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THE POSSIBLE $z = 0.83$ PRECURSORS OF $z = 0$, M^* EARLY-TYPE CLUSTER GALAXIES[1]

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ABSTRACT

We examine the distribution of stellar masses of galaxies in MS 1054.4−0321 and Cl 0152.7−1357, two X-ray–selected clusters of galaxies at $z = 0.83$. Our stellar mass estimates, from spectral energy distribution fitting, reproduce the dynamical masses as measured from velocity dispersions and half-light radii with a scatter of 0.2 dex in the mass for early-type galaxies. When we restrict our sample of members to high stellar masses, those over $10^{11.1}\ M_{\odot}$ (M^* in the Schechter mass function for cluster galaxies), we find that the fraction of early-type galaxies is 79% ± 6% at $z = 0.83$ and 87% ± 6% at $z = 0.023$ for the Coma Cluster, consistent with no evolution. Previous work with luminosity-selected samples has found that the early-type fraction in rich clusters declines from ≃80% at $z = 0$ to ≃60% at $z = 0.8$. The observed evolution in the early-type fraction from luminosity-selected samples must predominantly occur among sub-M^* galaxies. As M^* for field and group galaxies, especially late types, is below M^* for cluster galaxies, infall could explain most of the recent growth in the early-type fraction. Future surveys could determine the morphological distributions of lower mass systems, which would confirm or refute this explanation.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (MS 1054.4−0321, Cl 0152.7−1357) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: fundamental parameters

1. INTRODUCTION

The early-type galaxy fraction and morphology-density relation show that the mix of galaxies we observe in clusters today has significantly changed over the past 7–10 Gyr (Dressler et al. 1997; Lubin et al. 1998; van Dokkum et al. 2000, 2001; Holden et al. 2004; Smith et al. 2005; Postman et al. 2005). This observation raises the question of what the descendants of the additional late-type galaxies seen at higher redshifts are. One possible approach to this problem is to compare the distribution of masses of cluster galaxies at high and low redshifts. In this Letter, we use fundamental plane measurements and precise photometry to estimate the mass-to-light ratios (M/L), and masses, of $z = 0.83$ cluster galaxies and galaxies in the Coma Cluster. When combined with *Hubble Space Telescope* (*HST*) Advanced Camera for Surveys (ACS) imaging, we have a unique data set for examining the masses and morphologies of high-redshift cluster galaxies, which we can compare with a $z = 0$ sample. Throughout, we assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. DATA

We use imaging from the *HST* ACS to determine rest-frame optical colors and morphological types. Both MS 1054.4−0321 and Cl 0152.7−1357 were observed with F775W (hereafter i_{775}) and F850LP (hereafter z_{850}) filters. In addition, MS 1054.4−0321 was observed with the F606W (hereafter V_{606}), while Cl 0152.7−1357 was imaged in the F625W, or r_{625}, filter. For a thorough discussion of the ACS photometry, see Blakeslee et al. (2006). Postman et al. (2005) determined the morphological types of the cluster members using the i_{775} data. Postman et al. estimated the scatter on the early-type fraction to be 6% by comparing the fractions derived from different classifiers.

We have 143 spectroscopically confirmed members in MS 1054.4−0321 with $i_{775} < 23.5$ mag (Tran et al. 2003), with additional redshifts gathered since that publication. For the second cluster in our sample, Cl 0152.7−1357 at $z = 0.834$, we have 95 spectroscopic members with $i_{775} < 23.5$ mag from Demarco et al. (2005). We compute the completeness for each cluster empirically as a function of i_{775} magnitude and morphological type as was done by Postman et al. (2005; see Appendix B). We use these completeness values as weights when computing derived quantities below.

We compare the above data with the U, B, and r photometry for morphologically identified, spectroscopically confirmed Coma galaxies from Beijersbergen et al. (2002a, 2002b). Those authors constructed a new sample of redshifts that is complete to $r < 16.27$ mag, or $M_r < -18.75$ mag, and morphologically typed a large number of previously unidentified galaxies. We compute the rest-frame $g-r$ color from the relation $g-r = 0.61(B-r) - 0.07$, using templates from Bruzual & Charlot (2003) and Kinney et al. (1996), where $B-r$ comes from the catalog of Beijersbergen et al. (2002a).

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3. MASS ESTIMATION

In a number of recent papers, galaxy masses have been estimated by using observed spectral energy distributions. The correlation between rest-frame optical color and the mass-to-light ratio (M/L) of the population for a variety of spectral types has been explored by Kelson et al. (2000) and Bell & de Jong (2001). Interestingly, Bell et al. (2003) and B. P. Holden et al. (2006, in preparation) found that fitting spectral energy distributions to photometric data, in general, yielded results roughly equivalent to estimating M/L with only rest-frame optical colors.

