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THE FUNDAMENTAL PLANE OF CLUSTER ELLIPTICAL GALAXIES AT $z = 1.25$[1,2]

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ABSTRACT

Using deep *Hubble Space Telescope* Advanced Camera for Surveys imaging and Very Large Telescope FOcal Reducer/low dispersion Spectrograph 2 spectra, we determined the velocity dispersions, effective radii, and surface brightnesses for four early-type galaxies in the $z = 1.237$ cluster RDCS 1252.9−2927. All four galaxies are massive, greater than $10^{11}\ M_\odot$. These four galaxies, combined with three from RDCS 0848+4453 at $z = 1.276$, establish the fundamental plane of massive early-type cluster galaxies at $\bar{z} = 1.25$. The offset of the fundamental plane shows that the luminosity evolution in rest-frame B is $\Delta \ln (M/L_B) = (-0.98 \pm 0.06)z$ for galaxies with $M > 10^{11.5}\ M_\odot$. To reproduce the observed mass-to-light ratio (M/L) evolution, we determine the characteristic age of the stars in these $M > 10^{11.5}\ M_\odot$ galaxies to be $3.0^{+0.3}_{-0.3}$ Gyr; i.e., $z_* = 3.4^{+0.5}_{-0.4}$. Including selection effects caused by morphological bias (the "progenitor bias"), we estimate an age of $2.1^{+0.2}_{-0.2}$ Gyr, or $z_* = 2.3^{+0.2}_{-0.2}$ for the elliptical galaxy population. Massive cluster early-type galaxies appear to have a large fraction of stars that formed early in the history of the universe. However, there is a large scatter in the derived M/L values, which is confirmed by the spread in the galaxies' colors. Two lower mass galaxies in our $\bar{z} = 1.25$ sample have much lower M/L values, implying significant star formation close to the epoch of observation. Thus, even in the centers of massive clusters, there appears to have been significant star formation in some massive, $M \simeq 10^{11}\ M_\odot$, galaxies at $z \simeq 1.5$.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (RDCS 1252.9−2927) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: fundamental parameters — galaxies: photometry

1. INTRODUCTION

The fundamental plane (FP) allows one to directly measure the mass and the mass-to-light ratio, M/L, of early-type galaxies. The FP combines three variables: the effective radius (r_e), the average surface brightness within the effective radius (I_e), and the velocity dispersion (σ). These data are combined into the relation $\sigma^{1.20} \propto r_e I_e^{0.83}$ for the rest-frame B band (Jørgensen et al. 1996). With such quantities, we can measure $M/L \propto \sigma^2/r_e I_e$ and how it depends on mass, proportional to $r_e\sigma^2$. Massive galaxies out to $z \simeq 1$ appear to evolve as $\Delta \ln (M/L_B) \simeq z$ for both clusters (Kelson et al. 2000b; van Dokkum & Franx 2001; Wuyts et al. 2004) and in some field samples, although there is a larger scatter for the latter (van Dokkum et al. 2001; Gebhardt et al. 2003; van Dokkum & Ellis 2003; van de Ven et al. 2003; van der Wel et al. 2004a). This slow rate of evolution implies an early epoch of formation, $z_f \simeq 3$, for the stars in early-type galaxies, if we assume passively evolving simple stellar populations. However, at $z \simeq 1.25$, only ∼50% of the stellar mass we observe today has been formed (e.g., Madau et al. 1998; Steidel et al. 1999; Rudnick et al. 2003). This implies that the majority of stars in cluster early-type galaxies formed long before the average star in the universe. Observations determining the luminosity-weighted age of galaxies close to $z = 1.25$ will test this, and there are only three galaxies with FP measurements to date at these redshifts (van Dokkum & Stanford 2003).

We observed four luminous early-type galaxies in the $z = 1.237$ rich, massive, and X-ray luminous cluster of galaxies RDCS 1252.9−2927 (Rosati et al. 2004) using a combination of the Very Large Telescope (VLT) FOcal Reducer/low dispersion Spectrograph 2 (FORS2) and the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope* (*HST*). RDCS 1252.9−2927 is the most massive cluster found to date at $z > 1$; thus, it contains a number of luminous and, likely, massive galaxies. We use the FP to constrain the M/L evolution and set the mass scale for four galaxies in RDCS 1252.9−2927. These results, combined with those of van Dokkum & Stanford (2003), measure the ages of the stellar populations in early-type galaxies at $\bar{z} = 1.25$. We assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}. All observed magnitudes are in the AB system. However, for comparison with previous work, we convert observed magnitudes into rest-frame Johnson B using the Vega zero point.

