Schade et al. 1996), though observations are not as many as those of elliptical and S0 galaxies. The amounts of brightening of
E/S0 and spiral galaxies are similar to each other, and in agreement with the predictions of $\tau = 0.1$ Gyr models (with $z_p > 3$) and $\tau = 5$ Gyr models. However, because our distant clusters are rich clusters, it is likely that elliptical and S0 galaxies dominate in these clusters. Hence, the $\tau = 0.1$ Gyr models seem to be more plausible for describing the evolution of $L_B/M_b$. This is also supported by the fact that the mean color of galaxies in the Coma cluster, which is a very rich nearby cluster and is likely to be a counterpart of the distant clusters studied here, agrees with the color predicted by the $\tau = 0.1$ Gyr models.

van Dokkum et al. (1998) present observations of $M/L$ ratio in the $B$ band of early-type galaxies in five clusters at $0.02 \leq z \leq 0.83$. They find that the $M/L$ ratio evolves as $\Delta \log M/L_B \propto -0.40 z$ ($\Omega_0 = 0.3$, $\lambda_0 = 0$), which is consistent with single-burst models with $z_p > 1.7-2.8$. If the evolution of $M/L$ found by van Dokkum et al. (1998) is understood as pure luminosity evolution of $L_B$, the formula $\Delta \log M/L_B \propto -0.40 z$ implies that $L_B$ brightens by a factor of 2.5 from $z = 0$ to 1, which is in excellent agreement with the brightening of $L_B/M_b$ found in this study. Measurements of $M/L$ of individual galaxies are a direct measurement of the effects of luminosity evolution occurred in galaxies, while measurements of $L_B/M_b$ of clusters are less direct. Note, however, that information contained in $L_B/M_b$ is different from that in $M/L$ of individual galaxies. The quantity $L_B/M_b$ describes the evolution of luminosity summed over all galaxies in clusters. $L_B/M_b$ also gives us a hint about the star-formation efficiency in clusters (see below). In any case, the agreement of brightening between $M/L_B$ and $L_B/M_b$ found here can be regarded as indirect support of our conclusion that single-burst like models seem to be plausible for describing the evolution of $L_B/M_b$.

The absolute value of $L_B/M_b$ gives us a hint about the star-formation efficiency in clusters, i.e., the fraction of baryons in clusters used to form stars. If the star-formation efficiency differs among clusters, the absolute value of $L_B/M_b$ would also vary from cluster to cluster. The fact that there exist models, such as those with $\tau = 0.1$ Gyr, which reproduce the observed $L_B/M_b$ of many clusters at different redshifts within the observational errors suggest that the star-formation efficiency is universal among clusters up to $z \sim 1$.

In order to see when baryons are converted into stars, we plot in figure 7 the predicted evolution of $M_*/M_b$, where the evolution of $M_*$ is calculated from mass-to-luminosity ratios of galaxies predicted by the $z_p = 3$ models. The values of $M_*/M_b$ at $z = 0$ have been normalized so that they are consistent with the observed $L_B/M_b$ of the nearby clusters: $M_*/M_b(z = 0) = (M/L_B)_{\text{best}}(z = 0) \times (L_B/M_b)_{\text{obs}}(z = 0)$. The predicted values of $M_*/M_b$ at $z = 0$ are 0.05–0.13, depending on $\tau$, and are consistent with the observed value (the filled square with an error bar). This simply implies that the predicted $(M/L_B)_*$ values at $z = 0$ fall within $(6 \pm 3) h (M/L_B)_0$, which is the adopted value of $(M/L_B)_*$ for galaxies in nearby clusters. As expected, the evolution of $M_*/M_b$ largely differs among the models. A constant $M_*/M_b$ is predicted by the $\tau = 0.1$ Gyr model in the redshift range of this figure, while for the $\tau = 5$ Gyr model, half of the stars present today were formed at $z < 1$.

Finally, we mention how to put stronger constraints on models using the evolution of $L_B/M_b$. Unfortunately, the steepness of brightening up to $z = 1$ is not a monotonic function of $\tau$: the brightening is steepest for $\tau = 1 - 2$ Gyr models, and models with $\tau = 0.1$ Gyr and $\tau = 3 - 5$ Gyr give similar brightening. In order to place further constraints using the evolution of $L_B/M_b$, one needs data at $z > 1$: for example, for $z_p = 3$ and 2, $\tau = 0.1$ Gyr models predict much steeper brightening at $z > 1$ than $\tau = 5$ Gyr models.