We use theoretical (Bruzual & Charlot 2003) and empirical templates (Kinney et al. 1996) to interpolate between the observed ACS colors into the rest-frame optical $g-r$ colors. For MS 1054.4−0321, we compute the rest-frame values as $g-r = 1.01(i_{775}-z_{850}) - 0.05$ and $r = z_{850} - 0.32(V_{606}-z_{850}) + 0.84$, while for Cl 0152.7−1357, we use $g-r = 1.00(i_{775}-z_{850}) - 0.06$ and $r = z_{850} - 0.28(r_{625}-z_{850}) + 0.63$. Bell et al. (2003) give two relations between the rest-frame $g-r$ color and M/L in the r band, one from stellar population models and one from the fundamental plane (FP) results of Bernardi et al. (2003). We use the relation derived from stellar population models, but the results do not change significantly if we use the relation from Bernardi et al. (2003). We can also convert the ACS photometry into the rest-frame $B-V$. We find that using the rest-frame $B-V$ conversion to M/L does not significantly change our results.

We have collected a sample of 51 galaxies with half-light radii and velocity dispersions, 22 dispersions in MS 1054.4−0321 from Wuyts et al. (2004) and 29 dispersions in Cl 0152.7−1357 from Jørgensen et al. (2005), with sizes for both clusters from Holden et al. (2005b). In Figure 1, we compare the masses derived from the relation $M = 5\sigma^2 r_e/G$, or $M = 2\log\sigma + \log r_e + 6.07$ (Jørgensen et al. 1996), with the masses estimated using the rest-frame M/L_r values from ACS colors, combined with our total magnitude estimates. We find an offset of 0.13 dex between our stellar mass estimates and the dynamically estimated mass, shown in Figure 1. The scatter in the mass estimates for the elliptical galaxies is 60%, compared with 66% for the whole sample. It appears that at lower dynamical masses, our stellar masses are overestimates. This is likely a result of the luminosity limits used in selecting galaxies for the velocity dispersion samples, which we illustrate with a dotted line in Figure 1. Future studies of the fundamental plane to fainter magnitudes will test our color scaling of M/L to fainter luminosities.

For the Coma data, we use the same conversion between $g-r$ and M/L as for our two $z = 0.83$ clusters. Using the FP results of Jørgensen et al. (1995a, 1995b), we find good agreement between our photometrically estimated masses for the Coma Cluster data and the dynamical values, again with scatter of 46% and 0.07 dex offset. We apply this offset to the Coma data. Therefore, an object with the same rest-frame $g-r$ and total r magnitude will have the same mass in both the high-redshift and Coma samples.

We fitted a Schechter function (Schechter 1976) to the distribution of masses in Coma and found M^*, the characteristic mass, to be $10^{11.1\pm0.2}$ $M_\odot$. This value is higher than the $10^{11.00}$ $M_\odot$ (for $H_0 = 70$ km s^{-1} Mpc^{-1}) found in the field survey of Bell et al. (2003) because L^*, which is $M_r = -21.6$ mag AB for cluster galaxies (Beijersbergen et al. 2002a; Hansen et al. 2005) is brighter than L^*, $M_r = -21.3$ mag AB, for field galaxies found in Bell et al. (2003).

