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

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Abstract

We derive the ratio of total blue luminosity to total baryon mass, \( L_B/M_b \), for massive \( (M_{\text{gas}} \text{ at the Abell radius is } \geq 1 \times 10^{13} h^{-2.5} M_\odot) \) clusters of galaxies up to \( z \simeq 1 \) 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 \( L_B/M_b = 0.024(L_B/M)_{\odot} \) at \( z = 0 \) to \( \simeq 0.06(L_B/M)_{\odot} \) at \( z = 1 \), indicating a factor of \( 2 - 3 \) brightening (we assume \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). This amount of brightening is almost identical to the brightening of the \( M/L_B \) ratio of early-type galaxies in clusters at \( 0.02 \leq z \leq 0.83 \) reported by van Dokkum et al. (1998). 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 \( 0.1 \leq \tau \leq 5 \text{ Gyr} \) and the formation redshift \( z_F \) by \( 2 \leq z_F < \infty \). We find that \( \tau = 0.1 \text{ Gyr} \) ‘single burst’ models with \( z_F \geq 3 \) and \( \tau = 5 \text{ Gyr} \) ‘disk’ models with arbitrary \( z_F \) are consistent with the observed brightening, while models with \( \tau = 1 - 2 \text{ Gyr} \) tend to predict too steep brightening. We also derive the ratio of blue luminosity density to baryon density for field galaxies, adopting \( \Omega_b h^2 = 0.02 \), and find that blue luminosity per unit baryon is similar in clusters and in fields up to \( z \simeq 1 \) within the observational uncertainties.

Key words: Galaxies: clusters of — Galaxies: photometry — Galaxies: X-rays

1. Introduction

Clusters of galaxies are suitable objects for studying the evolution of galaxies in the 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 \( z \sim 1 \). The evolution of elliptical and S0 galaxies has been found to be reproduced well by the so-called single burst model (e.g., Schade, Barrientos, López-Cruz 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 redshift up to \( z \simeq 0.5 \), 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 \( z \simeq 0.5 \) (Dressler et al. 1997). An attempt of measuring the star formation rate of individual galaxies has also started (e.g., Balogh et al. 1998; Poggianti et al. 1999).

In this paper, we study 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 total blue luminosity \( (L_B) \) to total baryon mass \( (M_b) \) for clusters of galaxies up to \( z \simeq 1 \). 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 \( \lambda_M \) in various wavelengths has been measured by many workers on the basis of observations of field galaxies (e.g., Lilly et al. 1996; Madau, Pozzetti, Dickinson 1998). If the density parameter of baryons \( (\Omega_b) \) is given, one can compute from \( \lambda_M \) the mean luminosity per unit baryon mass in fields \( (\lambda_{bM}) \). We will derive B-band \( \lambda_{bM} \) in fields up to \( z \simeq 1 \) 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 \( \lambda_{bM} \) in fields is also given in section 3. We summarize our conclusions in section 4.

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 km s$^{-1}$ 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). To adopt 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 a lot of measurements of luminosity density of field galaxies in the $B$ band, which enables us to compare $L_B/M_b$ with $I_B/\rho_b$.

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 total $V$-band luminosity ($L_V$), morphological type mix of galaxies (E, S0, and S), and gas mass within a radius of $1.5h^{-1}$ 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 the 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 SO galaxies to the total luminosity for 18 clusters with 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 type mix. This implies that $L_V/M_{\text{gas}}$ is not sensitive to the 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 has 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 will see in the next subsection that all 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 and distant clusters.

For Arnaud et al.’s (1992) clusters which have morphological type mix, we compute total $B$-band luminosity ($L_B$) from $L_V$ using $B - V = 0.96$ (E), $0.85$ (S0), and $0.68$ (S) (see Fukugita, Shimasaku, Ichikawa 1995). For clusters without type mix data, we adopt $B - V = 0.85 \pm 0.2$ as the average color of galaxies. We compute baryon mass $M_b$ from gas mass $M_{\text{gas}}$ using:

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

where $(M/L_B)_\odot$ is the mean mass-to-luminosity ratio of the stellar population in galaxies. We neglect atomic and molecular gas in galaxies. We adopt $(M/L_B)_\odot = (6 \pm 3) h(M/L_B)_\odot$, 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, Couteau 1997). The errors in $L_B/M_b$ contain (i) errors in $L_V$ 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 $(M/L_B)_\odot$, 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 seen in figure 1, a clear trend is seen in figure 3 that clusters with $M_{\text{gas}} \lesssim 1 \times 10^{13} h^{-2.5} M_\odot$ have 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

$$L_B/M_b = (0.024 \pm 0.0004) (L_B/M_\odot).$$  \hspace{1cm} (2)

which we regard as the representative value for the present-day clusters. The contribution from elliptical and S0 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 $L_B/(E + S0)/L_B(\odot) = 45\%$.

