MASS SELECTION AND THE EVOLUTION OF THE MORPHOLOGY-DENSITY RELATION FROM $z = 0.8$ TO $0^{1,2}$

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Received 2006 November 29; accepted 2007 July 18

ABSTRACT

We examined the morphology-density relations for galaxy samples selected by luminosity and by mass in each of five massive X-ray clusters from $z = 0.023$ to 0.83 for 674 spectroscopically confirmed members. Rest-frame optical colors and visual morphologies were obtained primarily from *Hubble Space Telescope* images. The visual morphologies ensure consistency with the extensive published results on galaxy evolution in dense environments. Morphology-density relations (MDRs) are derived in each cluster from a complete, luminosity-selected sample of 452 galaxies with a magnitude limit $M_V < M_V^* + 1$. The change in the early-type fraction with redshift matches previous work for massive clusters of galaxies. We performed a similar analysis, deriving MDRs for complete, mass-selected samples of 441 galaxies with a mass limit of $10^{10.6} M_\odot$. Our mass limit includes faint objects, the equivalent of $\simeq 1$ mag below L^* for the red cluster galaxies, and encompasses $\simeq 70\%$ of the stellar mass in cluster galaxies. The MDRs in the mass-selected sample at densities of $\Sigma > 50$ galaxies Mpc^{-2} are similar to those in the luminosity-selected sample but show larger early-type fractions, with a weak indication of a shallower slope. However, the trend with redshift in the fraction of elliptical and S0 galaxies with masses $> 10^{10.6} M_\odot$ differs significantly between the mass- and luminosity-selected samples. The clear trend seen in the early-type fraction from $z = 0$ to $\simeq 0.8$ is not found in mass-selected samples. The early-type galaxy fraction changes much less and is consistent with being constant at $92\% \pm 4\%$ at $\Sigma > 500$ galaxies Mpc^{-2} and $83\% \pm 3\%$ at $50 < \Sigma < 500$ galaxies Mpc^{-2} . Given the mass limit in our sample, this suggests that galaxies of mass lower than $> 10^{10.6} M_\odot$ play a significant role in the evolution of the early-type fraction in luminosity-selected samples; i.e., they are larger contributors to the luminosity-selected samples at higher redshifts than at low redshifts.

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: fundamental parameters — galaxies: photometry

1. INTRODUCTION

At low redshift, the cores of clusters of galaxies are dominated by massive elliptical and S0 galaxies (Smith 1935; Zwicky 1942; Oemler 1974). Dressler (1980b) quantified this as the morphology-density relation (MDR), where the fraction of elliptical and S0 galaxies (hereafter early-type galaxies) increases with increasing local galaxy density. Much discussion has centered on the astrophysical reasons for this relation, with contributions from many

studies. For example, how galaxy morphology depends on the underlying mass in stars has been recently explored. Kauffmann et al. (2003) found that the concentration of galaxies (a structural parameter correlated with morphology) depends solely on the underlying stellar mass of the galaxies, not on their environment. Kauffmann et al. (2004) subsequently found that the star formation rate depends inversely on both the local galaxy density and the galaxy stellar mass. These results raise interesting questions about the relative dependence of galaxy morphologies on galaxy mass and on local galaxy environment.

At higher redshifts, the star formation rate increases rapidly (Lilly et al. 1996; Madau et al. 1998). Clusters of galaxies grow by the accretion of galaxies and groups of galaxies, many of which will have a larger star formation rate than galaxies today. Thus, we expect the fraction of star-forming (“late type”) galaxies to increase. Dressler et al. (1997), Treu et al. (2003), Smith et al. (2005), Postman et al. (2005), and Desai et al. (2007) all found an increase in the number of late-type galaxies at higher redshifts in clusters and a decreasing fraction of S0 galaxies at redshifts from the present day out to redshifts $z \sim 0.5$ – 1 . This points to a substantial buildup of cluster galaxies in the last half of the age of the universe, i.e., over look-back times from 4 to 8 Gyr.

Endeavoring to understand the details and the causes of these changes is challenging, however, since luminosity was used to select the galaxies. Variations in the star formation rate can cause large changes in the mass-to-light ratios of galaxies (these changes can exceed an order of magnitude). Galaxies of similar mass thus can be spread across a range of luminosities (or be excluded altogether if too faint). Selection directly by the stellar mass of galaxies

¹ Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

² This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.

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TABLE 1
SUMMARY OF CLUSTER DATA

Cluster (1)	z (2)	Observed Filters (3)	Redshift Range ^a (4)	No. of All ^b (5)	Members in Luminosity ^c (6)	Sample Mass ^d (7)
Coma.....	0.023	u, g, r	$0.013 < z < 0.033$	202	100	95
CL 1358.....	0.328	V_{606}, I_{814}	$0.315 < z < 0.342^e$	134	95	99
MS 2053.....	0.587	V_{606}, I_{814}	$0.57 < z < 0.60^f$	85	60	56
MS 1054.....	0.831	$V_{606}, i_{775}, z_{850}$	$0.80 \leq z \leq 0.86^g$	112	90	82
RX J0152.....	0.834	$r_{625}, i_{775}, z_{850}$	$0.81 \leq z \leq 0.87^g$	142	104	109

^a The redshift range used to define cluster membership.

^b The number of galaxies with redshifts in the range of the cluster with $M_V < M_V^* + 1.5$.

^c The number of galaxies with redshifts in the range of the cluster with luminosities $M_V < M_V^* + 1$.

^d The number of galaxies with redshifts in the range of the cluster with masses $> 10^{10.6} M_\odot$.

^e The catalog of Fisher et al. (1998) contains only galaxies in this redshift range.

^f From Tran et al. (2003).

^g From Blakeslee et al. (2006).

would remove some of these problems. For example, mass-selected samples would not include very low mass galaxies undergoing bursts of star formation. These galaxies would enter luminosity-selected samples and distort comparisons between galaxy populations at different epochs. The stellar mass of galaxies changes more modestly, even after a major mergers.

This has particular value for determining the progenitors of the galaxy population in present-day clusters. Galaxies of similar masses at higher redshifts are likely to form the majority of the progenitors of current galaxies. Except for the rare major merger, mass growth for the typical cluster galaxy is likely to be modest. Merging and star formation will move galaxies to higher masses over time, so our higher redshift mass-selected samples will not contain all progenitors of $z \simeq 0$ cluster galaxies. However, these processes will impact luminosity-selected samples much more dramatically. Proper accounting and understanding of the evolution of galaxy populations (and of the nature of relations such as the morphology-density relation) will be better done using mass-selected samples.

Given this, we set out to use mass-selected samples to investigate how the morphological mix in clusters of galaxies changes with local galaxy density and how the mix varies with time. The aim of our investigation is to determine whether the trends found in the luminosity-selected samples of Dressler et al. (1997), Smith et al. (2005), and Postman et al. (2005) appear in mass-selected samples. The ultimate goal is to establish the progenitors of the $z \simeq 0$ elliptical and S0 population by examining the masses of $z \simeq 0-1$ galaxies.

We have constructed a sample of five clusters of galaxies: Coma at $z = 0.023$, CL 1358.4+6245 (hereafter CL 1358) at $z = 0.33$, MS 2053.7-0449 (hereafter MS 2053) at $z = 0.59$, and MS 1054.4-0321 (hereafter MS 1054) and RX J0152.7-1357 (hereafter RX J0152), both at $z = 0.83$. Each cluster has a large catalog of spectroscopic members, combined with high-resolution imaging and precise colors in the optical rest frame. These clusters are massive systems with both large X-ray luminosities and substantial velocity dispersions. This provides two advantages: first, these rich systems provide large samples for studying the distribution of morphologies; second, our cluster selection minimizes the influence of the relation between X-ray luminosity or velocity dispersion and early-type galaxy fraction found in Postman et al. (2005) and Desai et al. (2007). For each cluster, we have rest-frame B imaging, generally from the *Hubble Space Telescope* (HST), which provides visual morphological classifications consistent with those used in previous work such as Dressler (1980a, 1980b), Postman & Geller (1984), Treu

et al. (2003), Dressler et al. (1997), Smith et al. (2005), Postman et al. (2005), and Desai et al. (2007). Many of the classifications come directly from the work of Dressler (1980a) and Postman et al. (2005). The underlying stellar mass is derived using the mass-to-light ratio (M/L) from the redshifted $B - V$ color (see Kelson et al. 2000c; Bell & de Jong 2001; Bell et al. 2003; Holden et al. 2006) and total magnitudes from our measurements.

We discuss our data in § 2, with emphasis on how we select galaxies to ensure that we have consistent morphologies and photometry across a variety of clusters. We discuss our mass estimates as well, with a longer discussion in Appendix B. In § 3, we turn to our estimates of local galaxy density, showing that we reproduce the observed evolution in the morphology-density relation reported by other authors. We then create mass-limited samples of galaxies in each cluster and examine the evolution of the morphology-density relation for galaxies that, at low redshift, are the massive early-type galaxies that dominate cluster cores. We discuss our results in § 4 and provide a summary in § 5.

Throughout this paper, we assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All stellar mass estimates are done using a “diet” Salpeter initial mass function (IMF; Bell & de Jong 2001; Bell et al. 2003). This IMF has the slope of a traditional Salpeter IMF ($\alpha = 1.35$; Salpeter 1955) over the range of $125-0.35 M_\odot$, with a flat slope below $0.35 M_\odot$. This IMF produces the same colors and luminosity as a Salpeter IMF, with 70%, or 0.15 dex, of the M/L of the original Salpeter IMF (Salpeter 1955). Bell & de Jong (2001) selected this IMF as it matches the properties of low-redshift galaxies. This IMF yields masses 0.1–0.15 dex larger than the IMF of Kennicutt (1983), Kroupa et al. (1993), or Chabrier (2003).

2. DATA AND OBJECT SELECTION

We studied five clusters of galaxies in this paper, and they are listed in Table 1. Each cluster in our sample is massive, with a velocity dispersion $> 850 \text{ km s}^{-1}$, and is X-ray luminous. All but Coma and RX J0152 were included as part of the *Einstein* Medium Sensitivity Survey cluster sample (Gioia et al. 1990; Henry et al. 1992; Gioia & Luppino 1994). We list velocity dispersions and bolometric X-ray luminosities in Table 2.

For each of the clusters, we used morphological types, photometry, and redshifts from the literature to compute the fraction of early-type galaxies as a function of luminosity, mass, and local galaxy density. In columns (5)–(7) of Table 1, we list the number of galaxies used to estimate the local galaxy densities, the number used to compute the MDR for luminosity-selected samples, and the number of galaxies included in the mass-selected samples.

