EVOLUTION SINCE $z = 1$ OF THE MORPHOLOGY-DENSITY RELATION FOR GALAXIES

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ABSTRACT

We measure the morphology-density relation of galaxies at $z = 1$ across the full 3 orders of magnitude in projected galaxy density available in low-redshift studies. Our study adopts techniques that are comparable with those applied at lower redshifts, allowing a direct investigation of how the morphological segregation of galaxies has evolved over the last 8 Gyr. Although the morphology-density relation, as described by the fraction of early-type ($E+S0$) galaxies, was in place at $z = 1$, its form differs from that observed at both $z = 0$ and $z = 0.5$. In the highest density regions the early-type fraction has increased steadily with time from $f_{E+S0} = 0.7 \pm 0.1$ at $z = 1$ to $f_{E+S0} = 0.9 \pm 0.1$ at the present epoch. However, in intermediate-density regions corresponding to groups and the accretion regions of rich clusters, significant evolution appears to begin only after $z = 0.5$. Finally, at the lowest densities, no evolution is observed for the early-type fraction of field galaxies, which remains constant at $f_{E+S0} = 0.4 \pm 0.1$ at all epochs. We examine a simple picture consistent with these observations where the early-type population at $z = 1$ is comprised largely of elliptical galaxies. Subsequent evolution in both intermediate and dense regions is attributed to the transformation of spirals into lenticulars. Further progress in verifying our hypothesis may be achieved through distinguishing ellipticals and lenticulars at these redshifts through resolved dynamical studies of representative systems.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: structure

1. INTRODUCTION

In the local universe the fraction of galaxies with elliptical and lenticular (i.e., early-type) morphologies is higher in clusters of galaxies than in less dense environments (Hubble 1926; Oemler 1974; Melnick & Sargent 1977; Dressler 1980). To first order, this morphology-density relation appears to be a universal characteristic of galaxy populations (e.g., Postman & Geller 1984; Helsdon & Ponman 2003). In quantitative terms, morphological fractions correlate over 3 orders of magnitude in projected galaxy density ($\Sigma$), thereby linking the properties of cluster galaxies ($\Sigma \sim 1000$ Mpc$^{-2}$) with those of the field galaxy population ($\Sigma \sim 10$ Mpc$^{-2}$).

The morphological segregation of galaxies is a generic prediction of cold dark matter simulations of large-scale structure formation (Frenk et al. 1985, 1988) and more recent semi-analytic galaxy formation models (Kauffmann 1995; Baugh et al. 1996; Benson et al. 2001; Diaferio et al. 2001; Springel et al. 2001). In that context, the observed morphology-density relation is interpreted as the combination of two mechanisms. First, the local density of galaxies and dark matter is a proxy for the epoch of initial collapse of a given structure; the most massive structures at any epoch represent the earliest that collapsed. Second, interactions between galaxies, dark matter, and the intracluster medium (i.e., environmental processes) are likely to transform infalling field galaxies from gas-rich spirals to gas-poor lenticular galaxies. The exact balance between these two mechanisms (i.e., nature vs. nurture) and the detailed physics of the environmental processes have yet to be identified unambiguously and are the focus of much ongoing research (e.g., Kodama & Smail 2001; Balogh et al. 2002; Treu et al. 2003).

An important element of investigating the physics of morphological transformation is to trace the cosmic evolution of the morphology-density relation over the full range of projected density available locally. The timescales on which the relation evolves in different density regimes will hold important clues to the physical processes responsible. Pioneering observations of the high blue fractions seen in intermediate-redshift clusters by Butcher & Oemler (1978) also raise the possibility of evolution in the morphological mix with look-back time. To that end, Dressler et al. (1997) used high-resolution imaging with the Hubble Space Telescope (HST) to measure the morphology-density relation in the core regions of a sample of rich clusters at $z \approx 0.5$. Dressler et al. found that the fraction of lenticular galaxies in clusters declined by a factor of 2–3 between $z = 0$ and $z = 0.5$, and this evolution was accompanied by a corresponding increase in the fraction of star-forming spirals (see also Andreon 1998; Couch et al. 1998; Fasano et al. 2000; Treu et al. 2003).