2. RDCS 1252.9−2927 FUNDAMENTAL PLANE DATA

Four galaxies in RDCS 1252.9−2927 were selected from among the nine known cluster members (Demarco et al. 2005; Lidman et al. 2004) with $z_{850} < 22.5$ mag that fit into a single multislit mask. These are the first, second, third, and fifth brightest cluster members. An image of each is shown in Figure 1 along with the spectra, in descending order of brightness. Below we discuss the measurement of r_e and I_e from the ACS data, the σ from the FORS2 spectra, and the conversion to the rest-frame Johnson B.

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[2] Also based on observations obtained at the European Southern Observatory using the ESO Very Large Telescope on Cerro Paranal (ESO programme 169.A-0458).

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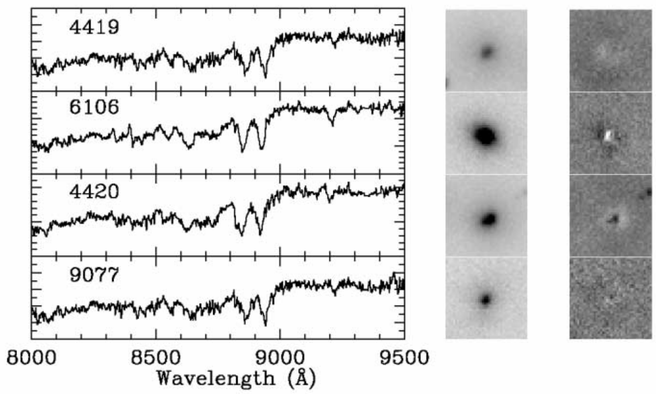

FIG. 1.—Mosaic showing, from left to right, the observed spectra near 4000 Å in the rest frame of the cluster, galaxy images, and images of the residuals. Each image is 2''.0 on a side with 0''.05 pixels from the z_{850} ACS data, corresponding to roughly rest-frame Johnson *B*. The fit results are listed in Table 1. The absolute value of flux in the residuals is ≤10% of the flux in the original data. For galaxies 4419 and 4420, the residuals have an "S" shape, which is interpreted as a sign of interaction (Blakeslee et al. 2003). The residuals for galaxy 6106 show an oversubtraction in the center; it is likely that the $r^{1/4}$ law is too steep; in this case, the best-fitting profile is proportional to $r^{1/3}$.

2.1. *HST ACS Imaging*

As described in Blakeslee et al. (2003), the ACS imaged RDCS 1252.9−2927 with four overlapping pointings. Each pointing has three orbits in the F775W filter, or i_{775}, and five orbits in the F850LP filter, or z_{850}. A de Vaucouleurs, or $r^{1/4}$ model, was fitted to each of the individual z_{850} images using the method of van Dokkum & Franx (1996). Each galaxy in each image had a unique point-spread function generated using the TinyTim version 6.2 package (Krist 1995). The two galaxies at the middle of the cluster, referred to as 4419 and 4420 in Table 1, were fitted simultaneously. Table 1 contains the average of the best-fitting parameters for each image with the galaxies listed in order of decreasing z_{850} flux. We plot in Figure 1 a mean image, corrected for the ACS distortion, of all the z_{850} images for each galaxy along with the average residuals from the fits.

The product $r_e I_e^{0.83}$ is used to measure the evolution in M/L. Because of the strong anticorrelation between the error for μ_e and the error for r_e (Jørgensen et al. 1993), the uncertainties on this product for all four galaxies is small at ≃5%.

2.2. *VLT FORS2 Spectra*

The four galaxies in Table 1 were observed using FORS2, on the VLT, through slit masks with the 600z grism in conjunction with the OG590 order separation filter. The observations were done in service mode with a series of exposures, dithered over four positions, for a total integration time of 24 hr. The resulting signal-to-noise ratios (S/Ns) at a 4100 Å rest frame are listed in Table 1. Details concerning the data reduction are described in van der Wel et al. (2004b).