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

2.2. Distant Clusters

Searching for 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 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 $M_{\text{gas}}$ by $M_b = M_{\text{gas}} + M_*$, we use $M_*/M_b = 0.10$ ($h = 0.7$) which is the value for the nearby clusters. Distant clusters may have lower $M_*/M_b$ values than the nearby clusters, but the uncertainties in $L_B/M_b$ due to this effect are at most $\approx 10\%$, which is negligible for our discussion. Below are the 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 Crimelé, Nesvi, Trévès's (1997) sample. This sample consists of 12 clusters with $z < 0.2$ for which $M_{\text{gas}}$ 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 $M_{\text{gas}}$ and $L_B$ from Squires et al. (1996).

(iii) Abell 2163 ($z = 0.20$) $M_{\text{gas}}$ 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) CL0500-24 ($z = 0.32$) $M_{\text{gas}}$ 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) CL0939+47 ($z = 0.41$) Schindler et al. (1998) found two substructures in this cluster, implying that this cluster has not been virialized yet. $M_{\text{gas}}$ 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) RXJ1347.5-1145 ($z = 0.45$) $M_{\text{gas}}$ 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.

(vii) CL0016+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%.

(viii) AXJ2019+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 rest-frame $B - V = 0.7 \pm 0.3$, which roughly covers the expected colors of elliptical and spiral galaxies at $z = 1$.

CNOC 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 5 of Carlberg et al. (1996). CL0016+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 $r = 1.67 h^{-1}$ Mpc, which is very close to the virial radius where $r$-band luminosity
is measured. The number of the CNOC 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 that the $L_B/M_b$ of the Coma cluster is nearly constant between a radius of $\sim 0.4 h^{-1}$ Mpc and the Abell radius (Taguchi et al. 1999). In this paper, we assume that the values of $L_B/M_b$ derived here represent the global values of individual clusters (For CL0939+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 $0 \leq z \leq 0.4$ and $0.4 < z \leq 0.7$, 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 gas mass is similar between the nearby and distant clusters: there is no distant cluster near $L_B/M_b$ increases with $z$, from $L_B/M_b = 0.024(L_B/M)_0$ at $z = 0$ to $\approx 0.06(L_B/M)_0$ at $z = 1$, though the error in each distant cluster is fairly large. CL0939+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 the 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 mergings 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 $\approx 1$ mag of the galaxy population. In the next subsection, we compare the observed brightening with predictions of simple luminosity evolution models of galaxies.

## 3. 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 the nearby clusters. Clusters without errors (but for CL0939+47 and CL0016+16) are the CNOC clusters. Lines indicate model predictions, which will be 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 $\approx 0.06(L_B/M)_0$ at $z = 1$, though the error in each distant cluster is fairly large. CL0939+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.

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### 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 $B$-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 $z_F = 2, 3, \text{ and } \infty$. 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 observed properties of these galaxies (e.g., Kodama et al. 1998; Shimasaku and Fukugita 1998).

Figure 6 compares the observed $L_B/M_b$ with predictions. 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, $z_F = 3$ 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 $z_F = 2$ 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 $z_F$, and we cannot rule out any value of $\tau$ on the basis of the current data if we permit $z_F = \infty$, 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 $z_F$ 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, Barrientos, López-Cruz 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 they are in agreement with the predictions of $\tau = 0.1$ Gyr models (with $z_F \geq 3$) and $\tau = 5$ Gyr models. However, our distant clusters are rich clusters and thus 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 $\Delta \log M/L_B \propto -0.4 z$ ($\Omega_0 = 0.3, \lambda_0 = 0$), which is consistent with single-burst models with $z_F > 1.7 - 2.8$. If the evolution of $M/L$ found by van Dokkum et al. (1998) is understood as pure luminosity evolution of $L_B$, the formula $\Delta \log M/L_B \propto -0.4 z$ 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 to 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 $L_B/M_b$ tells us a hint to 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 $z_F = 3$ 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. 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 are 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