TABLE 2
SUMMARY OF ANCILLARY DATA

Cluster	z	σ (km s ⁻¹)	L_X^a (10 ⁴⁴ erg s ⁻¹)
Coma	0.0231	1008 ± 33 ^a	9.0 ± 0.2 ^b
CL 1358	0.328	1027 ⁺⁵¹ ₋₄₅ ^c	10.2 ± 0.7 ^d
MS 2053	0.587	865 ± 71 ^e	6.5 ± 0.4 ^d
MS 1054	0.831	1156 ± 82 ^f	16.4 ± 0.8 ^g
RX J0152	0.834	919 ± 168 ^h	18.6 ± 1.9 ⁱ

^a Struble & Rood (1999).

^b Voevodkin & Vikhlinin (2004).

^c Fisher et al. (1998).

^d Henry (2004).

^e Tran et al. (2003).

^f Tran et al. (2007).

^g Gioia et al. (2004).

^h Demarco et al. (2005).

ⁱ Romer et al. (2000).

When estimating the local galaxy density, we selected galaxies down to the limiting magnitude of $M_V^* + 1.5$, where M_V^* is the absolute magnitude from the Schechter (1976) luminosity function in the V band. We used the same value for M_V^* as Postman et al. (2005), $M_V^* = -21.28$, and we used the same evolution with redshift, where $M_V^* = M_V^*(z = 0) - 0.8z$. We chose a different luminosity limit, $M_V^* + 1$, for our MDRs. This limit was simply selected to have about the same size as a mass selection. We selected a mass limit of $10^{10.6} M_\odot$ as that is our completeness limit at $z = 0.83$. We explain this further in § 2.5. Finally, we selected galaxies within 1.25 Mpc of the cluster center, a limit imposed by the *HST* imaging, except for the Coma Cluster, where we extended the data out to 1.5 Mpc for comparing our results with previous work in the literature.

We would like to emphasize that in this paper, early-type galaxies are morphologically classified visually as elliptical and S0 galaxies from the imaging data. The classification was done using the image with the filter closest to rest-frame B . Neither the galaxy color nor the spectrum was considered, thereby ensuring consistency with the extensive body of previous work. We made this distinction because strongly bulge-dominated systems, such as elliptical and S0 galaxies, have been shown to evolve differently from spiral galaxies. Furthermore, galaxies selected based on spectral energy distribution or color often show a mix of morphological types and star formation rates (see Popesso et al. 2007 for a recent example).

For all the galaxies in our clusters, we collected or determined rest-frame optical morphologies, $B - V$ colors in the redshifted passbands (hereafter $B_z - V_z$), total magnitudes, and stellar mass estimates. We discuss below the data we used to construct these samples.

2.1. Morphologies

The morphological classifications came from the literature for all the galaxies in our sample. For the Coma Cluster, we used the morphologies from Dressler (1980a) combined with imaging data from the Sloan Digital Sky Survey (SDSS). We selected early-type galaxies as those classified as D, E, E/S0, S0/E, S0, and S0/a in Dressler (1980a). Late-type galaxies are any galaxies with classifications in the spiral sequence and irregular galaxies. For all of the clusters in our sample, we used the same classification criteria.

For CL 1358, we used the morphological types from Fabricant et al. (2000). We selected early-type galaxies as those with a classification less than or equal to zero. This puts the Sa/S0 class

in the early-type galaxy category. We used the unpublished data of Tran et al. (2003, 2005b) to form a sample of spectroscopic cluster members with morphologies for MS 2053. These classifications were done in the same manner as in Fabricant et al. (2000), and we used the same divisions between early- and late-type galaxies. Finally, for MS 1054 and RX J0152, we used the previously published morphologies from Postman et al. (2005) and Blakeslee et al. (2006). The classifications in Postman et al. (2005) are on a very uniform system, one consistent with the earlier samples of Fabricant et al. (2000) and Dressler (1980b).

2.2. Photometry

We require a consistent set of magnitudes and colors to estimate stellar masses. We used the approach described in Blakeslee et al. (2006) to measure color and total magnitudes for the cluster galaxies in our sample. This procedure is a modification of the approach outlined in van Dokkum et al. (1998). Each galaxy's surface brightness distribution was fit by a Sérsic model with the exponent ranging from $n = 1$ to 4, using the program GALFIT (Sérsic 1968; Peng et al. 2002). The fitted model is convolved with a point-spread function, accounting for the different responses in our data. The fitted magnitude was used as our total magnitude estimate, as we have found that to be a reliable measure (Holden et al. 2004, 2005). We then applied the CLEAN algorithm (Högbom 1974) to the original images in all passbands. We measured the flux within the half-light radius determined from the surface brightness fit to measure the colors. We detail below how the colors were measured for each set of cluster galaxies since the uniformity and consistency with which we carried out the photometry is an important factor in ensuring reliable mass estimates across the redshift range studied here. Overall the agreement with other studies was very good.

2.2.1. Coma

We created a mosaic of SDSS imaging covering all the galaxies in Dressler (1980a). We fit the Sérsic model to the g image. For a second estimate of the galaxy colors, we froze all of the parameters of the model, except for normalization, and fit the surface brightness profiles in the u and r data. This is referred to as a model color and is used in the SDSS database.

We compared the total magnitudes with those from both Jørgensen et al. (1992) and Beijersbergen et al. (2002a, 2002b). We found that our total magnitudes were almost identical, a difference of 0.006 ± 0.017 from those of Jørgensen et al. (1992). However, we found that the Beijersbergen et al. (2002a, 2002b) magnitudes were 0.12 mag fainter than our measurements. The r magnitudes from Beijersbergen et al. (2002a, 2002b) are SExtractor MAG_AUTO magnitudes. For the very brightest galaxies, we found that the offset was larger, $\simeq 0.2$ – 0.4 mag, which we did not find when we compared our total magnitudes to those of Jørgensen et al. (1992). When we measured MAG_AUTO magnitudes from our mosaic, we found a similar offset for the brightest galaxies. This probably results from the large number of neighbors for the brightest galaxies in Coma, suggesting that these measurements are not as reliable for total magnitudes.

We compared our colors with those of the SDSS and those from Eisenhardt et al. (2007) and found very good agreement. We found that our colors, measured within a half-light radius, were redder by only 0.013 ± 0.004 mag than the SDSS model colors. We also compared our model colors with those of the SDSS and found that those were redder by 0.006 ± 0.005 mag. Eisenhardt et al. (2007) give $B - V$ colors for a number of Coma members. We computed a similar conversion to that in Table 3, but for observed $B - V$ instead of redshifted colors, $B_z - V_z$.

TABLE 3
PHOTOMETRIC CONVERSIONS

Cluster	Redshifted Filter	Transformation	Distance Modulus ^a
Coma.....	V_z	$g - 0.65(g - r) + 0.01^b$	35.01
	$B_z - V_z$	$1.00(g - r) + 0.15^b$	35.01
CL 1358.....	V_z	$I_{814} + 0.27(V_{606} - I_{814}) + 0.63$	41.18
	$B_z - V_z$	$0.91(V_{606} - I_{814}) - 0.19$	41.18
MS 2053.....	V_z	$I_{814} - 0.21(V_{606} - I_{814}) + 1.07$	42.68
	$B_z - V_z$	$0.70(V_{606} - I_{814}) - 0.30$	42.68
MS 1054.....	V_z	$z_{850} - 0.16(V_{606} - z_{850}) + 0.74^{b,c}$	43.60
	$B_z - V_z$	$1.05(i_{775} - z_{850}) + 0.11^{b,c}$	43.60
RX J0152.....	V_z	$z_{850} - 0.20(r_{625} - z_{850}) + 0.78^b$	43.61
	$B_z - V_z$	$1.05(i_{625} - z_{850}) + 0.11^b$	43.61

^a The distance modulus assumes $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^b The Coma gr data and the ACS photometry use an AB zero point.

^c The V_{606} filter used in this conversion refers to the ACS F606W and not the WFPC2 filter used in CL 1358 and MS 2053.

Using the relation $B - V = 1.00(g - r) + 0.15$ to transform our half-light radius $g - r$ colors, we compared our calculated $B - V$ colors with the measured $B - V$ colors in Eisenhardt et al. (2007). We found our colors are bluer by -0.008 ± 0.003 with a scatter of 0.029 mag when compared with the colors measured within r_1 , a size that roughly corresponds to half of the light; see Eisenhardt et al. (2007) for details.

2.2.2. CL 1358

For every galaxy in the redshift catalog of Fisher et al. (1998) we derived photometry from F606W (V_{606}) and F814W (I_{814}) Wide Field Planetary Camera 2 (WFPC2) imaging presented in van Dokkum et al. (1998). We used the zero points from Kelson et al. (2000a) for the WFPC2 photometry. We used our standard procedure, using the imaging in the I_{814} passband to determine the half-light radii. The colors were measured in a similar manner in van Dokkum et al. (1998). We found an offset of 0.018 ± 0.006 mag from the van Dokkum et al. (1998) colors, and we found a scatter of $\sigma(V_{606} - I_{814}) = 0.07$ mag between the two sets of data. Our total magnitudes are -0.021 ± 0.030 mag brighter than the total magnitudes from Kelson et al. (2000a).

2.2.3. MS 2053

The photometry we used is based on the archival WFPC2 V_{606} and I_{814} imaging. Wuyts et al. (2004) give velocity dispersions and the results of fitting surface brightness profiles to the WFPC2 imaging for a subset of the galaxies. We measured the apparent magnitudes for all cluster galaxies in the WFPC2 imaging using the same procedure as for CL 1358. We compared our total magnitudes from surface brightness profiles with those from Wuyts et al. (2004). We find that the I_{814} magnitudes of Wuyts et al. (2004) are fainter by 0.037 ± 0.020 mag than ours, so we consider the two sets of magnitudes in good agreement.

2.2.4. MS 1054 and RX J0152

Blakeslee et al. (2006) measured the colors within the half-light radius, with that radius determined from model fits, using the program GALFIT (Peng et al. 2002). Blakeslee et al. (2006) let the Sérsic exponent range from $n = 1$ to 4. The total magnitudes came from the SExtractor MAG_AUTO parameter (Bertin & Arnouts 1996). To determine total magnitudes, a 0.2 mag aperture correction was applied to the measured magnitude (see Holden et al. 2005; Blakeslee et al. 2006).

Blakeslee et al. (2006) only analyzed the then existing catalogs of redshifts from Demarco et al. (2005) and Tran et al. (2007). We have acquired additional redshifts for both clusters since the

publication of Blakeslee et al. (2006). We used the Magellan telescopes with both the Inamori-Magellan Areal Camera and Spectrograph (Bigelow & Dressler 2003; Dressler et al. 2006) and the Low-Dispersion Survey Spectrograph 3. These new members were analyzed in the same manner as presented in Blakeslee et al. (2006).