The high spectral resolution, 80 km s^{-1} $pixel^{-1}$, resulted in accurate internal velocity dispersions for the four cluster members (see Table 1). The spectra were fitted, by the method of van Dokkum & Franx (1996), with stellar spectra (Valdes et al. 2004) with a wide range in spectral type and metallicity. For more details concerning the usage of the templates and the derivation of velocity dispersions, see van der Wel et al. (2004b).

The velocity dispersions were aperture-corrected to a 1.7 kpc circular aperture at the distance of Coma, as described in Jørgensen et al. (1996). The listed errors include a statistical error derived from the χ^2-value of the fit and a systematic error estimated to be at most 5% for the spectra with the lowest S/N.

2.3. *Rest-Frame Magnitudes*

In order to compare with other FP results in the literature, the observed z_{850} magnitudes must be converted into B_{rest}, the equivalent of observing the galaxies with a rest-frame Johnson *B* filter (Bessell 1990) in the Vega system. The z_{850} filter is centered at 4058 Å in the rest frame of the galaxies in RDCS 1252.9−2927. This filter is close to the central wavelength of Johnson *B* at 4350 Å, but even the modest wavelength difference means that the conversion between z_{850} at $z = 1.237$ and the Johnson *B* will depend on the color of the galaxy. To compute this conversion, we redshifted the Sbc and E templates from Coleman et al. (1980) to $z = 1.237$ and calculated the B_{rest} magnitude as a function of the observed z_{850} and $i_{775} - J$ color, yielding $B_{rest} = z_{850} - 0.45(i_{775} - J) + 1.68$. This approach is slightly different than that used in Kelson et al. (2000a) or van Dokkum & Stanford (2003) but yields results that differ in the mean by ≤0.02 mag, with an error of only ≤5% (see Holden et al. 2004). The *J*, along with K_s, photometry comes from the VLT ISAAC and New Technology Telescope SOFI observations discussed in Lidman et al. (2004). We will also use this data to examine the rest-frame optical $B - I$ colors below. All colors were measured within an aperture of 2 effective radii. The ACS imaging was smoothed to match the seeing in the ISAAC data to measure this color.

The statistical errors on the FP are dominated by the error on the velocity dispersions, which are around 10% including an estimate of the systematic error. Because this error dominates the error budget, we will take the error on σ to be the FP error for the rest of the Letter.

3. THE FUNDAMENTAL PLANE AT $\bar{z} = 1.25$

The most straightforward way to measure the evolution in M/L_B is to compute the offsets for the seven galaxies at $\bar{z} = 1.25$ from the FP of the Coma Cluster (Jørgensen et al. 1996). In Figure 2, we plot our data, along with the FP for Coma, using the rest-frame *B*. We show the average offset for the five

TABLE 1
DE VAUCOULEURS MODEL PARAMETERS AND VELOCITY DISPERSION

Galaxy	$r_{e,z}$ (arcsec)	μ_e[a] (mag $arcsec^{-2}$)	S/N[b] ($Å^{-1}$)	σ (km s^{-1})	$(i - J)_{2r_e}$[a] (mag)	log Mass (log $M_{\odot}$)	log (M/L_B)
4419	2.806	24.899	24	302 ± 24	2.09 ± 0.02	12.40 ± 0.08	0.81 ± 0.06
6106	0.487	21.573	57	294 ± 10	2.07 ± 0.02	11.61 ± 0.08	0.22 ± 0.03
4420	1.016	23.279	29	323 ± 21	2.11 ± 0.02	12.01 ± 0.06	0.66 ± 0.06
9077	1.008	23.529	24	130 ± 14	1.90 ± 0.02	11.22 ± 0.08	0.01 ± 0.09

[a] All magnitudes are AB.
[b] Spectra have a resolution of 3.7 Å (FWHM).