3.2. Comparison with Evolution of Field Galaxies

The quantity $L_B/M_b$ is the $B$-band luminosity per unit baryon in clusters. The corresponding quantity for field galaxies is the ratio of the blue luminosity density, $l_B[M_L/M_b\, \text{MPc}^{-3}]$, to the mean baryon density, $\rho_b[M_b/H_0 \, \text{MPc}^{-3}]$. In this subsection, we derive $l_B/\rho_b$ of field galaxies up to $z \sim 1$ from the literature and compare...
them with $L_B/M_b$ of clusters.

Data of $I_B$ are taken (or computed) from recent measurements of the luminosity function based on redshift surveys: Lilly et al. (1996; CFRS; data points are at $z = 0.35, 0.625, 0.875$), Ellis et al. (1996; Autofib; $z = 0.085, 0.25, 0.55$), Colless (1998; 2dF; $z = 0.11$), Loveday et al. (1992; APM; $z \simeq 0.05$), Zucca et al. (1997; ESP; $z \simeq 0.1$), and Marzke et al. (1998; SSRS2; $z \simeq 0.025$).

Lilly et al. (1996) give $l_B$, itself, while the other papers give only luminosity functions in the $B$ band. For those, except for Lilly et al. (1996), we integrate the luminosity function given in each paper from $M_B = -25$ to $-10$ to obtain $l_B$.

In order to compute $\rho_b$, we adopt $\Omega_b = 0.02 h^{-2}$ following Tytler and his coworkers’ results (e.g., Burles, Tytler 1998). Their estimates of $\Omega_b$ are based on measurements of the deuterium abundance (D/H) of QSO absorption systems at high redshifts. Note that the measurements of $\Omega_b$ have not completely converged among authors, ranging from $\Omega_b h^2 \simeq 0.01$ to 0.02, though Tytler et al.’s measurements seem to be the most reliable (e.g., Turner 1999).

The $l_B/\rho_b$ of field galaxies discussed above are plotted in figure 8 as open circles with error bars. A gradual increase in $l_B/\rho_b$ with redshift is seen. This is due to a brightening of $l_B$. For field galaxies, the global star formation rate ($\dot{\rho}_L [M_b \text{ yr}^{-1} \text{ Mpc}^{-3}]$) has also been measured from UV and emission-line luminosities of galaxies (e.g., Madau et al. 1998; for recent observations, see Cowie et al. 1999). These measurements suggest that $\dot{\rho}_L$ increases by a factor of $\sim 3$–$10$ from $z = 0$ to 1, but the scatter among the data is still large.

A fact which needs attention is that the values of $l_B/\rho_b$ at $z \lesssim 0.05$ are smaller than those at $z \simeq 0.1$ by as large as a factor of $\simeq 2$. It is unlikely that the luminosity density evolves so rapidly for such a short time from $z = 0.1$ to the present. A possible explanation for this problem is that the number density of galaxies in the local ($z \lesssim 0.1$) universe happens to be lower than the global value (e.g., Marzke et al. 1998), though further investigations are needed in order to prove or disprove this explanation. In this paper, we regard the values at $z \simeq 0.1$ as the local ($z = 0$) value.

### 3.2.1. Local values for $L_B/M_b$ and $I_B/\rho_b$.

The filled circles in figure 8 indicate the $L_B/M_b$ of the distant clusters of galaxies. The filled square at $z = 0$ corresponds to the average of the nearby clusters. We find that the local $L_B/M_b$ agrees with the local $l_B/\rho_b$: $L_B/M_b$ is $(0.024 \pm 0.004) (L_B/M_b)^{0.02}$ and the average of the three $l_B/\rho_b$ values at $z \simeq 0.1$ is $(0.026 \pm 0.002) (L_B/M_b)^{0.02}$.

The agreement found here does not hold if very different values for $\Omega_b$ and $h$ are adopted, because (i) $l_B/\rho_b$ changes linearly with $\Omega_b^{0.02}$ and (ii) the dependence of $l_B/\rho_b$ and $L_B/M_b$ on $h$ is different ($l_B/\rho_b \propto h$ if $\Omega_b h^2$ is fixed, while $L_B/M_b \propto h^{0.02}$), though we think that the values of $\Omega_b$ and $h$ adopted in this paper are the most probable at present.