$$M_*/M_b(z = 0) = (M/L_B)^{\text{pred}}(z = 0) \times (L_B/M_b)_{\text{obs}}(z = 0)$$
function of τ: the brightening is the steepest for τ = 1−2 Gyr models, and models with τ = 0.1 Gyr and τ = 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 \( z_f = 3 \) and 2, τ = 0.1 Gyr models predict much steeper brightening at \( z > 1 \) than τ = 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 \( l_B [L_{B⊙}\text{ Mpc}^{-3}] \) to the mean baryon density \( ρ_b [M_{b⊙}\text{ Mpc}^{-3}] \). In this subsection, we derive \( l_B/ρ_b \) of field galaxies up to \( z \approx 1 \) from the literature and compare it with \( L_B/M_b \) of clusters.

Data of \( l_B \) are taken (or computed) from recent measurements of 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; \( z \approx 0.05 \)), Zucca et al. (1997; ESP; \( z \approx 0.1 \)), and Marzke et al. (1998; SSRS2; \( z \approx 0.025 \)). 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 \( ρ_b \), we adopt \( Ω_b = 0.02h^{-2} \) following Tytler and his coworkers’ results (e.g., Burles, Tytler 1998). Their estimates of \( Ω_b \) are based on measurements of deuterium abundance \((D/H)\) of QSO absorption systems at high redshifts. Note that the measurements of \( Ω_b \) have not completely converged among authors, ranging from \( Ω_b h^2 \approx 0.01 \) to 0.02, though Tytler et al.’s measurements seem to be the most reliable (e.g., Turner 1999).

The \( l_B/ρ_b \) of field galaxies calculated above are plotted in figure 8 as open circles with error bars. A gradual increase in \( l_B/ρ_b \) with redshift is seen. This is due to the brightening of \( l_B \).

A fact which needs attention is that the values of \( l_B/ρ_b \) at \( z \leq 0.05 \) are smaller than those at \( z \approx 0.1 \) by as large as a factor of \( \approx 2 \). 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 \((z \leq 0.1)\) 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.

3.2.1. Local values for \( L_B/M_b \) and \( l_B/ρ_b \)

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 \( l_B/ρ_b \): \( L_B/M_b \) is \((0.024±0.004)(L_B/M_b)_⊙ \) and the average of the three \( l_B/ρ_b \) values at \( z \approx 0.1 \) is \((0.026±0.002)(L_B/M_b)_⊙ \).

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 star formation efficiency, is the same between clusters and fields (Note that morphological type mix largely differs between clusters and fields and that \((M/L_B)_* \) of galaxies varies with morphology). In order to examine this, we do a simple (but more detailed than that given in §2.1) estimation of \( M_*/M_b \) of clusters and fields below. We assume the \((M/L_B)_* \) of elliptical and S0 galaxies to be \( 8h(M/L_B)_⊙ \) and of that of spiral and irregular galaxies to be \( 4h(M/L_B)_⊙ \). Using these values and taking account of the mean morphological type mix of the 12 clusters, we obtain \( M_*/M_b = 0.114±0.020 \). A similar calculation for the field galaxies gives \( M_*/M_b = 0.097±0.009 \) (We use the type mix given in Colless 1998: \( l_B(E+S)/l_B(\text{tot}) = 34.5\% \) and \( l_B(S+Irr)/l_B(\text{tot}) = 65.5\% \)). Hence, the \( M_*/M_b \) of clusters is in agreement with that in fields within errors. Renzini (1997) has also obtained a similar result from a rough calculation for \( M_*/M_b \) of the Coma cluster and field galaxies.

3.2.2. Evolution of \( L_B/M_b \) and \( l_B/ρ_b \)

From figure 8, it is found that the evolution of \( L_B/M_b \) as a function of redshift is the same as for \( l_B/ρ_b \) 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 \( l_B/ρ_b \) 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 \( \sim 3−10 \) 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 $L_B/M_b$ as well, should be a solution for the mean star formation history of cluster galaxies, quite different models can also be solutions, as has been seen in §3.1. Simple models having just two parameters ($\tau$ and $z_f$) were examined in §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 §3.1).