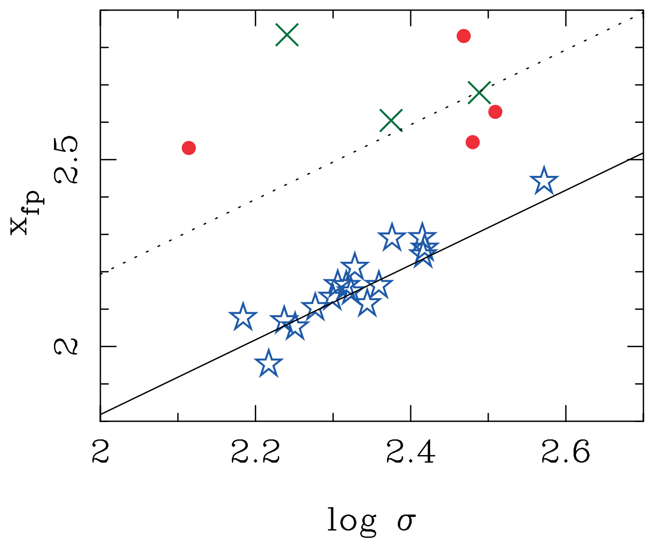

FIG. 2.—Projection of the FP for our sample and Coma. The results for RDCS 1252.9−2927 ($z = 1.237$) are plotted as filled red circles, the green crosses are from RDCS 0848+4453 (van Dokkum & Stanford 2003; $z = 1.276$), and the blue open star symbols are from Coma (Jørgensen et al. 1996; $z = 0.023$). The *y*-axis is $x_{\rm FP} = 0.83 \log r_e + 0.69 \log I_e$, one of the projections of the FP. The solid line is the FP for Coma, while the dotted line has the same slope but is shifted $\Delta M/L_B = -0.98$ for the five massive galaxies at $\bar{z} = 1.25$.

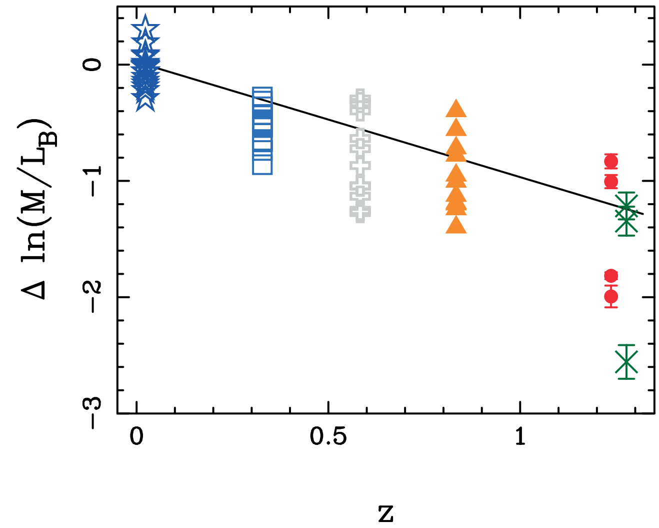

FIG. 3.—Change in M/L_B for early types as a function of redshift. We use the same symbols as in Fig. 2, with the addition of light blue open squares for MS 1358+62 (Kelson et al. 2000b; $z = 0.328$) and gray open plus signs from MS 2053−04 ($z = 0.583$) and filled orange triangles from MS 1054−03 ($z = 0.832$), both from Wuyts et al. (2004). The resulting evolution, with respect to the Coma FP, is shown as a line with the form $\Delta \ln (M/L_B) \propto (-0.98 \pm 0.06)z$.

most massive galaxies out of the total of seven in our sample. We will discuss below why we remove those two lower mass galaxies. Measuring the offset from the FP ensures that we are measuring $\Delta M/L_B$ for galaxies at the same part of the FP or roughly the same mass. The offset $\Delta M/L$ and rate of M/L_B evolution is readily apparent in Figure 3. We find $\overline{\Delta M/L_B} = -1.23 \pm 0.08$ for five $\bar{z} = 1.25$ early-type galaxies, three from RDCS 1252.9−2927 and two from RDCS 0848+4453 with masses $M > 10^{11.5}\ M_\odot$. This corresponds to an evolution in $\Delta \ln (M/L_B) \propto (-0.98 \pm 0.06)z$, a small deviation from the $\Delta \ln (M/L_B) \propto (-1.06 \pm 0.09)z$ of van Dokkum & Stanford (2003) and the $\Delta \ln (M/L_B) \propto -1.08z$ of Wuyts et al. (2004).

There is a large scatter seen in Figure 3 in $\Delta \ln (M/L_B)$, $\sigma [\ln (M/L_B)] = 0.32$ for the seven $\bar{z} = 1.25$, early-type galaxies. This scatter is twice the size of the scatter in Coma or MS 1358+62, regardless of whether the scatter is computed for all galaxies or only the seven most luminous galaxies in either MS 1358+62 or the Coma Cluster sample. A large part of this scatter comes from the two lower mass galaxies in the sample. The five galaxies with $M > 10^{11.5}\ M_\odot$ show $\sigma [\ln (M/L_B)] = 0.22$, which is not statistically different from the Coma or MS 1358+62 value. There is an obvious selection effect toward low M/L galaxies in a luminosity-selected sample. This may both increase the scatter and bias the mean change in the M/L ratio; hence, we remove the two low-mass galaxies from our sample.