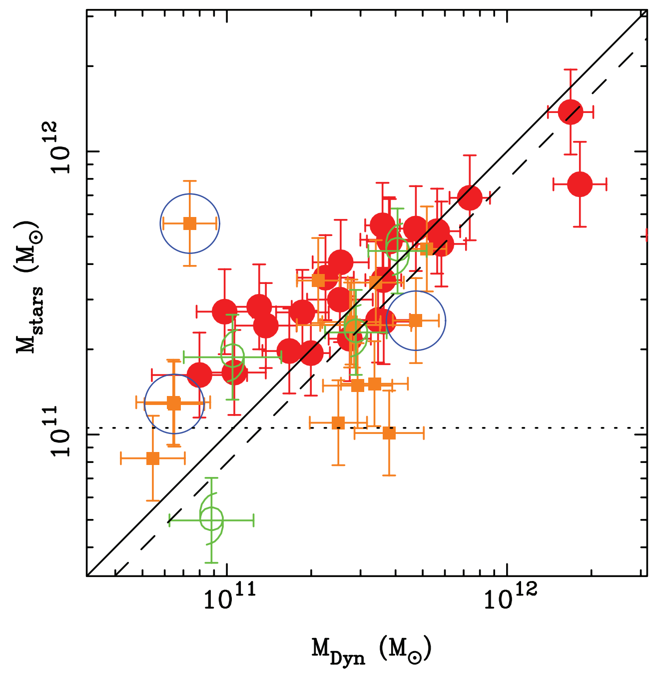

FIG. 1.—Mass derived from rest-frame optical colors compared with the dynamical mass for galaxies in MS 1054.4−0321 and Cl 0152.7−1357. The symbols show elliptical galaxies as red circles, S0–S0/a's as orange squares, and Sa–Sbc's as green spirals (Postman et al. [2005] contains the classification). Those galaxies from Wuyts et al. (2004) and Postman et al. (2005) that are classified as in close pairs, or mergers, are enclosed by blue circles. The dotted line shows the effective stellar mass limit assuming the colors of early-type galaxies in the clusters and the magnitude limit for the velocity dispersion samples. In general, we find that the photometrically measured masses match the dynamically measured ones but with an offset of, on average, 0.13 dex. The mean relation before the offset is applied we show with the dashed line, while the solid line shows a one-to-one agreement. A smaller offset is required to match the Coma photometry to the Coma dynamical masses (see text for details). We apply these offsets to both samples to ensure that the color-based mass estimates are consistent at high and low redshift.

4. MASS AND THE EARLY-TYPE FRACTION

We find an early-type fraction of 87% ± 6% for all galaxies in Coma with masses above $10^{11.1}$ $M_\odot$ (errors for the Coma early-type fractions are computed by using bootstrap resampling). At $z = 0.83$, we find the early-type fraction to be 79% ± 6% (82% ± 8% for MS 1054.4−0321, 74% ± 8% for Cl 0152.7−1357), a not significant change of 9% ± 8% from Coma. In contrast, when using the same data but taking a luminosity-selected sample of galaxies to $L^* + 0.5$, or $M_r = -21.1$ mag, we find an early-type fraction of 78% ± 4% for Coma. At $z = 0.83$ we have 62% ± 6% (65% ± 8% for MS 1054.4−0321, 60% ± 8% for Cl 0152.7−1357), which is typical for what is found for the cluster samples in van Dokkum et al. (2001) or Holden et al. (2004) at the same magnitude limit. We note that the $z = 0.83$ early-type fractions are corrected for incompleteness, but this is usually a small, ≤2%, effect.

As can be seen in Figure 2, the mix of galaxy types selected by a mass cut ($M > M^*$; Fig. 2, *dotted line*) is quite different from that selected by a luminosity cut (Fig. 2, *solid line*). To quantify, a blue late-type galaxy at L^* will have a mass that can be up to 0.4 dex below M^*. Figure 2 shows that the morphological mix for a mass-selected sample is different from that of a luminosity-selected sample for Coma as well.

