THE POSSIBLE PRECURSORS OF $Z = 0.83$ PRECursors of $Z = 0$, $M^*$ EARLY-TYPE CLUSTER GALAXIES

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ABSTRACT

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

Subject headings: galaxies: clusters: general — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: fundamental parameters — galaxies: photometry — galaxies: clusters: MS 1054.4-0321 — CL 0152.7-1357

1. INTRODUCTION

The early-type galaxy fraction and morphology-density relation show that the mix of galaxies we observe in clusters today has significantly changed over the past 7-10 Gyrs (Dressler et al. 1997; Lubin et al. 1998; van Dokkum et al. 2000, 2001; Holden et al. 2004; Smith et al. 2005; Postman et al. 2005). This observation raises the question of what the descendants of the additional late-type galaxies seen at higher redshifts are. One possible approach to this problem is to compare the present-day early-type galaxy fraction to the early-type fraction of members to high stellar masses, those over $M^*$ at $z = 0$, which we can compare with a $z = 0$ sample. Throughout, we assume $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA

We use imaging from the F775W (hereafter $i_{775}$) and F850LP (hereafter $z_{850}$) filters. In addition, MS 1054.4-0321 was observed with the F606W (hereafter $V_606$) while CL 0152.7-1357 was imaged in the F625W, or $r_625$, filter. For a thorough discussion of the ACS photometry, see Blakeslee et al. (2006). Postman et al. (2005) determined the morphological types of the cluster members using the $i_{775}$ data. Postman et al. (2003) estimated the scatter on the early-type fraction to be 6% by comparing the fractions derived from different classifiers.

We have 143 spectroscopically confirmed members in MS 1054.4-0321 with $i_{775} < 23.5$ mag (Tran et al. 2003), with additional redshifts gathered since that publication. For the second cluster in our sample, CL 0152.7-1357 at $z = 0.834$, we have 95 spectroscopic members with $i_{775} < 23.5$ mag from Demarco et al. (2003). We compute the completeness for each cluster empirically as a function of $i_{775}$ magnitude and morphological type as was done by Postman et al. (2005). We compare the above data with the $U$, $B$, and $r$ photometry for morphologically identified, spectroscopically confirmed Coma galaxies from Beijersbergen et al. (2002). Those authors constructed a new sample of
redshifts that is complete to \( r < 16.27 \) mag or \( M_r < -18.75 \) mag, and morphologically typed a large number of previously unidentified galaxies. We compute the rest-frame \( g - r \) color from the relation \( g - r = 0.61(B - r) - 0.07 \), using templates from Bruzual & Charlot (2003) and Kinney et al. (1996), where \( B - r \) comes from the catalog of Beijersbergen et al. (2002).

3. MASS ESTIMATION

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

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

We have collected a sample of 51 galaxies with half-light radii and velocity dispersions, 22 dispersions from MS 1054.4-0321 (Wuyts et al. 2004) and 29 dispersions in CL 0152.7-1357 (Jørgensen et al. 2003), with sizes for both clusters from Holden et al. (2005). In Figure 1 we compare the masses derived from the relation \( M = 5\sigma^2r_e/G \) or \( M = 2\log 10r + \log 10\sigma + 6.07 \) (Jorgensen et al. 1996), with the masses estimated using the rest-frame \( M/L_r \) values from ACS colors, combined with our total magnitude estimates. We find an offset of 0.13 dex between our stellar mass estimates and the dynamically estimated mass, shown in Figure 1. The scatter in the mass estimates for the elliptical galaxies is 60%, compared with 66% for the whole sample. It appears that, at lower dynamical masses, our stellar masses are overestimates. This is likely a result of the luminosity limits used in selecting galaxies for the velocity dispersion samples, which we illustrate with a dotted line in Figure 1. Future studies of the fundamental plane to fainter magnitudes will test our color scaling of \( M/L \) to fainter luminosities.

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

We fit a Schechter function (Schechter 1976) to the distribution of masses in Coma and find \( M^* \), the characteristic mass, to be \( 10^{11.1 \pm 0.2} \) \( M_\odot \). This value is higher than \( 10^{11.0} \) \( M_\odot \) (for \( H_0 = 70 \) \( \text{km s}^{-1} \text{Mpc}^{-1} \)) found in the field survey of Bell et al. (2003) because \( L^* \), which is \( M_r = -21.6 \) mag AB for cluster galaxies (Beijersbergen et al. 2002a; Hansen et al. 2005) is brighter than \( L^* \). \( M_r = -21.3 \) mag AB, for field galaxies found in Bell et al. (2003).