This agreement implies that the blue luminosity per unit baryon mass is very close between clusters and fields. Then, the next question may be whether the stellar mass per unit baryon mass ($M_*/M_b$), i.e., the starformation efficiency, is the same between clusters and fields. [Note that morphological type mix largely differs between clusters and fields and that $(M/L_B)_b$ of galaxies varies with morphology.] In order to examine this, we do a simple (but more detailed than that given in subsection 2.1) estimation of $M_*/M_b$ of clusters and fields below. We assume the $(M/L_B)_b$ of elliptical and S0 galaxies to be $8 h (M/L_B)_b$ and that of spiral and irregular galaxies to be $4 h (M/L_B)_b$. The value for elliptical and S0 galaxies is based on van der Marel’s (1991) study, which found that the $M/L_B$ of elliptical galaxies with $1 \times 10^{10} h^{-2} L_B$ is $8.4 h (M/L_B)_b$. The value for the galactic disk, $M/L_B \simeq 3 (M/L_B)_b$, is adopted as the value for spiral and irregular galaxies ($4 h \simeq 3$ for $h = 0.7$). Using these values and taking account of the mean morphological type mix of the 12 clusters, we obtain $M_*/M_b = 0.114 \pm 0.020$. A similar calculation for the field galaxies gives $M_*/M_b = 0.097 \pm 0.009$. (We use the type mix given in Colless 1998: $l_B(E+S0)/l_B(\text{tot}) =$
3.2.2. Evolution of $L_B/M_b$ and $l_B/\rho_b$

From figure 8, it is found that the evolution of $L_B/M_b$ as a function of redshift is the same as that for $l_B/\rho_b$ within the observational errors. Both 'brighten' by a factor of 2-3 from $z = 0$ to $z = 1$.

The agreement between the evolution of $L_B/M_b$ and $l_B/\rho_b$ may be interpreted as the mean star formation history of cluster galaxies being similar to that of field galaxies. However, we think that this agreement is probably superficial. The observed global star-formation rate of field galaxies increases by a factor of ~3-10 from the present epoch to $z = 1$, and then has a peak at $z = 1-2$ (e.g., Madau et al. 1998; Cowie et al. 1999).

Though this star-formation history, which reproduces the observed evolution of $l_B/\rho_b$ as well, should be a solution for the mean star-formation history of cluster galaxies, quite different models can also be solutions, as shown in subsection 3.1. Simple models having just two parameters ($\tau$ and $z_p$) were examined in subsection 3.1, and many models have been found to reproduce the observed evolution of $L_B/M_b$, and the color of galaxies in nearby rich clusters suggests that $\tau = 0.1$ Gyr models are favored (see subsection 3.1).

In any case, we cannot give any clear conclusion about the mean star-formation history of cluster galaxies on the basis of the current data. As mentioned in subsection 3.1, data at $z > 1$ are useful to place further constraints on the star-formation history. More desirable may be data of the ultraviolet luminosity per unit baryon mass, $L_{UV}/M_b$, from which one can measure the star-formation rate (and efficiency) directly.

4. Conclusions

We have derived $L_B/M_b$ for massive ($M_{gas}$ at the Abell radius is $\geq 1 \times 10^{13} h^{-2.5} M_\odot$) clusters of galaxies up to $z \approx 1$ from optical and X-ray data in the literature. Twenty-two clusters in our sample are at $z > 0.1$. Assuming that the relative mix of hot gas and galaxies in clusters does not change (i.e., no segregation in hot gas or galaxies) during cluster evolution, we use $L_B/M_b$ to probe the star-formation history of the galaxy population as a whole in clusters. We have found that the $L_B/M_b$ of clusters increases with redshift from $L_B/M_b = 0.024 (L_B/M_b)_0$ ($z = 0$) to $\approx 0.06 (L_B/M_b)_0$ ($z = 1$), indicating a factor of ~2-3 brightening. This amount of brightening is almost identical to the brightening of the $M/L_B$ ratio of early-type galaxies in clusters at $0.02 \leq z \leq 0.83$ reported by van Dokkum et al. (1998).

We have compared this result with luminosity evolution models for the galaxy population as a whole by changing the e-folding time of star formation, $\tau$, by $0.1 \leq \tau \leq 5$ Gyr and the formation redshift, $z_p$, by $2 \leq z_F < \infty$. We have found that 'single burst' models ($\tau = 0.1$ Gyr models) with $z_p \geq 3$ and 'disk' models ($\tau = 5$ Gyr) with arbitrary $z_F$ are consistent with the observed brightening of blue luminosity to $z = 1$, while models with $1 \leq \tau \leq 2$ Gyr tend to predict brightening that is too steep though we cannot rule out these models.

We have also derived the ratio of the blue luminosity density to the baryon density, $L_B/\rho_b$, for field galaxies up to $z \approx 1$ from various existing data, adopting $\Omega_b h^2 = 0.02$, and have found that the observed evolution of $L_B/M_b$ agrees with that of $L_B/\rho_b$, including the absolute values, from the present epoch to $z \approx 1$ within the observational uncertainties, indicating that blue luminosity per unit baryon mass is similar between clusters and fields up to $z \approx 1$. We have made a simple estimate of the star-formation efficiency ($M_*/M_b$) to find no difference between clusters and fields. To place further constraints on the mean star-formation history of cluster galaxies needs new data at higher redshifts or direct measurements of the star-formation rate.

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