The M/L_B values for the $M > 10^{11.5}\ M_\odot$ galaxies at $\bar{z} = 1.25$ correlate with the rest-frame $B - I$ colors, as seen in Figure 4. Both the colors and the M/L_B track a rapidly declining star formation rate model from Bruzual & Charlot (2003). As this relatively simple stellar population reproduces most of the observations, the observed scatter in M/L_B is then likely the result of a spread in the luminosity-weighted ages.

At lower redshifts, the M/L is a function of the total mass (Jørgensen et al. 1996). Such a trend is observed at $\bar{z} = 1.25$ (see Fig. 5), where lower mass galaxies have lower M/L_B and, therefore, bluer colors (see Fig. 4.) The slope of the mass-M/L relation appears to steepen at higher redshifts. This is expected for a population where the spread in the M/L comes from the spread in age. As a stellar population becomes younger, the M/L changes more quickly, so the spread in M/L will grow as observations probe closer to the epoch of formation. However, this trend will be exaggerated by the selection of galaxies at a fixed luminosity, as the sample selection will prefer lower M/L galaxies. Lower mass galaxies with larger values for M/L_B will not appear in

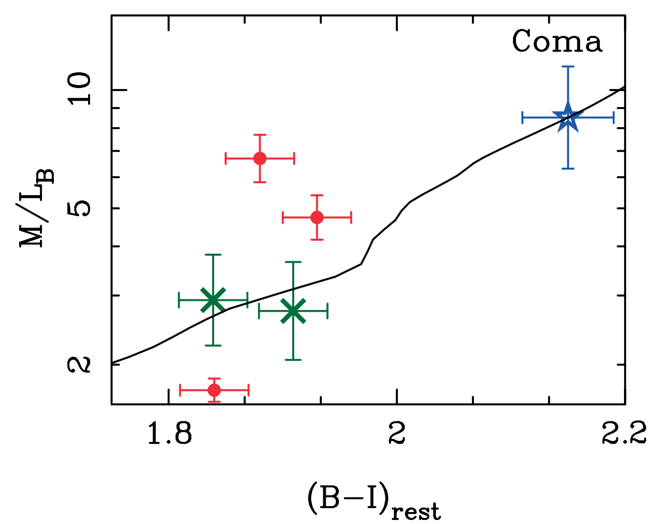

FIG. 4.—Values of M/L_B as a function of the rest-frame Vega $B - I$ color for galaxies with $M > 10^{11.5}\ M_\odot$. The average Coma values are represented as a blue star symbol, while the three galaxies from RDCS 1252.9−2927 are filled circles and the two galaxies from RDCS 0848+4453 are green crosses. The line shows the trajectory of a solar metallicity model with an exponentially declining, $\tau = 200$ Myr, star formation rate Bruzual & Charlot (2003) model normalized to the average Coma Cluster observations. The highest M/L_B is galaxy 4419, the brightest cluster galaxy. The colors of galaxy 4419 are significantly bluer than predicted for its observed M/L_B, ruling out the offset being a result of dust or metallicity effects. The lowest mass galaxy in RDCS 0848+4453 is excluded (see text).