For MS 1054, we also used the imaging data from the Faint Infrared Extragalactic Survey (FIRES; Förster Schreiber et al. 2006). These data cover $UBVJHK$ along with the archival WFPC2 photometry for MS 1054. We replaced the WFPC2 data with the Advanced Camera for Surveys (ACS) imaging and recreated the catalogs. In Appendix A, we discuss how we processed the data. For most filters, we found very small scatter, <0.01 mag, between our measured magnitudes and those provided in the FIRES catalogs. Once we constructed a photometric catalog, we fit spectral energy distributions to measure redshifted colors and the mass in stars for cluster members. We used these mass and color estimates as a check for our masses and colors using only *HST* imaging. We discuss these in §§ 2.3 and 2.4 below.

2.3. Redshifted Magnitudes and Colors

To compute the rest-frame magnitudes in B_z and V_z from the observed magnitudes and colors, we used the technique of Blakeslee et al. (2006) and Holden et al. (2006). We calculated the magnitudes of templates in the rest-frame filters. We then redshifted the templates and computed the magnitudes in the observed filters. For the templates, we used exponentially decaying star formation rate models from Bruzual & Charlot (2003, hereafter BC03). These models had exponential timescales of 0.1–5 Gyr, covering a range of ages from 0.5 to 12 Gyr and three metal abundances, 2.5, 1, and 0.4 $Z_\odot$. We list the transformations between the observed filters and the redshifted ones in Table 3 and include the distance modulus to the cluster in our chosen cosmology. For the rest-frame filters, we used the B and V curves from Buser (1978), specifically the B3 curve for the B_z . Both sets of curves are tabulated by BC03.

For MS 1054 and RX J0152, B_z lies within the observed wavelength range of the ACS filters, while the center of V_z is redshifted to reddest part of the z_{850} filter at $z = 0.83$. To compute the MDR for luminosity-selected samples as was done in previous work, we need to compute the V_z magnitude. We compared our $B_z - V_z$ colors for MS 1054 with those estimated from the broader baseline of photometry from the FIRES survey. We fit spectral energy distributions to the FIRES data (see Appendix B). We use those fits to interpolate the observed colors to predict B_z and V_z for each galaxy. We found that the B_z and V_z had an average

offset between the FIRES predictions and the results from Table 3 of $\delta(B_z - V_z) = -0.006$ mag with a scatter of $\sigma(B_z - V_z) = 0.005$ mag. When we compare the two estimates of the V_z magnitude, we find $\delta V_z = -0.033$ mag with a scatter of $\sigma V_z = 0.027$ mag. Reassuringly, we find that our redshift colors and magnitudes from the ACS imaging alone match what we expect from a much broader wavelength coverage.

We have computed the transformations between the observed F606W and F814W WFPC2 photometry and the redshifted B_z and V_z magnitudes for MS 2053 and CL 1358. These are different conversions from those previously listed in the literature. For CL 1358, we found good agreement between our transformations and those previously published by van Dokkum et al. (1998). We found offsets of $\simeq 0.1$ mag in the colors of red galaxies in MS 2053 between our transformations, listed in Table 3, and the published ones of Tran et al. (2003). However, our transformation between the observed colors and V_z agrees with that of Wuyts et al. (2004) to within < 0.05 mag. For consistency across our data sets, we used the conversions we derived that are listed in Table 3.

2.4. Mass Estimation

Estimating stellar masses requires a total magnitude and an estimate of the mass-to-light ratio (M/L). We used the redshifted colors and magnitudes discussed in the previous subsections to compute the total magnitude in the B_z filter, and we used the linear relation between M/L_B and the $B_z - V_z$ color given in Bell et al. (2003), $M/L_B = 1.737(B - V) - 0.942$, to derive M/L . We assumed the absolute magnitude of the Sun to be $M_B = 5.45$.¹¹ The relations of Bell et al. (2003) use a “diet” Salpeter IMF (see Bell & de Jong 2001 for an explanation). This IMF has the same colors and luminosity as in a Salpeter IMF, but only 70% of the mass. The offsets between the derived stellar masses assuming this IMF and other popular IMFs are given at the end of § 1 and in Bell et al. (2003). Generally, most other IMFs predict masses 0.1–0.15 dex lower than our estimates.

The assumption of a single relation between rest-frame color and M/L has two likely sources of error. First, there is an intrinsic scatter in M/L at a fixed color, which Bell et al. (2003) estimate as 0.1–0.2 dex. Second, the Bell et al. (2003) M/L estimates are appropriate for $z = 0$ stellar populations. At higher redshifts, star-forming galaxies may have lower stellar masses, as they have formed fewer stars, yet they may have similar colors. Kassin et al. (2007) find some evidence that star-forming, field galaxies at higher redshift may have lower stellar masses than galaxies with the same rest-frame colors at $z = 0$. Kassin et al. (2007) find a shift of $\simeq 0.1$ dex in the stellar mass of star-forming galaxies at a fixed dynamical mass. This shift is larger, $\simeq 0.2$ dex, if Kassin et al. (2007) use the Bell et al. (2003) stellar mass estimates. For passively evolving galaxies, van der Wel et al. (2006) find that systematic shifts of $\simeq 0.1$ dex are possible. To estimate the sizes of the errors in our masses, we computed separate M/L estimates for a subset of our data. We also compared the M/L from the Bell et al. (2003) relations with dynamical mass estimates in all of the clusters in our sample, and we find a robust set of mass estimates that are consistent with redshift. The results of these tests are given below.

2.4.1. Comparison of M/L Estimates

For MS 1054, we fit spectral energy distributions to the photometric data from the FIRES catalog. In Appendix B, we dis-

FIG. 1.— Photometric stellar masses vs. dynamical masses. Red circles are elliptical galaxies, orange squares are S0 and S0/a galaxies, and blue spirals are later type galaxies. Each cluster has a subset of galaxies with velocity dispersion measurements which we use to compute masses using the relation $M_{\text{dyn}} = 5r_{\text{eff}}\sigma^2/G$. The dotted lines show the approximate mass limits for the velocity dispersion samples assuming the magnitude limits and the typical colors of the samples. The $z = 0.83$ panel (top right) contains galaxies from two different clusters with two different magnitude limits; we show only the fainter limit. When computing statistics, we only use galaxies with masses above that line. The solid line has a slope of one, and the dashed line shows the best-fitting relation from Gallazzi et al. (2006) using the de Vaucouleurs relation between size, velocity dispersion, and mass. We show the scatter around the relation of Gallazzi et al. (2006) as a vertical error bar and the average error for the dynamical masses as a horizontal error bar. It appears that for the most massive galaxies, masses from the color estimates of M/L may systematically, although slightly, underestimate the dynamical masses. The average for each sample agrees with the Gallazzi et al. (2006) intercept within $\pm 5\%$. Overall the photometric estimates provide a reliable and consistent estimate of the stellar mass in galaxies at all redshifts.

cuss our results from fitting spectral energy distributions (SEDs), using exponentially declining star formation rate, or τ , models, to the data of MS 1054 and a complementary sample of SDSS Fourth Data Release (DR4) galaxies (Adelman-McCarthy et al. 2006). For both sets of data, we found that the average M/L_B agrees with the linear relation of Bell et al. (2003); see Figure 10. We found a scatter of 33%, 0.14 dex, in M/L around the best-fitting relation for MS 1054. Early-type galaxies have a very similar scatter of 34%, or 0.15 dex, while late-type galaxies have 30%. In our lower redshift sample created using the SDSS DR4, we find a smaller scatter of 28%, or 0.12 dex. These error estimates agree well with the errors expected from Bell et al. (2003).

2.4.2. Comparison with Dynamical Masses

We compared our mass estimates with dynamical masses (M_{dyn}) from fundamental plane measurements from the literature (Jørgensen & Franx 1994; Jørgensen et al. 1995a, 1995b, 2005; Kelson et al. 2000b, 2000c; Wuyts et al. 2004). For each cluster, we combined the published velocity dispersions (σ) and sizes (r_{eff}) for the member galaxies using the relation $M_{\text{dyn}} = 5r_{\text{eff}}\sigma^2/G$ (Jørgensen et al. 1996). We find that the relations between the dynamical mass, derived from the velocity dispersion and r_e , and the stellar mass have consistent zero points; the difference was ± 0.02 dex, or $\pm 5\%$, for all of the clusters in our sample (see Fig. 1).

¹¹ This value of M_B varies slightly from the value in Binney & Merrifield (1998); see <http://www.ucolick.org/~cnaw/sun.html>.

The good agreement between the dynamical and stellar masses at all redshifts shows that we have a consistent mass scale for all early-type galaxies in our sample, and one that matches that of others (van der Wel et al. 2006; Rettura et al. 2006).

We do note that the slope between the two mass estimates appears to be slightly less than one. It seems as if the highest mass galaxies have lower than expected stellar masses. This is also seen in some other comparisons (Gallazzi et al. 2006; Rettura et al. 2006; Kassin et al. 2007). We find that we recover the same zero point for this relation as do Gallazzi et al. (2006) after adjusting for the different IMF used in that paper, over the same redshift range as Rettura et al. (2006) or Kassin et al. (2007). We conclude that there is no systematic shift with redshift in our stellar mass estimates, and that our photometric stellar mass scale matches the dynamical mass scale very well.

When we compared the stellar mass estimates from our colors and total magnitudes to the dynamical estimates, we found that the scatter increased with redshift (see the vertical error bars in Fig. 1). This increase occurs regardless of whether we compare with the best-fitting relation, the relation of Gallazzi et al. (2006), or a simple slope of one. For Coma, we found a scatter of 30%, or 0.13 dex, close to the 0.17 dex scatter between color-based stellar masses and dynamical ones quoted in van der Wel et al. (2006). At $z = 0.83$, we found a scatter of 58%, or 0.25 dex, close to the scatter found at $z \simeq 1$ by van der Wel et al. (2006). One possible reason for the increased scatter is that the errors on the velocity dispersion measurements increase. If we remove the contribution from the velocity dispersion error in the dynamical masses, the scatter only reduces to 55%, or 0.24 dex, so the increased scatter we find is not from the statistical errors on the dynamical mass measurements. Kassin et al. (2007) find a scatter of 0.16 dex between the stellar mass and the dynamical mass at all redshifts. Kassin et al. (2007) use relations between color and M/L that are different from ours, but they recover the same slope and zero point as we do in Figure 1. The difference between the scatter found by Kassin et al. (2007) and our results most likely comes from the details in how the measurements are made. Kassin et al. (2007) explicitly model a rotational component for later type galaxies, which they found to reduce the scatter. Both Gallazzi et al. (2006) and Kassin et al. (2007) find that the slope of the relation between the dynamical mass and the stellar mass is less than one. Using that best-fitting slope from Gallazzi et al. (2006) we reduce the measured scatter to 25%, or 0.11 dex, for Coma and 46%, or 0.20 dex, for our two $z = 0.83$ clusters. Such scatter is well in line with the expectations from Bell et al. (2003).