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

4. Conclusions

We have derived $L_B/M_b$ for massive ($M_{gas}$ at the Abell radius is $> 1 \times 10^{13} h^{-2.5} M_\odot$) 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 $L_B/M_b = 0.024(L_B/M)_\odot (z = 0)$ to $0.06(L_B/M)_\odot (z = 1)$, indicating a factor of $\sim 2 - 3$ 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 $z_f$ by $2 \leq z_f < \infty$. We have found that ‘single burst’ models ($\tau = 0.1$ Gyr models) with $z_f > 3$ 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 too steep brightening though we cannot rule out these models.

We have also derived the ratio of blue luminosity density to baryon density, $l_B/\rho_b$, for field galaxies up to $z \approx 1$ from various existing data, adopting $\Omega_m h^2 = 0.02$, 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 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 star formation rate.

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References

Andreon, S. 1996, A&A 314, 763
Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., Vangioni-Flam, E. 1992, A&A 254, 49
Bahcall, J. N. 1984, ApJ 287, 926
Balogh, M., Schade, D., Morris, S. L., Yee, H. K. C., Carlberg, R. G., Ellington, E. 1998, ApJ 504, L75
Benitez, N., Broadhurst, T., Rosati, P., Courbin, F., Squires, G., Lidman, C., Magain, P. 1998, astro-ph/9812218
Broeils, A. H., Couteau, S. 1996, in Dark and Visible Matter in Galaxies, ASP Conference Series, Vol. 117; 1997; ed. M. Persic and P. Salucci, p74
Burles, S., Tytler, D. 1998, ApJ 507, 732
Carlberg, R. G., Yee, H. K. C., Ellington, E., Abraham, R., Gravel, P., Morris, S., Pritchet, C. J. 1996, ApJ 462, 32
Cirimele, G., Nesli, R., Trèvese, D. 1997, ApJ 475, 11
Colless, M. 1998, astro-ph/9804077
Cowie, L. L., Songaila, A., Barger, A. J. 1999, astro-ph/9904345
Dressler, A., Oemler, A., Jr., Couch, W. J., Smail, I., Ellis, R. S., Barger, A., Butcher, H., Poggianti, B. M., et al. 1997, ApJ 490, 577
Ellis, R. S., Colless, M., Broadhurst, T., Hely, J., Glazebrook, K. 1996, MNRAS 280, 235
Ellis, R. S., Smail, I., Dressler, A., Couch, W. J., Oemler, A., Jr., Butcher, H., Sharples, R. M. 1997, ApJ 483, 582
Fischer, P., Tyson, A. J. 1997, AJ 114, 14
Freedman, W. L. 1999, astro-ph/9905222
Fukugita, M., Shimasaku, K., Ichikawa, T. 1995, PASP 107, 945
Hattori, M., Ikebe, Y., Asaoka, I., Takeshima, T., Böhringer, H., Mihara, T., Neumann, D. M., Schindler, S., Tsuru, T., Tamura, T. 1997, Nature 388, 146
Infante, L., Fouque, P., Hertling, G., Way, M. J., Giraud, E., Quintana, H. 1994, A&A 289, 381
Kodama, T., Arimoto, N. 1997, A&A 320, 41
Kodama, T., Arimoto, N., Barger, A. J., Aragón-Salamanca, A. 1998, A&A 334, 99
Lewis, A. D., Ellingson, E., Morris, S. L., Carlberg, R. G. 1999, ApJ 517, 587
Lilly, S. J., Le Fèvre, O., Hammer, F., Crampton, D. 1996, ApJ 460, L1
Lilly, S. J., Schade, D., Ellis, R., Le Fèvre, O., Brinchmann, J., Tresse, L., Abraham, R., Hammer, F., et al. 1998, ApJ 500, 75
Loveday, J., Peterson, B. A., Efstathiou, G., Maddox, S. J. 1992, ApJ 390, 338
Madau, P., Pozzetti, L., Dickinson, M. 1998, ApJ 498, 106
Marzke, R. O., da Costa, L. N., Pellegrini, P. S., Willner, C. N. A., Geller, M. J. 1998, ApJ 503, 617
Neumann, D. M., Böhringer, H. 1997, MNRAS 289, 123
Renzini A. 1997, ApJ 488, 35
Pizzella, A., Amico, P., Bertola, F., Buson, L. M., Danziger, I. J., Dejonghe, H., Sadler, E. M., Saglia, R. P., de Zeeuw, P. T., & Zeilinger, W. W. 1997, A&A 323, 349
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, A., Butcher, H., Ellis, R. S., Oemler, A., Jr., 1999, ApJ 518, 576
Sahu, K. C., Shaw, R. A., Kaiser, M. E., Baum, S. A., Ferguson, H. C., Hayes, J. J. E., Gull, T. R., Hill, R. J., Hutchings, J. B., Kimble, R. A., Plait, P., & Woodgate, B. E. 1998, ApJ 492, L125
Schade, D., Carlberg, R. G., Yee, H. K. C., López-Cruz, O., Ellingson, E. 1996, ApJ 465, L103
Schade, D., Barrientos, L. F., López-Cruz, O. 1997, ApJ 477, L17
Schindler, S. 1999, astro-ph/9908130
Schindler, S., Belloni, P., Ikebe, Y., Hattori, M., Wambsganss, J., Tanaka, Y. 1998, A&A 338, 843
Schindler, S., Wambsganss, J. 1997, A&A 322, 66
Shimasaku, K., Fukugita, M. 1998, ApJ 501, 578
Squires, G., Kaiser, N., Babul, A., Fahlman, G., Woods, D., Neumann, D. M., Böhringer, H. 1996, ApJ 461, 572
Squires, G., Neumann, D. M., Kaiser, N., Arnaud, M., Babul, A., Böhringer, H., Fahlman, G., Woods, D. 1997, ApJ 482, 648
Taguchi, H., Shimasaku, K., Doi, M., Okamura, S. 1999, in preparation
Turner, M. S. 1999, astro-ph/9904051
van der Marel, R. P. 1991, MNRAS 253, 710
van Dokkum, P. G., Franx, M., Kelson, D. D., Illingworth, G. D. 1998, ApJ 504, L17
Vogt, N. P., Phillips, A. C., Faber, S. M., Gallego, J., Gronwall, C., Guzmán, R., Illingworth, D., Koo, D. C., & Lowenthal, J. D. 1997, ApJ 479, L121
Young, C. K., Currie, M. J. 1998, A&AS 127, 367
Zucca, E., Zamorani, G., Vettolani, G., Cappi, A., Mignoli, R., Mignoli, M., Stirpe, G. M., MacGillivray, H., et al. 1997, A&A 326, 477
Table 1. Distant Clusters.