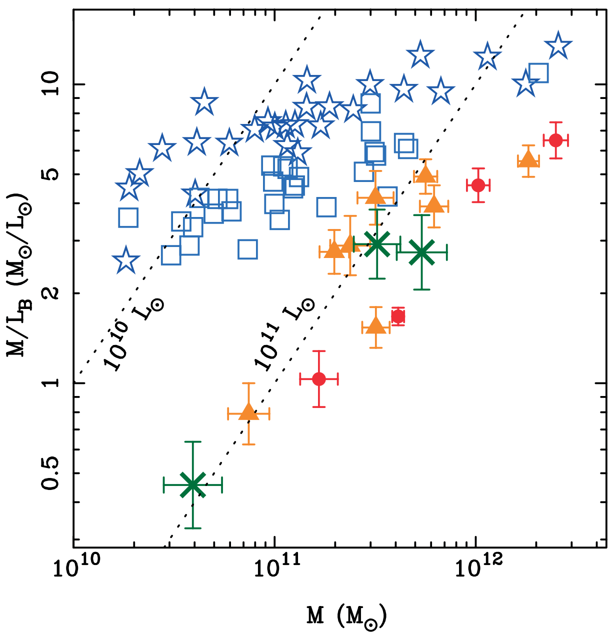

FIG. 5.—Values of M/L_B as a function of mass, using the same symbols as in Fig. 3 but not including the results for MS 2053−04. The lower redshift trend of higher M/L_B at higher masses appears to be preserved at $\bar{z} = 1.25$, even when we ignore the lowest mass galaxy in RDCS 0848+4453. The dotted lines represent $L_B = 10^{11}$ and 10^{10} $L_\odot$. Our $z_{850} = 22.5$ selection limit corresponds to $L_B \simeq 10^{10.9}$ $L_\odot$ for a galaxy with the colors of a Coma elliptical galaxy.

this sample because of our magnitude limit, effectively $L_B \simeq 10^{11}$ $L_\odot$.

4. IMPLICATIONS FOR THE EVOLUTION OF EARLY-TYPE CLUSTER GALAXIES

The rate of the M/L evolution can be used to constrain the luminosity-weighted age for early-type galaxies. The most straightforward estimate is to assume all galaxies formed at one epoch and find the age of the galaxies that will produce the observed change in M/L from $z = 0.023$ to $\bar{z} = 1.25$ using population synthesis models. For our sample of five $M > 10^{11.5}$ $M_\odot$ galaxies, the mean age is $\tau_* = 3.0^{+0.3}_{-0.3}$ Gyr before the time of the observations, or a formation redshift of $z_* = 3.4^{+0.5}_{-0.4}$ using the same models as van Dokkum & Stanford (2003), namely, Worthey (1994). This agrees with the results from the high-mass sample of Wuyts et al. (2004), who found $z_* = 2.95^{+0.81}_{-0.46}$ for galaxies regardless of morphology.

When computing the age for the early-type galaxy population, there is an overestimate of the age of a population caused by young galaxies not being counted as part of the early-type population, even if those young galaxies will evolve into early types after the epoch of observation. This "progenitor bias" depresses the rate of observed evolution in M/L by up to 20% (van Dokkum & Franx 2001). Using this same assumption, namely, that the true evolution is $\Delta \ln (M/L_B) \propto (-1.18 \pm 0.06)z$, we instead find $\tau_* = 2.1^{+0.2}_{-0.2}$ Gyr before $\bar{z} = 1.25$, or a formation redshift of $z_* = 2.3^{+0.2}_{-0.2}$. Blakeslee et al. (2003) and Lidman et al. (2004) both find a mean age of ≥2.6 Gyr using the colors of the galaxies in RDCS 1252.9−2927. Blakeslee et al. (2003) remove the progenitor bias with simulations, whereas Lidman et al. (2004) use all galaxies, regardless of morphology, to similar effect.

The above results imply that the stars that formed these massive galaxies were created at redshifts of $z_* \simeq 2$–3, at which time less than one-third of today's observed stellar mass was formed (e.g., Bell 2005). However, there is a large spread in the M/L_B for all of the early-type galaxies at $z \simeq 1.25$, larger than at lower redshifts. Using colors confirms the spread, which can be interpreted as an underlying spread in the age of the populations. Thus, although $z_* \simeq 2.5$ for the most massive galaxies, some early-type galaxies show much lower M/L values and corresponding younger ages. In fact, the lowest M/L galaxy in Figure 3 was tentatively classified by van Dokkum & Stanford (2003) as having a recent starburst based on the spectrum. Such younger appearing galaxies have lower masses than the high M/L galaxies in our sample but are still massive galaxies with $\log (M/M_\odot) \simeq 11$. The implication of all these results is that a significant fraction of the stars in the most massive galaxies appear to have formed very early in the history of the universe, before the majority of stars present today. The massive cluster galaxies appear to follow the same low-redshift trend of the higher mass systems having higher M/L_B. However, the larger spread at $\bar{z} = 1.25$ in the M/L_B indicates that we have identified some massive, $M \simeq 10^{11}$ $M_\odot$, galaxies whose last burst of star formation occurred in the relatively recent past, $z \simeq 1.5$.

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