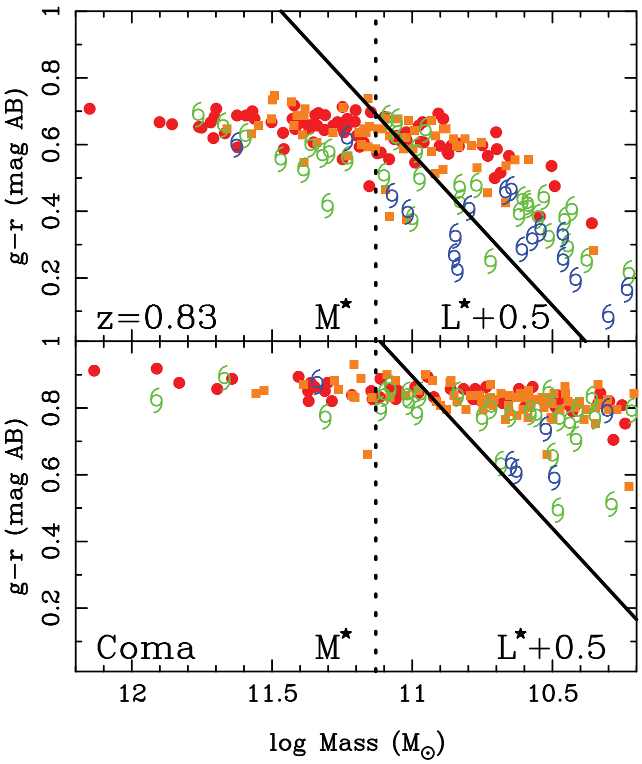

FIG. 2.—Color as a function of mass for galaxies at $z = 0.83$ (*top*) and in Coma (*bottom*). The mass comes from the relation of M/L_r and $g-r$ given by Bell et al. (2003). The symbols represent the same galaxy types as Fig. 1, with the addition of blue spirals for Sc and later types. The lower M/L values of bluer galaxies mean that the fraction of early-type galaxies at large masses is much higher than the fraction at bright luminosities. The solid line is $L^* + 0.5$, a common luminosity limit for computing the early-type fraction. L^* comes from the Schechter function fits in Beijersbergen et al. (2002a) and Hansen et al. (2005), and we correct for the luminosity evolution of early-type galaxies at $z = 0.83$ (Holden et al. 2005a). The dotted line is M^* from fitting a Schechter function to the mass function using the Coma data of Beijersbergen et al. (2002a). The early-type galaxy fraction above M^* is the same in both plots.

The smaller early-type fractions we find at fainter magnitudes mean that below a certain mass, we should see the early-type fraction decrease. We examined the galaxies down to mass equivalent to $L^* + 0.5$ mag for a red-sequence galaxy, which is $M > 10^{10.9}\ M_\odot$. The early-type fraction for this mass limit is 79% ± 6% for Coma and 71% ± 7% at $z = 0.83$ (78% ± 8% for MS 1054.4−0321 and 64% ± 8% for Cl 0152.7−1357). Unfortunately, below this mass threshold of $M = 10^{10.9}\ M_\odot$, the early-type fraction decreases quickly because we are incomplete (less than 50% of early-types at those masses have redshifts). The completeness corrections for the early-type fraction with $M > 10^{10.9}\ M_\odot$ are on the order of 5%. Thus, we find no evidence for evolution in the early-type galaxy fraction even when we examine lower mass samples, with two caveats: there is a larger spread in the measured fractions between MS 1054.4−0321 and Cl 0152.7−1357, and we are much more incomplete for redshifts at these masses.

5. DISCUSSION AND RESULTS

When using magnitude-limited samples of galaxies, there is evolution in the fraction of early-type galaxies over the redshift range $z = 0$ to $z = 1$ (Dressler et al. 1997; Lubin et al. 1998; Fasano et al. 2000; van Dokkum et al. 2000, 2001; Holden et al. 2004; Smith et al. 2005; Postman et al. 2005). In contrast, Figure 3 shows that we see minimal differences in the early-type fraction among galaxies with masses above M^*, a difference of 9% ± 8%, in the early-type galaxy fraction above the mass threshold of M^* between $z = 0.83$ and $z = 0$. The difference in luminosity-selected samples comes from an increase in the ratio of late-type galaxies, which have a peak, or modal, mass of $\simeq 10^{10.7}\ M_\odot$, and a corresponding decrease in the number of sub-M^* early-type galaxies.

A number of recent papers have also claimed to see a lack of evolution in cluster populations at high masses. De Propris et al. (2003) compared the evolution in the blue fraction of cluster galaxies in both the rest-frame V and the observed K band. The evolution of the blue fraction is less strong in K, a filter that should be more dominated by massive galaxies than the traditional rest-frame V. Strazzullo et al. (2006) also find that the bright end of the K-selected luminosity function does not strongly evolve at redshifts out to $z \simeq 1.2$. Tran et al. (2005) finds more direct evidence for the majority of late-type galaxies' being low-mass from a study of the recently accreted field galaxies in MS 2053−04, at $z = 0.587$. These bright, late-type galaxies have star formation rates similar to that of field galaxies. However, based on their mass estimates, these galaxies will fade onto the lower mass end of the early-type sequence, presumably to galaxies with less than $10^{11}\ M_\odot$. The excess of lower mass, late-type galaxies that we observe at