2.5. Completeness Corrections and Catalog Limits

Each data set we used has a different completeness limit for the redshifts and morphological identifications. For each cluster in our sample, we needed to give a weight to each galaxy based on the probability that it would have either a redshift or a morphological type, based on the galaxy's observed magnitude, hereafter $w(m, T)$. The same approach was used by Postman et al. (2005).

For MS 1054, RX J0152, and CL 1358, the spectroscopic redshift catalogs were less complete than our morphological catalogs. Thus, we weighted the galaxies with redshifts based on the fraction of objects with redshifts as a function of morphological type and magnitude, as was done in Appendix B of Postman et al. (2005). The weight, $w(m, T)$, is the inverse of the fraction of galaxies with redshifts, $N(z, m, T)/N(m, T)$, where $N(m, T)$ is the number of objects with classifications and $N(z, m, T)$ is the number of objects with classifications and redshifts. Both fractions are calculated in a magnitude bin $m_h \geq m \geq m_l$ (we selected bins of 0.5 mag in size).

FIG. 2.—Photometric stellar masses as a function of absolute V magnitude. Red circles are elliptical galaxies, orange squares are S0 and S0/a galaxies, and blue spirals are later types. The cluster samples are Coma (*bottom left*), CL 1358 (*bottom right*), MS 2053 (*top left*), and the combination of MS 1054 and RX J0152 (*top right*). The horizontal line is $M = 10^{10.6} M_\odot$, the completeness limit for mass-selected samples. They are derived by determining where the completeness is 50% for the reddest galaxies at $z = 0.83$ (see § 2.5 for a complete explanation). The vertical line is the magnitude limit, $M_V^* + 1$, we used for luminosity-selected samples, where $M_V^* = -21.28 - 0.8z$ (Postman et al. 2005).

The data for MS 2053 have the inverse problem, namely, complete redshift catalogs but incomplete classifications. We therefore weighted each galaxy by the fraction of objects classified by the magnitude and type, $w(m, T)$, such that $w(m, T) = N(m_h \geq m \geq m_l, z, T)/N(m_h \geq m \geq m_l, T)$, where $N(m, z, T)$ is the number of late-type or early-type galaxies in a magnitude bin $m_h \geq m \geq m_l$ with redshifts and $N(z, m)$ is the total number objects in that bin with redshifts.

We plot, in Figure 2, the stellar mass estimates as a function of absolute V magnitude for the five clusters in our sample. To create a sample with a uniform selection across all redshifts, we selected a mass limit where we were 50% complete at $z = 0.83$. That limit is $M = 10^{10.6} M_\odot$ for our choice in IMF ($M \simeq 10^{10.45} M_\odot$ for the Kennicutt [1983], Kroupa et al. [1993], or Chabrier [2003] IMFs).

2.6. Projected Galaxy Density

To estimate the projected galaxy density we used the same methodology as Postman et al. (2005), i.e., a $n = 7$ nearest neighbor distance. We included all galaxies within 1.5 Mpc of the cluster center with $M_V < M_V^* + 1.5$. In total, there are 674 galaxies in all five clusters at or above this magnitude limit.

The local density was calculated to be

$$\Sigma = \frac{1}{\Omega_N D_A^2} \sum_{n=1}^7 w_n(m_n, T_n)^{-1},$$

where Ω_N is the angular area to the N th nearest neighbor, D_A is the angular diameter distance for the redshift of the cluster, and $w_n(m_n, T_n)$ are the weights for galaxy n with a given magnitude

m and a classification T . We discuss how the weights are calculated in § 2.5.

Because the weights are used in estimating both our densities and our fractions by galaxy type, we derived errors for our density estimates by bootstrapping. We found that the errors on the density estimates ranged from 0.17 dex for Coma to 0.24 dex for MS 1054. Therefore, when we computed the MDR, we used bin sizes of at least 0.5 dex.

Dressler (1980b), Dressler et al. (1997), and Postman et al. (2005) all used a fainter magnitude limit, $M_V^* + 2$, than we did when computing the densities. We selected a brighter magnitude limit to minimize the impact of sample incompleteness. For comparison with these previous results, we needed to correct our densities. Postman et al. (2005) had a similar problem. Since their data were not always complete at that magnitude limit ($M_V^* + 2$), Postman et al. (2005) computed a correction factor for their densities. This correction factor was the ratio of the number of galaxies in a Schechter luminosity function with $\alpha = -1.22$ down to $M_V^* + 2$ over the number of galaxies in the same luminosity function down to the magnitude limit of the data. Using a similar procedure, and assuming the same luminosity function, the densities for a magnitude limit of $M_V^* + 2$ would be larger than our densities by 0.18 dex. In order to compare our results with Dressler (1980b), Dressler et al. (1997), and Postman et al. (2005) we have rescaled our densities by 0.18 dex.

3. THE MORPHOLOGY-DENSITY RELATION AND THE EVOLUTION IN THE EARLY-TYPE GALAXY FRACTION

We combined the data discussed above and created two samples for each cluster in order to derive MDRs and to study the evolution in the early-type galaxy fraction with redshift. First, we replicated the previous work using luminosity-selected samples, then we selected galaxies using the masses estimated above. For each sample, we estimated the MDR in a consistent manner, using the same sets of densities for both luminosity- and mass-selected samples. In the following subsections, we outline how we derived MDRs for our clusters.

3.1. Early-type Fraction Estimates

The early-type fractions for the clusters were not simply based on an integer number of objects. Instead, the early-type fraction was the sum of weights of elliptical and S0 galaxies above our magnitude limit or mass limit, divided by the sum of the weights of all galaxies meeting that same limit. In general, these weights are close to one, and not using these weights changes the resulting fractions by only a few percent. While the changes are small we felt it important to be consistent and thorough in our approach. The errors on the fractions range from 3% to 15%, depending on the number of galaxies. These errors are close to, but slightly larger, than those expected from using Poisson errors. We added in quadrature an error of 6% on the early-type fractions we find for RX J0152 and MS 1054. This is the rms classification error found by Postman et al. (2005).

3.2. Luminosity-Selected Samples

Our first step was to create luminosity-selected samples to compare with previous work on the MDR. As discussed in § 2, we computed the morphology-density relation down to a magnitude limit of $M_V^* + 1$ for all clusters, the same limit as was selected by Smith et al. (2005). We plot the resulting morphology-density relations for a sample of a total of 452 galaxies in Figure 3. We tabulate the plotted fractions in Table 4. We see MDRs in our

FIG. 3.— Morphology-density relation for luminosity-selected galaxies by cluster. We selected all galaxies to an absolute V magnitude of $M_V^* + 1$ or $M_V = -20.28 - 0.8z$ (see Postman et al. 2005), for a total of 452 galaxies in all five clusters. The circles connected by lines represent Coma (blue circles), CL 1358 (green circles), MS 2053 (orange circles), and the combined sample of MS 1054 and RX J0152 (red circles). The bins are shown along the bottom, with triangles marking the centers. The galaxy fractions are derived in the same density bins but are spread out for clarity around the bin centers in redshift order. The data for Coma consist of the morphologies from Dressler (1980a) but photometry from the SDSS. For comparison, the updated Dressler (1980b) results from Dressler et al. (1997) are shown as squares, the results of Dressler et al. (1997) at $z \simeq 0.4$ are shown as triangles, and the Postman et al. (2005) results at $z \simeq 1$ are shown as black circles with error bars. We find good agreement between our morphology-density relations and the previous results from the literature. A trend in the early-type fraction with redshift is apparent and is quantified further in Fig. 4. We list the values for this figure in Table 4.

clusters. Our data clearly show a decrease in the early-type fraction with decreasing density for luminosity-selected samples. This evolution is consistent with that shown in previous work such as Dressler et al. (1997), Smith et al. (2005), and Postman et al. (2005).

3.2.1. Evolution of the Luminosity-Selected Early-type Fraction

The MDRs in Figure 3 also show a clear trend of decreasing early-type fraction with redshift. To quantify this we examined the fraction of early-type galaxies in two density bins as a function of redshift, $\Sigma > 500$ representing high galaxy densities and $500 \text{ galaxies Mpc}^{-2} > \Sigma > 50 \text{ galaxies Mpc}^{-2}$ for low densities. The cutoff of $\Sigma = 500 \text{ galaxies Mpc}^{-2}$ was chosen to split the combined MS 1054 and RX J0152 into two equal-sized subsamples. The lower limit is the density that contains 95% of our sample. We plot our early-type fractions in each of these density bins as a function of cluster redshift in Figure 4. We find a trend of a decreasing early-type fraction with redshift, as seen before (Dressler et al. 1997; Smith et al. 2005; Postman et al. 2005). For comparison, we show the average fractions in the same density bins from the low-redshift sample of Dressler (1980b, updated in Dressler et al. 1997), the Dressler et al. (1997) $z \simeq 0.4$ sample, and the $z \simeq 1$ sample of Postman et al. (2005). Our data agree with the trend shown in the other published work, given the size of our sample.

TABLE 4
LUMINOSITY-SELECTED MORPHOLOGY-DENSITY RELATIONS

Cluster	z	1580 galaxies $\text{Mpc}^{-2} >$ $\Sigma > 500 \text{ galaxies } \text{Mpc}^{-2a}$ (%)	500 galaxies $\text{Mpc}^{-2} >$ $\Sigma > 167 \text{ galaxies } \text{Mpc}^{-2a}$ (%)	167 galaxies $\text{Mpc}^{-2} >$ $\Sigma > 50 \text{ galaxies } \text{Mpc}^{-2a}$ (%)
Coma	0.023	95 ± 5	95 ± 5	75 ± 8
CL 1358	0.328	84 ± 9	82 ± 6	74 ± 9
MS 2053	0.587	74 ± 12	65 ± 10	47 ± 12
MS 1054 and RX J0152.....	0.83	83 ± 8	69 ± 8	69 ± 11

^a The fraction of elliptical and S0 galaxies with luminosities $M_V < M_V^* + 1$ in the density range.

The dashed line in Figure 4 is a fit to the data that includes errors on the estimated early-type fraction. We find slopes that differ from zero by more than 2σ for both fits; i.e., the nonzero slope is significant at the 95% confidence limit. At high densities, we find that the early-type galaxy fraction decreases by $-0.20z \pm 0.10z$, evolution at the 95% confidence limit. For the low-density sample we find $-0.29z \pm 0.10z$, evidence at the 99% confidence

limit for evolution. Generally, studies find that most of the evolution at low to moderate redshifts happens at lower densities (Treu et al. 2003; Smith et al. 2005; Desai et al. 2007), a result we replicate with our data. Our results at all densities are clearly consistent with the trend seen from the previous work of Dressler (1980b), Dressler et al. (1997), and Postman et al. (2005). We list the fractions in columns (3) and (4) of Table 6.