| name          | $z$  | $L_B/M_\odot^a$ | $L_B^b$ | $M_{gas}^{1.5}$ | radius$^d$ | error$^e$ |
|---------------|------|-----------------|---------|-----------------|------------|-----------|
| A1413         | 0.14 | 0.028           | 7.6     | 2.42            | 0.77       | 21        |
| A1689         | 0.18 | 0.042           | 14.0    | 2.80            | 0.78       | 21        |
| A2218         | 0.18 | 0.043           | 8.4     | 1.81            | 0.42       | 33        |
| A2163         | 0.20 | 0.037           | 3.0     | 0.74            | 0.26       | 48        |
| CL0500-24     | 0.32 | 0.037           | 3.9     | 0.95            | 0.53       | 30        |
| CL0939+47     | 0.41 | 0.089           | 1.8     | 0.18            | 0.14       | —         |
| RXJ1347-5-1145| 0.45 | 0.053           | 65.7    | 11.3            | 1.09       | 37        |
| CL0016+16     | 0.55 | 0.044           | 50.6    | 10.4            | 1.67       | —         |
| AXJ2019+1127  | 1.01 | 0.075           | 5.6     | 0.68            | 0.30       | 30        |
| A2390         | 0.23 | 0.030           | 11.3    | 3.3             | 0.60       | —         |
| MS0302+16     | 0.42 | 0.055           | 5.1     | 0.84            | 0.60       | —         |
| MS0440+02     | 0.20 | 0.027           | 2.5     | 0.84            | 0.60       | —         |
| MS0451+02     | 0.20 | 0.021           | 6.3     | 2.7             | 0.60       | —         |
| MS0451-03     | 0.54 | 0.036           | 14.7    | 3.7             | 0.60       | —         |
| MS0839+29     | 0.19 | 0.054           | 4.5     | 0.74            | 0.60       | —         |
| MS0906+11     | 0.17 | 0.066           | 9.2     | 1.3             | 0.60       | —         |
| MS1006+12     | 0.26 | 0.028           | 6.4     | 2.0             | 0.60       | —         |
| MS1008-12     | 0.31 | 0.051           | 11.2    | 2.0             | 0.60       | —         |
| MS1224+20     | 0.33 | 0.066           | 7.1     | 0.98            | 0.60       | —         |
| MS1358+62     | 0.33 | 0.062           | 11.4    | 1.7             | 0.60       | —         |
| MS1455+22     | 0.26 | 0.021           | 4.9     | 2.1             | 0.60       | —         |
| MS1512+36     | 0.37 | 0.028           | 4.2     | 1.4             | 0.60       | —         |

a) In units of $h^{0.5}(L_B/M_\odot)$.
b) In units of $h^{-2} \times 10^{11}L_\odot$.
c) In units of $h^{-2.5} \times 10^{13}M_\odot$.
d) Radius in units of $h^{-1}$ Mpc adopted to measure $L_B$ and $M_{gas}$.
e) Relative error (%).
Figure Captions