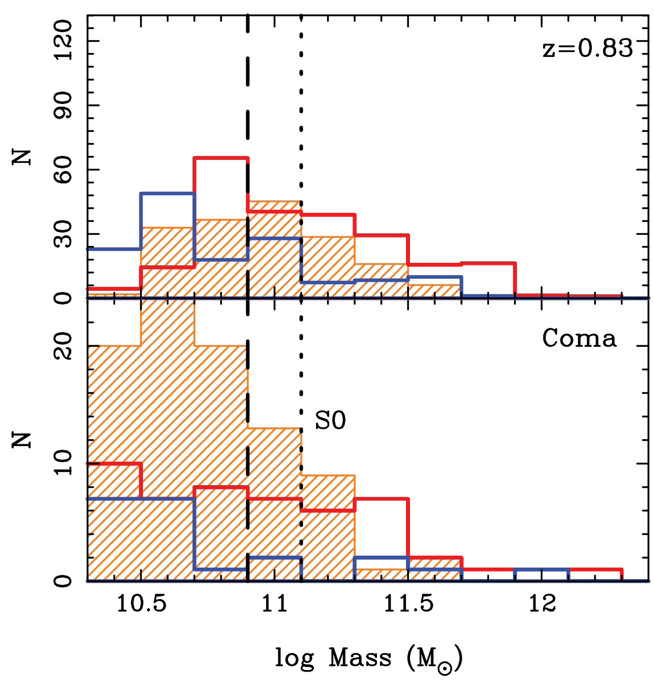

FIG. 3.—Distribution of masses of the galaxies in our two $z = 0.83$ clusters (*top*) and in Coma (*bottom*). The red histogram shows the elliptical population, the orange hatched histogram shows the S0's and S0/a's, and the blue histogram represents the late-type galaxies. The top sample contains all $z = 0.83$ galaxies with $i_{775} < 23.5$ mag. The bottom sample contains those Coma members with morphological classifications. Above M^* for Coma (*dotted line*), the fraction of early-type galaxies, E and S0, are the same at both redshifts. All of the evolution in the early-type galaxy fraction observed by others occurs at lower masses. The early-type (E/S0) galaxies in the $z = 0.83$ sample become significantly incomplete (<50%) at masses below $10^{10.9}\ M_\odot$, marked with a dashed line. The Coma sample is complete to much fainter masses, but we draw the same line for comparison. There is a rapid rise in the number of lower mass S0 galaxies in Coma; these masses are coincident with the masses we observe for late-type spirals at $z = 0.83$. The bin values for $z = 0.83$ are weighted by our completeness function, though the early-type fractions above M^* are the same without this weighting.

high redshift appear to be at the same mass as the infalling field galaxy population observed in Tran et al. (2005). There is a complication in that the star formation histories of cluster and field late-type galaxies may be significantly different (Homeier et al. 2006).

Postman et al. (2005) found that the fraction of S0 galaxies at almost all galaxy densities doubles between $z \sim 1$ and $z \sim 0$. We find that the fraction of early-type galaxies at high mass, greater than M^*, does not change, within the limits of our errors, over that same redshift range. Therefore, most of the evolution observed in Postman et al. (2005) in the galaxy population must occur among lower mass but still luminous galaxies. The observed decrease between $z \sim 1$ and $z \sim 0$ in luminous late-type galaxies could happen in two ways: the galaxies could be transformed into early-types by a stopping of star formation, or the galaxies simply fade below the luminosity limit by $z = 0$. We cannot directly constrain either scenario with our data. However, we would like to point out two observations. First, Bell et al. (2003) find that M^* for late-type galaxies is $10^{10.8}$–$10^{10.9}$ $M_\odot$ at $z \simeq 0$. If there is no evolution in M^* for late-type galaxies and a typical-mass late-type galaxy becomes an early-type galaxy through the truncation of star formation, it should appear as an early-type at masses below our cutoff of $10^{11.1}$ $M_\odot$. At masses of $10^{10.8}$–$10^{10.9}$ $M_\odot$ in Coma, there is a steep rise in the number of S0 galaxies (see Fig. 3). We note that the modal mass of late-type galaxies at $z = 0.8$ is $10^{10.6}$ $M_\odot$, near the mass where the S0 number peaks. Second, Nelan et al. (2005) predict, based on the ages inferred from absorption-line strengths, that the $10^{10.8}$–$10^{10.9}$ $M_\odot$ cluster early-type galaxies have a median "age" of 8–9 Gyr. This result provides a natural explanation for the change in the early-type galaxy fraction at these look-back times. However, these speculations must be tempered by the results of Homeier et al. (2005) and Crawford et al. (2006), for example. It is possible that a large fraction of the luminous late-type galaxies at $z = 0.8$ are luminous but low-mass galaxies undergoing starbursts. These galaxies will simply fade into the dwarf elliptical population by $z = 0$. Both of these scenarios are directly testable by measuring the properties of early-type galaxies at lower masses.

Remarkably, most of the massive early-type galaxies appear to be in place at $z = 0.8$, as indicated by the lack of evolution in the early-type fraction at high masses. In contrast, at this redshift we could be seeing the epoch when roughly half of the galaxies with masses of (4–8) $\times 10^{10}$ $M_\odot$ have transformed from late-type galaxies into low-redshift S0 galaxies. This suggests that we might have identified the galaxies that will become the bulk of the L^* early-type population at $z = 0$, namely, late-type galaxies with (4–8) $\times 10^{10}$ $M_\odot$, or $\sim M^*$ for the field population.

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