3.3. Mass-Selected Samples

3.3.1. The Mass-Selected MDR

The next step was to determine the MDR for mass-selected samples. We used the same weights and densities as in Figure 3 and § 3.2. Our redshifts or morphological classifications became incomplete at $M < 10^{10.6} M_\odot$, so we select this as our mass limit. There are a total of 441 galaxies above that mass limit in all five clusters. This mass limit corresponds to a factor of 4 below $z = 0M^*$ for high-density regions (Baldry et al. 2006),¹² assuming no evolution in the mass function. If we integrate over this mass function, our mass limit encompasses 68%–73% of the total stellar mass of the cluster population, depending on the mass limit for the galaxy population (10^8 or $10^{9.5} M_\odot$, respectively). To compute this, we used the best-fitting mass function from Baldry et al. (2006) for high-density regions, i.e., $\Sigma > 10 \text{ galaxies } \text{Mpc}^{-2}$. Thus, our mass-limited sample encompasses a wide range of masses for cluster galaxies and includes the majority of the stellar mass in galaxies in clusters.

We show the resulting mass-selected MDR in Figure 5. The mass-selected MDR (Fig. 5) is different from the luminosity-selected MDR (Fig. 3). First, the slopes appear to be slightly less. Second, at low redshift the MDRs appear roughly comparable, but at higher redshift, at a given density, the mass-selected early-type fraction is 10%–20% higher than the luminosity-selected fraction. The contrast is quite striking, considering that our mass sample extends significantly below M^* (and below L^* , since the mass limit corresponds to $\simeq 1 \text{ mag}$ below L^* for the reddest cluster galaxies). See Tables 4 and 5 for the resulting fractions in comparison with those from luminosity-selected samples.

The MDR we show in Figure 5 is somewhat of a hybrid. We estimated the galaxy densities using magnitude-limited samples, while the early-type fractions came from mass-limited samples. We used a luminosity-selected sample to estimate the local galaxy to minimize the changes in comparing the two samples (luminosity-selected and mass-selected). In Figure 6, we show the morphological fractions as a function of a galaxy density estimated using a mass-selected sample. The mass limit we used was $10^{10.6} M_\odot$, and we used the same weights as discussed in § 2.5. We find that the mass-selected local galaxy densities are generally a factor of

FIG. 4.—Early-type fraction as a function of redshift in two density bins for luminosity-selected samples. The density bins are listed on the figure in galaxies per square megaparsec (and differ from the bins used in Fig. 3). Blue, green, orange, and red circles represent Coma, CL 1358, MS 2053, and the two $z = 0.83$ clusters, respectively. For comparison, the squares at low redshift are the average fractions in the listed density bin from Dressler et al. (1997), an updated version of Dressler (1980b), the triangles show the average fraction at $z \simeq 0.4$ from Dressler et al. (1997), and the black circles represent the high-redshift fractions from Postman et al. (2005). We note that these are not weighted by the number of galaxies at each density but are simply the average early-type fraction inside the range of densities listed in the panel. The dashed line represents a fit to the data from this paper; see Table 6. We see a strong trend in the evolution of the early-type fraction with redshift and a lower early-type fraction at lower densities at most redshifts. The evolution with redshift in the early-type fraction is significant at the $>95\%$ confidence limit and is similar to that seen by others.

¹² As noted above, we use an IMF that adds 0.15 dex to the masses of galaxies, raising the value of $\log M^*$ from 11.05 to 11.2.

FIG. 5.— Morphology-density relations for mass-selected samples of galaxies in our clusters. The sample consists of all galaxies in our five clusters above a mass limit of $>10^{10.6} M_{\odot}$ ($>10^{10.45} M_{\odot}$ for the IMFs from Kennicutt [1983], Kroupa et al. [1993], and Chabrier [2003]), or $0.25M^*$ for a total of 441 galaxies in all five clusters. Our mass-selected sample thus extends significantly below M^* (and L^* , since the mass limit corresponds to 1 mag below L^* for the reddest cluster galaxies), and includes $\sim 70\%$ of the stellar mass in galaxies in the cluster. The symbols are the same as in Fig. 3. The samples of galaxies at $\Sigma < 50 \text{ galaxies Mpc}^{-2}$ are too small to be statistically significant. In contrast with Fig. 3 the early-type fraction is larger, and the morphology-density relation is less clear. The trend with redshift also is noticeably less; see Fig. 7. We list the values for this figure in Table 5.

$\simeq 2$ lower than those from luminosity-selected samples for the same galaxy, similar to that found by van der Wel (2007) for field galaxy samples. This offset in the density does not, as expected, change the overall shallow slope; we find the same value for the slope as we do in Figure 5. When plotting against these new densities, we still find a lack of evolution as we found in Figure 5.

The mass-selected MDR appears more shallow than the luminosity-selected relation. We tested this in a simple way. We fit the data from Dressler (1980b) with a linear slope in the density range our sample covers. We compared that slope to the average range for the MDR of all five clusters in our sample that we plot in Figures 3 and 5. The measured slopes are 0.26 ± 0.09 for Dressler (1980b) and 0.25 ± 0.13 for Postman et al. (2005). Our mean luminosity-selected MDR has a slope of 0.18 ± 0.07 , while our mean mass-selected MDR has a slope of 0.12 ± 0.08 . To

measure these slopes, we average the samples after removing the offset between the average early-type fractions for each cluster. This preserves the shape of the MDR for each sample. The slope in the mass-selected MDR appears to be less than our luminosity-selected MDR, but it is not statistically significant. We find a larger, but still not statistically robust, difference between the slope of the relation from Dressler (1980b) and Postman et al. (2005) and our mass-selected sample.

Overall, the mass-selected MDRs do not differ substantially from the luminosity-selected MDRs, except in one very important aspect—their evolution with redshift.

3.3.2. Evolution of the Mass-Selected Early-type Fraction

Again, as for the luminosity-selected sample, we split the sample into high- and low-density bins to establish the trend with redshift in the early-type galaxy fraction. We measured the mass-selected early-type fractions in the same two density bins as in Figure 4. This is shown in Figure 7. Clearly the trend with redshift seen in Figure 4 is much weaker in Figure 7. At high densities, we find that the early-type galaxy fraction decreases by $-0.13z \pm 0.09z$, while for the low-density sample we find $-0.14z \pm 0.10z$. These slopes are shown as dashed lines in Figure 7. Neither represents evolution at the 95% confidence limit. We note here that the errors are the same size as those given earlier for the luminosity-selected samples, but the slopes are half the size. We find mean early-type fractions of $83\% \pm 3\%$ at $500 \text{ galaxies Mpc}^{-2} > \Sigma > 50 \text{ galaxies Mpc}^{-2}$ and $92\% \pm 4\%$ at $\Sigma > 500 \text{ galaxies Mpc}^{-2}$. This reaffirms the lack of evolution seen in Figures 5 and 6. We show the mean value of the early-type fraction as a solid line. The early-type fractions for the mass-selected sample in Figure 7 are $\sim 20\%$ higher than the $z > 0.3$ results from the literature shown in Figure 4, and $\sim 10\%$ – 20% higher than our own results from the luminosity-selected samples. These results can be seen in columns (5) and (6) of Table 6 as well.

We measured the slopes for the mass-selected local galaxy densities in two density bins as well. We simply use $250 \text{ galaxies Mpc}^{-2} > \Sigma > 25 \text{ galaxies Mpc}^{-2}$ and $\Sigma > 250 \text{ galaxies Mpc}^{-2}$ as the typical mass-selected density is half that of the luminosity-selected density. We find slopes of $-0.13z \pm 0.12z$ at high densities and $-0.16z \pm 0.12z$ at low densities. The fraction of early-type galaxies in the high-density bin is $89\% \pm 4\%$ while we find $82\% \pm 3\%$ in the low-density bin. These are the same within the errors as was found for the early-type fractions in the luminosity-selected density bins.

The lack of a trend in the mass-selected sample points to galaxies of mass less than $10^{10.6} M_{\odot}$ as being the likely contributors to the evolution at high redshift seen in the luminosity-selected samples, as shown in Figures 3 and 4. This would be consistent with expectations from the increasing global star formation rate at higher redshift. The resulting substantial changes in their M/L

TABLE 5
MASS-SELECTED MORPHOLOGY-DENSITY RELATIONS

Cluster	z	1580 galaxies $\text{Mpc}^{-2} > \Sigma > 500 \text{ galaxies Mpc}^{-2a}$ (%)	500 galaxies $\text{Mpc}^{-2} > \Sigma > 167 \text{ galaxies Mpc}^{-2a}$ (%)	167 galaxies $\text{Mpc}^{-2} > \Sigma > 50 \text{ galaxies Mpc}^{-2a}$ (%)
Coma	0.023	96 ± 5	99 ± 3	80 ± 8
CL 1358	0.328	87 ± 7	88 ± 5	79 ± 8
MS 2053	0.587	77 ± 10	81 ± 9	60 ± 13
MS 1054 and RX J0152	0.83	88 ± 7	75 ± 8	82 ± 10

^a The fraction of elliptical and S0 galaxies with masses $>10^{10.6} M_{\odot}$ in the density range.

FIG. 6.—Morphology-density relation for mass-selected samples of galaxies using mass-selected galaxy densities. The symbols are the same as in Fig. 3. This figure is similar to Fig. 5, where we plot the fraction of elliptical and S0 galaxies above the mass limit of $>10^{10.6} M_{\odot}$. In this figure, the local galaxy densities are computed from the mass-selected sample (Σ_M), not the luminosity-selected sample as in Fig. 5. The change in our estimate of the local galaxy density does not change our results. The typical values for Σ_M are a factor of ~ 2 smaller than from our $M_V < M_V^* + 1.5$ luminosity-limited sample, which van der Wel (2007) finds as well for field galaxies.

would lead to low-mass galaxies brightening into the luminosity-selected samples.