![Figure 1](image_url)

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

4. MASS AND THE EARLY-TYPE FRACTION

We find an early-type fraction of 87% \( \pm 6\% \) for all galaxies in Coma with masses above \( 10^{11.1} \) \( M_\odot \) (errors for the Coma early-type fractions are computed by using bootstrap re-sampling). At \( z = 0.83 \), we find the early-type fraction to be 79% \( \pm 6\% \) (82% \( \pm 8\% \) for MS 1054.4-0321, 74% \( \pm 8\% \) for CL 0152.7-1357), a not significant change of 9%\( \pm 8\% \) from Coma. In contrast, when using
a red-sequence galaxy, which is $M > 10^{10.9} M_\odot$. The early-type fraction for this mass limit is 79% ±6% for Coma and 71% ±7% at $z = 0.83$ (78% ±8% MS 1054.4-0321 and 64% ±8% for CL 0152.7-1357). Unfortunately, below this mass threshold of $M = 10^{10.9} M_\odot$, the early-type fraction decreases quickly because we are incomplete, (less than 50% of early-types at those masses have redshifts). The completeness corrections for the early-type fraction with $M > 10^{10.9} M_\odot$ are on the order of 5%. Thus, we find no evidence for evolution in the early-type galaxy fraction even when we examine lower mass samples with two caveats: there is a larger spread in the measure fractions between MS 1054.4-0321 and CL 0152.7-1357, and we are much more incomplete for redshifts at these masses.

5. DISCUSSION AND RESULTS

The same data but taking a luminosity-selected sample of galaxies to $L^* + 0.5$, or $M_r = -21.1$ mag, we find an early-type fraction of 78 ± 4% for Coma. At $z = 0.83$ we have 62 ± 6% (65 ± 8% for MS 1054.4-0321, 60 ± 8% for CL 0152.7-1357), which is typical for what is found for the cluster samples in van Dokkum et al. (2001) or Holden et al. (2004) at the same magnitude limit. We note that the $z = 0.83$ early-type fractions are corrected for incompleteness, but this is usually a small, ~2% effect.

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

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

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The possible precursors of $z = 0$ cluster early-types

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The smaller early-type fractions we find at fainter magnitudes means that, below a certain mass, we should see the early-type fraction decrease. When using magnitude limited samples of galaxies, there is evolution in the fraction of early-type galaxies over the redshift range $z = 0$ to $z = 1$ (Dressler et al. 1997; Lubin et al. 1998; Fasano et al. 1983).
of star-formation or the galaxies simply fade below the detection threshold. In contrast, Figure 3 shows that we see minimal differences in the early-type fraction among galaxies with masses above $M^*$, a difference of 9% $\pm$ 8%, in the early-type galaxy fraction above the mass threshold of $M^*$ between $z = 0.83$ and $z = 0$. The difference in luminosity-selected samples comes from an increase in the ratio of late-type galaxies, which have a peak, or modal, mass of $\sim 10^{10.7} M_\odot$, and a corresponding decrease in the number of sub-$M^*$ early-type galaxies.

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

Postman et al. (2005) found that the fraction of S0 galaxies at almost all galaxy densities doubles between $z \sim 1$ and $z \sim 0$. We find that the fraction of early-type galaxies at high mass, greater than $M^*$, does not change, within the limits of our errors, over that same redshift range. Therefore, most of the evolution observed in Postman et al. (2005) in the galaxy population must occur among lower mass but still luminous galaxies. The observed decrease between $z \sim 1$ and $z \sim 0$ in luminous late-type galaxies could happen in two ways, the galaxies could be transformed into early-types by a stopping of star-formation or the galaxies simply fade below the luminosity limit by $z = 0$. We cannot directly constrain either scenario with our data. However, we would like to point out two observations. First, Bell et al. (2003) finds that $M^*$ for late-type galaxies is $10^{10.8} - 10^{10.9} M_\odot$ at $z \sim 0$. If there is no evolution in $M^*$ for late-type galaxies and a typical-mass late-type galaxy becomes an early-type galaxy through the truncation of star formation, it should appear as an early-type at masses below our cutoff of $10^{11.3} M_\odot$. At masses of $10^{10.8} - 10^{10.9} M_\odot$ in Coma, there is a steep rise in the number of S0 galaxies (see Fig. 3). We note that the modal mass of late-type galaxies at $z = 0.8$ is $10^{10.6} M_\odot$, near the mass where the S0 number peaks. Second, Nelan et al. (2005) predict, based on the ages inferred from absorption line strengths, that the $10^{10.8} - 10^{10.9} M_\odot$ cluster early-type galaxies have a median “age” of 8–9 Gyr. This result provides a natural explanation for the change in the early-type galaxy fraction at these look-back times. However, these speculations must be tempered by the results of Homeier et al. (2005) and Crawford et al. (2004), for example. It is possible that a large fraction of the luminous late-type galaxies at $z = 0.8$ are luminous but low mass galaxies undergoing starbursts. These galaxies will simply fade into the dwarf elliptical population by $z = 0$. Both of these scenarios are directly testable by measuring the properties of early-type galaxies at lower masses.

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

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