Fig.1. $L_V$ plotted against $M_{\text{gas}}$ for Arnaud et al.’s (1992) nearby clusters. The filled and open circles indicate clusters with and without type mix data, respectively. The dashed and solid lines indicate the best fit of a power law to all and massive ($M_{\text{gas}} \geq 1 \times 10^{13} h^{-2.5} M_\odot$) clusters, respectively. The dotted line corresponds to the best fit of $L_V \propto M_{\text{gas}}$ to the massive clusters.

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.

Fig.4. $L_B$ versus $M_{\text{gas}}$ for the 12 nearby and the 22 distant clusters adopted in this paper. Filled circles indicate the nearby clusters. Open circles and crosses are for $0.1 < z \leq 0.4$ and $0.4 < z \leq 0.7$ clusters, respectively. The star corresponds to the most distant cluster AXJ2019+1127 at $z = 1.01$. The thick solid line indicates the best fit of $L_B \propto M_{\text{gas}}$ to the nearby clusters. The thin solid line and the dotted line correspond to a similar fit to the distant clusters at $0.1 < z \leq 0.4$ and $0.4 < z \leq 0.7$, respectively.

Fig.5. Dependence of the measurement of $L_B/M_{\text{gas}}$ on $\Omega_0$ and $\lambda_0$. The ratio of $L_B/M_{\text{gas}}(\Omega_0,\lambda_0)$ to $L_B/M_{\text{gas}}(0.2,0)$ is plotted as a function of redshift for $(\Omega_0,\lambda_0) = (1,0)$ and $(0.2,0.8)$ cases.

Fig.6. Observed $L_B/M_b$ of clusters as a function of redshift. The filled circles present the 22 distant clusters and the filled square indicates the average $L_B/M_b$ of the nearby clusters. Model predictions are overlaid. Predicted values of $L_B/M_b$ are normalized to match the observed value at $z = 0$. Panels (a), (b), and (c) are for $z_F = \infty, 3,$ and 2, respectively. Thick and thin solid lines indicate models with $\tau = 0.1$ and 1 Gyr, respectively. Dotted, dashed, and long-dashed lines correspond to models with $\tau = 2, 3,$ and 5 Gyr, respectively.

Fig.7. The ratio of stellar mass to baryon mass, plotted as a function of redshift. The five lines indicate predictions of models with different $\tau$. All models are for $z_F = 3$. The meanings of lines are the same as in figure 6. The filled square corresponds to the observed value.

Fig.8. $l_B/\rho_b$ of field galaxies as a function of redshift, compared with $L_B/M_b$ of clusters. The filled circles indicate the 22 distant clusters and the filled square is for the average $L_B/M_b$ of the nearby clusters. The open circles with error bars correspond to $l_B/\rho_b$ of field galaxies.
$L_v/M_{\text{gas}} \left( \frac{L_v}{M_{\odot}} \right)_{\odot}$

- $M_{\text{gas}}(h=1) < 10^{13} M_{\odot}$
- $M_{\text{gas}}(h=1) \geq 10^{13} M_{\odot}$
$(\Omega_0, \lambda_0) = (0.2, 0)$

\[ L_{B(\leq 1.5h^{-1}\text{Mpc})} \left[ h^{-2} L_{B,\odot} \right] \]

\[ M_{\text{gas}(\leq 1.5h^{-1}\text{Mpc})} \left[ h^{-2.5} M_\odot \right] \]

- $z \leq 0.1$
- $0.1 < z \leq 0.4$
- $0.4 < z \leq 0.7$
- $z > 0.7$
(a) $z_p = \infty$
(b) $z_F = 3$
(c) $z_F = 2$
$L_b/M_b$ or $L_b/\rho_b \ (L_b/\rho_b)_0$; $h=0.7$.