3.3.3. Is Coma Unusual?

A minor but interesting issue arises regarding Coma and its somewhat higher early-type fraction. In Figures 5–7, Coma appears to have a larger number of early-type galaxies at the highest densities. We find that Coma has an early-type fraction $9\% \pm 6\%$ higher than the average early-type fraction in the highest density bin in Figure 7. The apparent higher fraction of early-type galaxies and the lack of any late-type galaxies at very high densities for Coma could have several causes. First, the number of spiral and late-type galaxies in the other clusters could be overestimated. Diaferio et al. (2001) provides a cautionary note, stating that in some simulations, star-forming field galaxies could be projected into a cluster even for redshift-selected samples. Using the data from GOODS (van der Wel 2007), we estimate that 2 ± 2 late-type galaxies above our mass threshold per cluster would fall within the redshift windows listed in Table 1. This would change the early-type fraction by 2% (for MS 1054 or RX J0152) to 10% (for MS 2053), depending on the richness of the cluster and the density bin in question. This would raise the higher redshift cluster early-type fractions, to an average of 89%, closer to the Coma value. A second, more interesting, possibility is that there is evolution in the number of spirals in the cores of clusters from $z \simeq 0.3$ to $\simeq 0$. This would be mild evolution, $9\% \pm 6\%$ at the highest densities we sample, as compared with the changes of 25%–30% seen in previous luminosity-selected samples, such as Dressler et al. (1997), Postman et al. (2005), or Desai et al. (2007). Third, Coma could be on the high side of the distribution

FIG. 7.—Early-type fraction as a function of redshift for mass-selected samples in two density bins. The symbols are the same as in Fig. 4. The density range in galaxies per square megaparsec and the mass limit are labeled in each plot. We show the average early-type fraction in each bin as a solid line, with the height of the bar showing the error on the average. We find mean early-type fractions of $83\% \pm 3\%$ at $500 \text{ galaxies Mpc}^{-2} > \Sigma > 50 \text{ gal Mpc}^{-2}$ and $92\% \pm 4\%$ at $\Sigma > 500 \text{ galaxies Mpc}^{-2}$. The dashed line is the best-fitting linear relation to the change in fraction with redshift, as in Fig. 4. We list the fractions in Table 6. There is little evidence for evolution in the morphology-density relation above the mass limit, with the best-fitting slopes half or less than half of those of Fig. 4. The evolution in the luminosity-selected samples must occur predominately in galaxies with $M < 10^{10.6} M_{\odot}$.

of early-type fraction among low-redshift clusters, as indicated in Figure 3. The significance of contributions from these effects could be evaluated better with larger numbers of clusters and larger mass-selected galaxy samples.

3.3.4. The Mass Dependence of the Early-type Fraction

As a further check on the lack of evolution, we investigated whether, in some particular mass range, we could see evolution in the early-type fraction. We subdivided our sample into different mass bins and derived the early-type fraction in Figure 8. We found no significant change of the early-type fraction with mass. Linear fits to the data in Table 7, the fraction of early-type galaxies in each mass bin, yield slopes of 0.09 ± 0.12 for Coma, 0.23 ± 0.15 for CL 1358, 0.15 ± 0.30 for MS 2053, and 0.01 ± 0.13 for the combined sample of MS 1054 and RX J0152. For all five clusters, we find no statistically significant variation from a slope of zero. The offsets in the mean with increasing cluster redshift can also be seen to be very small (consistent with the lack of evolution seen in Fig. 7 for the mass-selected sample). In general, the lack of a change in the early-type fraction seen in Figures 5–7 appears to be true for the whole of the sample, not just a subset of galaxies in a certain mass range.

TABLE 6
EARLY-TYPE GALAXY FRACTIONS IN TWO DENSITY BINS

CLUSTER (1)	z (2)	LUMINOSITY $M_V < M_V^* + 1^a$		MASS $> 10^{10.6} M_\odot^b$	
		$\Sigma > 500$ galaxies Mpc^{-2} (%) (3)	500 galaxies $\text{Mpc}^{-2} >$ $\Sigma > 50$ galaxies Mpc^{-2} (%) (4)	$\Sigma > 500$ galaxies Mpc^{-2} (%) (5)	500 galaxies $\text{Mpc}^{-2} >$ $\Sigma > 50$ galaxies Mpc^{-2} (%) (6)
Coma	0.023	96 ± 4	86 ± 4	96 ± 4	86 ± 4
CL 1358	0.328	86 ± 8	80 ± 5	89 ± 6	85 ± 4
MS 2053	0.587	74 ± 12	57 ± 8	77 ± 11	74 ± 7
MS 1054 and RX J0152	0.83	83 ± 7	69 ± 8	89 ± 7	77 ± 7

^a The fraction of elliptical and S0 galaxies with luminosities $M_V < M_V^* + 1$ in the density range.

^b The fraction of elliptical and S0 galaxies with masses $> 10^{10.6} M_\odot$ in the density range.

We also tested whether changing the mass limit at lower redshifts made any difference. This arises from a potential concern that we may have introduced a systematic bias in our results by keeping a constant mass limit for all redshifts, given the expectation of some systematic increase in the mean mass of galaxies (from merging and/or star formation). We increased the limit for Coma by a factor of 2 to correspond to a significant mass buildup between $z \simeq 0.8$ and $\simeq 0$. This would accommodate any likely mean mass buildup (e.g., for the field, Bell et al. [2006] find that $\sim 50\%$ – 70% of today's galaxies with masses $> 10^{10.5} M_\odot$ may have undergone mergers since $z \sim 0.7$). The changes in the early-type fraction were insignificant, as would be expected from Figure 8. This is discussed further in § 4.1.

4. RESULTS AND DISCUSSION

4.1. Mass-Selected and Luminosity-Selected Samples

As discussed in § 1, we used mass-selected samples because we expect only modest and systematic evolution in galaxy masses with time, unlike luminosity-selected samples where galaxies can

enter and leave the sample as bursts of star formation dramatically increase the luminosity for a period. A mass selection provides a more robust means of identifying likely progenitors of $z = 0$ cluster galaxies in higher redshift clusters. However, even the mass-selected sample of higher redshift cluster galaxies will not contain all the progenitors, for two reasons. First, galaxies will continue to grow in mass, either through star formation or by merging. Mass growth will bring objects from below our mass limit at high redshift into the sample at low redshift. Second, the early-type fraction is lower in the surrounding field (Noeske et al. 2007; van der Wel 2007). Field galaxies will continue to infall into clusters and build up the cluster population. Thus, even if there is no evolution from $z = 0.83$ to the current epoch in the fraction of early-type galaxies in mass-selected samples, *we do not expect that the total mass in early-type galaxies remains constant*. The total mass in early-type galaxies in the cluster environment is likely to increase (as has been suggested for the field by, e.g., Bell et al. 2004; Faber 2007; Brown et al. 2007)—it just has to increase through processes which maintain a similar high fraction of early-type galaxies at masses $> 10^{10.6} M_\odot$ at any time over the last 7 Gyr.

It is interesting to explore the types of galaxies in our samples. Our mass-selected samples of cluster galaxies show little or no change in the early-type galaxy fraction with redshift for masses $> 10^{10.6} M_\odot$, i.e., for masses above $\sim 25\%$ of the $z = 0$ characteristic mass, or M_* . This mass limit encompasses the majority ($\simeq 70\%$) of the stellar mass in galaxies in these clusters. When we use the same parent sample but select galaxies by luminosity, we recover the MDR and the evolution seen by other authors. We illustrate this selection for the combined sample of MS 1054 and RX J0152 in Figure 9, where we show the distribution of masses and galaxy morphological types over a range of densities for galaxies in a luminosity-selected sample (all galaxies have $M_V < M_V^* + 1$). At masses lower than $10^{10.6} M_\odot$, this sample of galaxies becomes dominated by late-type galaxies. These lower mass, late-type galaxies do not fall into our primary sample—because we are incomplete at these low masses—but do fall into the luminosity-selected sample, and so must be the primary contributors to evolution in luminosity-selected samples.

4.2. Merging and Mass Assembly

Merging may play an important role in the formation of massive, red galaxies between $z \simeq 1$ and today. For example, van Dokkum et al. (1999) found that the merger rate in MS 1054 was significantly higher than in $z \simeq 0$ clusters and that the large majority of these are “dry” mergers. Bell et al. (2006) find that, in the field, as many as 50% – 70% of today's galaxies with masses $> 10^{10.5} M_\odot$ could have undergone mergers since $z \simeq 0.7$, although

FIG. 8.—Morphology-mass relation for all five clusters. Each mass bin is 0.2 dex in width, starting at $10^{10.6} M_\odot$. The data points represent the fraction of early-type galaxies with Coma (blue circles), CL 1358 (green circles), MS 2053 (orange circles), and both MS 1054 and CL 1358 (red circles). The data points are offset in mass about the mean in the bin for clarity. The triangles show the bin centers. The last bin contains all galaxies with masses $> 10^{11.2} M_\odot$. We examined this distribution to see if the early-type galaxy fraction did change at, for example, the lower end of our mass distribution. We find no statistically significant slope in the early-type galaxy fraction with mass, and the average fractions agree with those we find in different density bins; see Table 7. The constant early-type fraction we see in Figs. 5–7 comes from contributions over the whole of the mass function, and is not caused by just the peak of the mass function being dominated by early-type galaxies. The typical mass of a late-type galaxy contributing to Figs. 3 and 4 must be below our mass limit of $10^{10.6} M_\odot$.

TABLE 7
EARLY-TYPE GALAXY FRACTIONS IN MASS BINS

Cluster	z	$M > 10^{11.2} M_{\odot}^a$ (%)	$M > 10^{11.1} M_{\odot}^a$ (%)	$M > 10^{10.9} M_{\odot}^a$ (%)	$M > 10^{10.7} M_{\odot}^a$ (%)
Coma.....	0.023	89 ± 6	96 ± 4	88 ± 7	89 ± 5
CL 1358.....	0.328	86 ± 10	100 ± 5	75 ± 8	85 ± 6
MS 2053.....	0.587	79 ± 1	80 ± 14	75 ± 9	71 ± 13
MS 1054 and RX J0152.....	0.83	85 ± 9	87 ± 8	76 ± 9	87 ± 8

^a The fraction of elliptical and S0 galaxies in the listed mass range at all local galaxy densities; the bin width is 0.2 dex except for the highest mass bin, which includes all galaxies above the mass limit.

Masjedi et al. (2006) find little evidence of mergers among massive, non-star-forming galaxies at $z < 0.36$.

Merging raises an interesting issue. Could a significant fraction of the $z \simeq 0$ cluster population lie below our mass limit at high redshift? As the following arguments show, this appears to be unlikely. One estimate of the merger rate is the number of close pairs of galaxies. Tran et al. (2005a) and M. Postman et al. (2008, in preparation) searched for close pairs of galaxies in MS 1054 and RX J0152. Close pairs are defined in M. Postman et al. (2008, in preparation) as galaxies within $30 h^{-1}$ kpc of but more than $200 h^{-1}$ kpc from the brightest cluster galaxy. Our sample includes a subset of those pairs from M. Postman et al. (2008, in preparation)

as we required both galaxies to be members of RX J0152 and the galaxies to be separated by less than 300 km s^{-1} in the rest frame of the cluster, the same criteria of the whole sample discussed in Tran et al. (2005a). These two samples of potential mergers, 14 in MS 1054 and 9 in RX J0152, resulted in 23 galaxies in pairs or triplets likely to merge in the next 1 Gyr, or 12% of our $M_V < M_V^* + 1$ sample. The fraction of merger candidates in the rest of our sample is small, $< 1\%$ (van Dokkum et al. 1999), pointing to the possibility that cluster galaxy mergers were more prevalent either at higher redshift or in certain kinds of clusters. Nonetheless, 12% could represent the rate of merging in $z \simeq 0.8$ clusters.

We show the 23 members of these close pairs of galaxies as black open circles in Figure 9. The average mass of a galaxy in these pairs, for galaxies above our luminosity limit, is $10^{11.2 \pm 0.3} M_{\odot}$. The mean early-type galaxy in the whole sample is the same mass, $10^{11.2 \pm 0.4} M_{\odot}$. Therefore, the samples of close pairs in Tran et al. (2005a) and M. Postman et al. (2008, in preparation) appear to have masses typical of M_* at $z \sim 0$ cluster early-type galaxies. It is possible that the progenitors of some low-mass (close to our limit) $z \simeq 0$ early-type galaxies have a mass at $z \simeq 0.8$ such that they would fall below our $> 10^{10.6} M_{\odot}$ limit. The close pairs we observe suggest this possibility, but most (19 of 23) of the galaxies observed have masses significantly more than a factor of 2 above our mass threshold. Second, only two are spirals, pointing to a prevalence of “dry” merging. Assuming no new galaxies, “dry” merging will decrease the number of early-type galaxies above our mass limit. However, galaxies below our mass limit could also merge. The overall impact from merging on the early-type galaxy population depends on a number of factors and requires up-to-date galaxy formation models to disentangle. However, if the close pairs in our sample are representative of the typical mergers between massive galaxies, the progenitors of the $z \simeq 0$ galaxies near our mass limit may not have built up through massive mergers and merging will not have dramatically changed the early-type galaxy fraction.

As mentioned in § 3 we carried out a test to see if setting the mass limit in Coma at a higher value, $> 10^{10.9} M_{\odot}$, made any difference (compared to $> 10^{10.6} M_{\odot}$ for the $z = 0.83$ clusters). This would correspond to a large $\simeq 2$ times mass buildup from $z \simeq 0.8$ to $\simeq 0$ (e.g., Bell et al. 2006; results mentioned above). Not unexpectedly, the results are unchanged (see Fig. 8). The early-type galaxy fraction increases, as would be expected, but very modestly by 4% at high densities and by only 1% at low densities, well within the errors. Our results will not be changed by choosing time-dependent mass limits, at least for levels that correspond to any likely evolution in the mean mass buildup in clusters.

4.3. Field Galaxy Infall

Infall of late-type galaxies from the low-density region surrounding the cluster is expected to play a continuing role in the buildup of early-type cluster galaxies through their transformation to elliptical

FIG. 9.— Mass-density relation for MS 1054 and RX J0152 at $z = 0.83$ for a magnitude-limited sample. The red circles are elliptical galaxies, the orange squares are S0 galaxies, and the blue spirals are late-type galaxies. Each galaxy has $M_V < M_V^* + 1$, the criterion we use for luminosity-selected samples. The horizontal green dashed line shows our mass selection limit, while the vertical black dashed line shows the division between the two density bins in Figs. 4 and 7. Black open circles highlight red galaxies that are potential mergers in MS 1054 (Tran et al. 2005a) and in RX J0152 (M. Postman et al. 2008, in preparation). The mean mass of a late-type galaxy, in our luminosity-selected sample, is at the green line, or $10^{10.6 \pm 0.4} M_{\odot}$, one-quarter of the mean mass, $10^{11.2 \pm 0.4} M_{\odot}$, of the early-type galaxies in our luminosity-selected sample. A significant fraction of the late-type star-forming galaxies are below our mass limit, yet they would be included in the luminosity-selected MDR for these $z = 0.83$ clusters. At lower redshifts, as star formation ends and they fade to lower luminosities, they will drop out of the luminosity-selected MDR. The result would be an apparent increase in the early-type fraction in the luminosity-selected samples.

and S0 galaxies (and thus leads to a buildup in the total mass in early-type galaxies with time). Since the early-type fraction in the field above our mass limit, $10^{10.6} M_{\odot}$, is 30% lower than in the cluster ($\simeq 50\%$; Noeske et al. 2007; van der Wel 2007), the infalling spiral and late-type galaxies must transform to early-type galaxies if the infall rate adds significant mass to the cluster (even if the mechanisms of the transformation are unclear at this time). Otherwise the fraction of early-type galaxies would decrease with time, which is inconsistent with what is seen in either the mass- or luminosity-selected samples. One caveat on this argument is that the low-density regions around rich clusters are likely to be unlike the “true” field (see, e.g., Diaferio et al. 2001), and so studies of the cluster environment within ~ 10 Mpc (comoving) will be needed for quantitative discussions of the role of infall.

We expect clusters of galaxies to be continually growing in mass by the infall of galaxies and groups of galaxies from larger radii. Yet we find no change in the morphological mix above our mass limit. No change in the fraction of early-type galaxies does not preclude significant mass growth, however. A simple argument based on the rough constancy of the observed $\sim 85\%$ early-type fraction allows us to estimate how the mass in early-type cluster members could grow. First, we assume that the infall rate is always high enough to keep the fraction of late-type galaxies $\simeq 15\%$. Second, we assume that galaxies take $\simeq 1.5$ Gyr to transform from a late-type spiral into an early-type galaxy, the assumption from van Dokkum & Franx (2001). Between $z = 0.83$ and 0, there are 7 Gyr, slightly more than 4 times the transformation timescale. Every 1.5 Gyr, the mass in early-type galaxies in this scenario increases by 18%, as 15% of the total population of galaxies transforms into same type as the remaining 85% of the population. These assumptions lead to a doubling of the $z \simeq 0.8$ mass by $z = 0$. In other words, $\simeq 50\%$ of the $z \simeq 0$ early-type galaxy population enters the cluster as late-type galaxies between $z \simeq 0.8$ and $\simeq 0$. Interestingly, this rate of increase in the mass density of ellipticals and S0 galaxies is roughly comparable to that typically measured in field surveys (see, e.g., Bell et al. 2004; Faber 2007; Brown et al. 2007). The timescale of transformation and the infall rate are the largest uncertainties. A longer transformation timescale would in turn lower the amount of inferred evolution among early-type galaxies above our mass threshold, and this calculation neglects that many infalling massive galaxies would already be elliptical and S0 galaxies.

4.4. The Role of Low-Mass Galaxies—Transformation at Low Masses

Our mass-selected sample reaches down to masses $10^{10.6} M_{\odot}$, and the lack of evolution of the early-type fraction in that sample leads us to infer that changes at lower masses are playing a role in the evolution seen in luminosity-selected samples, a possibility discussed in De Propris et al. (2003). No comprehensive studies have been carried out that are complete from high to very low galaxy masses.

However, there is some evidence of evolution at low masses (transformation from late-type to early-type), but the results have not been consistent. For example, a number of authors have argued for evolution in the faint, red cluster population (De Lucia et al. 2004; Goto et al. 2005; Tanaka et al. 2005; De Lucia et al. 2007; Stott et al. 2007). This evolution is observed as an increase in the ratio of faint—often called “dwarf”—red-sequence galaxies to the “giant” galaxies with luminosities of L^* . In Holden et al. (2006) we speculated that these additional “dwarf” galaxies would become low-mass S0 galaxies in $z = 0$ clusters. The samples of De Lucia et al. (2007) and Stott et al. (2007) are selected to contain galaxies with masses below $10^{10.6} M_{\odot}$, so there is no conflict

between the observed evolution in that sample for galaxies with masses of $\simeq 0.25M^*$ and the lack of evolution in our mass-selected sample containing $>0.25M^*$. However, the reported results are not unanimous. Andreon (2006) finds no change in the population of faint galaxies in the cluster MS 1054. Tanaka et al. (2005, 2007) find a similar result, i.e., no change in the luminosity function for the red sequence in RX J0152 and RDCS 1252.9–2927 at $z = 1.24$. Interestingly, Tanaka et al. (2005, 2007) find a truncation in the red sequence for the lower mass groups of galaxies outside the cluster cores. Tanaka et al. (2005) and Andreon (2006) both imply that one might find no evolution in the early-type galaxy fraction at even lower masses for the clusters in our sample, a result that can be verified with deeper spectroscopic samples of mass-selected galaxies.

The inconsistencies in these results suggest that robust, mass-selected samples that are complete to substantially below $>10^{10.6} M_{\odot}$ are needed to establish the nature of the evolution of the star-forming galaxies in the cluster environment.

5. SUMMARY

We selected a sample of clusters spanning a range in redshift from $z = 0.023$ to 0.83. Each cluster we included has approximately the same X-ray luminosity and velocity dispersion to mitigate the observed correlations between cluster mass estimates and the fraction of elliptical and S0 galaxies seen in Postman et al. (2005) and Desai et al. (2007). Using high-quality photometry, largely from *HST*, we computed rest-frame optical colors for the spectroscopically confirmed members and derived mass-to-light ratios (M/L). From M/L , we determined stellar masses of the 674 galaxies in our sample. We find that these stellar masses agree well with those from dynamical measurements, with a scatter ranging from 0.11 dex at $z \simeq 0$ –0.20 dex at our highest redshifts.

All of the galaxies in our sample have morphological classifications. While the classifications come from a variety of sources (Dressler 1980a; Fabricant et al. 2000; Tran et al. 2003, 2005b; Postman et al. 2005), all of the $z > 0.1$ catalogs were constructed to be consistent with the classification scheme of Dressler (1980a). We used these catalogs to derive the morphology-density relations (MDRs) in the five clusters and to establish the evolution in that relation for luminosity-selected samples (for luminosities $< M^* + 1$). As shown in Figures 3 and 4, we found good agreement for both the $z = 0$ MDR from Dressler (1980b) and Postman & Geller (1984) as well as for the evolution seen in previous work (Dressler et al. 1997; Smith et al. 2005; Postman et al. 2005) for the 452 galaxies brighter than $< M^* + 1$ in our sample.

We contrast the results for the luminosity-selected samples with a similar large completeness-corrected mass-selected sample of 441 galaxies with masses $>10^{10.6} M_{\odot}$ ($0.25M_*$ at $z = 0$) in each of the clusters. At this mass limit, the majority ($\simeq 70\%$) of the stellar mass in galaxies in the clusters is in our mass-selected sample.

Very interesting differences are seen between the mass- and luminosity-selected MDRs. First, the MDRs derived for the individual clusters from the mass-selected galaxy samples typically have larger early-type galaxy fractions, by 10%–20%, and show marginal evidence of a lower slope with density. Second, and particularly striking, is that essentially no evolution is seen in the mass-selected early-type galaxy fraction with redshift. The change of the slope is substantially less than for the luminosity-selected sample and is consistent with no change with redshift. We find mean early-type fractions of $83\% \pm 3\%$ at 500 galaxies $\text{Mpc}^{-2} > \Sigma > 50$ galaxies Mpc^{-2} and $92\% \pm 4\%$ at $\Sigma > 500$ galaxies Mpc^{-2} . This indicates that the evolution in the early-type fraction observed in luminosity-selected samples of galaxies arises predominately

from the inclusion of lower mass, $<10^{10.6} M_{\odot}$, late-type galaxies at higher redshifts.

Despite finding no evolution in the mass-selected early-type fraction with redshift, we recognize that the cluster galaxy formation process is not finished at $z = 0.83$. The overall mass in early-type galaxies is expected to increase, but this increase must happen so as to leave the early-type galaxy fraction largely unchanged. The early-type fraction in the field above the same mass limit is very significantly lower ($48\% \pm 7\%$ at $z = 0.8$; van der Wel 2007). Infall of field galaxies, with a larger fraction of spiral and late-type galaxies, into clusters is expected and must be accompanied by transformation to early-type galaxies to ensure that the fraction of early-type galaxies remains constant.

Mass-selected samples to low masses, along with detailed morphologies, are realizable and would be of great value for characterizing and constraining galaxy evolution over the last 7–8 Gyr out to $z \sim 1$. Identifying these physical processes and the nature of the transition from the field early-type fraction is the next step—for a range of cluster masses (see, e.g., Postman et al. 2005; Desai et al. 2007). Of particular value will be the outer regions, where future cluster members will be transformed during their infall into the cluster by $z \simeq 0$. Significant insights into the buildup of galaxies in dense environments over the last 7–8 Gyr would result from increasing the sample of clusters with mass-selected galaxies that have redshifts, morphologies and excellent photometry. These data would be of particular value for developing insight into the formation of S0 galaxies, which show strong evolution in luminosity-selected samples from $z \simeq 1$ to $\simeq 0$.

In summary, we have derived luminosities, masses, and morphologies for a large and complete sample of cluster galaxies ranging from $z = 0.023$ to 0.83 . The luminosity-selected galaxy samples show, in all clusters, a clear MDR. Furthermore, the early-type galaxy fraction evolves substantially with redshift, as found by others. When we construct mass-selected samples,

the MDRs are offset toward larger early-type fractions and are marginally weaker. More dramatically, the evolution in the early-type galaxy fraction is very weak, being consistent with no evolution over the 7 Gyr period. As these two samples are drawn from the same parent sample of five massive clusters of galaxies, we conclude that the galaxies that lead to the evolution of the luminosity-selected MDR must be galaxies less than our mass limit, namely, those with masses $<10^{10.6} M_{\odot}$.

We would like to thank Erica Ellingson, Sandy Faber, Justin Harker, Susan Kassin, David Koo, Anne Metevier, Kai Noeske, S. Adam Stanford, and Pieter van Dokkum for useful discussions. We would like to thank the anonymous referee for helping us substantially improve this paper. The Advanced Camera for Surveys (ACS) was developed under NASA contract NAS5-32865, and this research was supported by NASA grant NAG5-7697. We are grateful to K. Anderson, J. McCann, S. Busching, A. Framarini, S. Barkhouser, and T. Allen for their invaluable contributions to the ACS project at Johns Hopkins University. Some of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

APPENDIX A

FIRES DATA FOR MS 1054

We used additional photometry for MS 1054 from the Faint Infrared Extragalactic Survey (FIRES), discussed in Förster Schreiber et al. (2006). The FIRES team used FORS1 on the Very Large Telescope (VLT) to obtain the UBV data and ISAAC to obtain the J_sHK_s data. The ISAAC imaging data consist of four overlapping pointings with 77 hr of total exposure covering a $5.5' \times 5.3'$ field of view.

The original FIRES catalog was created using a combination of the VLT data and older WFPC2 imaging in F606W and F814W. We elected to replace the WFPC2 data with our ACS imaging, as our data should be of higher quality and include an additional filter, z_{850} . To obtain accurate colors, we smoothed the ACS imaging, along with the rest of the VLT imaging, to the same effective seeing as the worst of the ground-based imaging. We then rebinned the ACS data to the same scale, $0.0996'' \text{ pixel}^{-1}$, and orientation as the VLT K_s image. We used the unsmoothed K_s image as a detection image. All magnitudes for the colors were measured in fixed apertures on the smoothed data. The apertures ranged in size from $1.0''$ to $2.4''$ in size in increments of $0.2''$. We selected the aperture in which the signal-to-noise ratio for the color measurements was maximized. We used SExtractor (Bertin & Arnouts 1996) for object detection and photometry for the FIRES imaging.

As we have remeasured the magnitudes in all the images, we compared our resulting magnitudes with those as measured by the FIRES team. For the near-infrared data, the scatter was less than 0.01 mag. For the B and V data, the scatter was around 0.02 mag, with the U showing 0.04 mag in scatter. Given that the images are the same, this scatter came from different choices of parameters used for object detection parameters, resulting in slightly different object positions and sizes. We examined the scatter for those objects labeled by SExtractor as “biased,” i.e., objects with close neighbors in the FIRES catalog. We found that the scatter increased (at times it doubled) only for those objects flagged as “biased.” Thus, the difference in detection parameters is most likely what causes the scatter in the photometry between our measurements and those of the FIRES team. In addition to the scatter, we found a small offset between our magnitudes and those from FIRES. This result came from the different point-spread function smoothing kernels used by us and by the FIRES team. This offset is less than 0.01 mag for all filters.

Our photometric catalog was then merged with the ACS imaging catalog. We selected galaxies from the FIRES catalog, then matched those to identifications from the ACS catalog. This catalog contains morphological types from Postman et al. (2005) and the colors from Blakeslee et al. (2006). When two objects from the ACS imaging were identified as a single object in the FIRES imaging, we removed them. The final catalog contains 1221 galaxies, with a subset of 482 that have morphological classifications from Postman et al. (2005).

FIG. 10.—Ratio M/L_B as a function of rest-frame $B - V$ color for the MS 1054 sample (*top*) and the SDSS DR4 sample (*bottom*). In each panel, the blue spirals are late-type galaxies while the orange squares are early-type galaxies. The solid lines represent the best fit to the relation between the $B - V$ color and the mass-to-light ratio in the B band. The dashed lines are the relations from Bell et al. (2003). We reproduce the results of Bell et al. (2003) and thus used that relation to estimate M/L_B for the whole of our cluster sample. The scatter around the relation is 0.14 dex in the high-redshift sample and 0.12 dex in the low-redshift sample, with no significant difference in the scatter for early- or late-type galaxies.

We found a small 0.018 ± 0.012 mag offset between our z_{850} magnitudes and those from Blakeslee et al. (2006). The magnitudes in Blakeslee et al. (2006) have a 0.2 mag aperture correction to estimate the total magnitudes. The FIRES magnitudes are based on the five Kron radius aperture magnitudes from SExtractor as measured on the K_s imaging. The $z_{850} - K_s$ color is then used to compute the total flux in the z_{850} filter. However, no aperture correction is made, so this 0.018 mag offset reflects how much light is lost in the K_s imaging.

APPENDIX B

MASS ESTIMATES BASED ON MULTIBAND PHOTOMETRY

For MS 1054, we estimated stellar masses by fitting spectral energy distributions (SEDs) to the photometric data from the FIRES data set. Specifically, we used two sets of BC03 models: simple stellar populations (SSPs) and models with exponentially decaying star formation rates. These were fit to the combination of the FIRES data and ACS imaging. For both sets of BC03 models, we assumed a Salpeter initial mass function. When using models with exponentially decaying star formation rates, or τ models, we assumed timescales (τ) ranging from 100 Myr to 5 Gyr. For both the SSPs and the τ models, we used three different metallicity values, 0.4, 1, and $2.5 Z_\odot$.

Given a SED and the photometry of a galaxy in one of the clusters in our sample, we redshifted the SED to the observed value. We computed the fluxes in the observed filters using the filter curves provided by ESO for FORS and ISAAC and by the Space Telescope Science Institute for the ACS (Sirianni et al. 2005). For a given metallicity and τ , we allowed the range of ages to vary. For every model, we computed the normalization n that minimized the χ^2 for that model. This eliminates the need to fit for the best model and the best normalization, as the normalization is the one that automatically minimizes the χ^2 for a given model. The normalization is $n = (\sum f_i m_i / \sigma_i^2) / (\sum m_i^2 / \sigma_i^2)$, where i denotes a filter, f_i is the observed flux, m_i is the model flux, and σ_i is the estimated error. The error on n is $\sigma_n = (\sum \sigma_i^2 / \sum m_i^2)^{1/2}$. This normalization provides the mass in stars required to reproduce the observed flux in the color aperture. We used the total magnitudes in the K_s filter to correct this normalization to a “total” stellar mass. We then compared the χ^2 for each model using this normalization while varying the other parameters of interest.

These model fits were also used to derive rest-frame colors. We computed the model’s $z = 0$, or rest-frame, magnitudes in the desired filters, such as B and V . We then computed the model magnitudes in the observed filters as part of the χ^2 fitting. We used the offset between the best-fitting model’s observed and rest-frame magnitudes to estimate the rest-frame magnitudes from the data for each galaxy.

For both the SSP and τ models, we included the effect of dust by adding an additional foreground screen to our spectral energy distribution model fits. The typical change in the resulting stellar mass was minimal. For example, the average mass changes by 7% between τ models with dust and those without. The models generally fit the data with a minimal amount of dust for most galaxies, except for the bluer, star-forming objects. Removing the filters that sample the rest-frame UV, the U and B in the FIRES data sample $< 2500 \text{ \AA}$ at $z = 0.83$, reduces this change in the mass to 4%. When combined with τ models, dust removes any mass-metallicity relation and, as expected, moves the average age to younger values. The mode of the age distribution, however, stays the same. The modal age of the population is the age of the “red sequence,” and those galaxies are all fit with little or no dust. The addition of dust adds a tail of younger

ages. Thus, dust models significantly changed the ages and masses only for the bluer populations, as expected for galaxies with ongoing star formation, and do not affect the majority of the cluster population.

Bell et al. (2003) give, in § 2 of their Appendix A (Table 7), a relation between rest-frame color and M/L in the Johnson B , V , and R passbands. We found, as in Bell et al. (2003), the best-fitting SED M/L_B correlates strongly with the $B - V$ rest-frame color for the galaxies in MS 1054; see Figure 10. This plot is made by fitting dust-free τ models to all of the FIRES and ACS filters. We show our best-fitting relation between M/L_B and the rest-frame $B - V$ color. We find that our relations are very similar to the results from Bell et al. (2003), shown as dashed lines in Figure 10.

We found a scatter of 33%, or 0.14 dex, in M/L around the best-fitting relation for MS 1054. Early-type galaxies have a slightly larger scatter of 34%, or 0.15 dex, while late-type galaxies have 30%, or 0.13 dex. In our lower redshift sample created using the SDSS DR4, we find a smaller scatter, 28%, or 0.12 dex, with the same scatter for both late- and early-type galaxies.

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