At higher redshifts, the distinction between elliptical and lenticular morphologies becomes increasingly difficult to draw (Smail et al. 1997; Fabricant et al. 2000). Nevertheless, several authors have measured the total early-type fraction $f_{E+S0}$ in individual clusters at $z \approx 1$ (e.g., van Dokkum et al. 2000, 2001; Lubin et al. 2002). These authors find $f_{E+S0} = 0.5$ in clusters at $z \approx 1$, i.e., a smaller fraction than that found in the densest environments at $z = 0$. However, as van Dokkum & Franx (2001) caution, these estimates are preliminary because they are based on a very small number of clusters.

In this paper we measure the morphology-density relation at $z = 1$ across the full 3 orders of magnitude in galaxy density spanned in local samples. We compare our results with those obtained at lower and intermediate redshifts (Dressler 1980; Dressler et al. 1997; Treu et al. 2003) and thus chart, for the first
time, the form of the morphology-density relation over a cosmologically significant time interval (∼8 Gyr).

A plan of the paper follows. In §2 we develop a strategy for measuring the morphology-density relation at z = 1 and summarize the data used for this purpose. Then in §3 we describe the analysis, focusing separately on high- and low-density environments. The main results, the morphology-density relation at z = 1 and its evolution to the present day, are presented in §4. In §5 we discuss a possible interpretation, including how it relates to previous measurements of $\frac{f_{\text{gal}}}{f_{\text{gal+}}}$ in high-redshift clusters. We summarize our conclusions in §6. We parameterize the Hubble expansion as $h = H_0/100$ km s$^{-1}$ Mpc$^{-1} = 0.65$ and adopt the currently favored values of $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ when our analysis requires us to make distance estimates. In this cosmology $1$ Mpc$^3$ ≈ 8.63 kpc physical size at $z = 1$. Unless otherwise stated, all error bars are stated at 1 $\sigma$ significance. All magnitudes are quoted in the Vega system.

2. DATA

2.1. Strategy

The primary aims of this paper are to measure the morphology-density relation at $z \approx 1$ and to identify broad evolutionary trends by comparing our measurements with those at $z \approx 0$ (Dressler 1980) and $z \approx 0.5$ (Dressler et al. 1997; Treu et al. 2003). To facilitate this comparison, we adopt the same analysis methods used in the lower redshift studies and provide two measurements for carefully selected galaxy populations at $z = 1$ that form the basis of our analysis: The projected number density ($\Sigma$) of galaxies down to $M_V \leq M^*_{V} + 1$ allows us to measure the projected density, $\Sigma \equiv 10/A$, where $A$ is the solid angle within which the 10 nearest neighbors are found (see §3 for more details). We also morphologically classify the galaxies in the various $z = 1$ samples. Both $\Sigma$ and morphologies need to be derived in a homogeneous fashion across the full range in projected density: 1 Mpc$^{-2} < \Sigma < 1000$ Mpc$^{-2}$.

Dressler et al. (1997) used HST observations of 10 optically selected clusters to measure the morphology-density relation for cluster galaxies at $z \approx 0.5$, i.e., $50$ Mpc$^{-2} < \Sigma < 1000$ Mpc$^{-2}$. Treu et al.’s (2003) wide-field (out to a projected clustercentric radius of 5 Mpc) study of Cl 0024 extends Dressler et al.’s results out to field environments $\Sigma \approx 1$ Mpc$^{-2}$ for one cluster. To extend this body of work to $z = 1$ we sought HST imaging of a similar sized sample of clusters at $z \approx 1$. A search of the HST archive for Wide Field Planetary Camera 2 (WFPC2) observations of clusters at $0.75 \leq z \leq 1.25$ through the F814W filter (i.e., a reasonable match to rest-frame $V$ band) yielded a sample of six clusters for which 13 individual WFPC2 pointings are available (Table 1). This cluster sample is quite heterogeneous, spanning a factor of $\geq 10$ in X-ray luminosity; however, it represents the best sample available at the present time and is less homogeneous than those used in the lower redshift studies against which we compare our results (Dressler 1980; Dressler et al. 1997).

To measure the morphological fractions at $\Sigma \approx 1$ Mpc$^{-2}$, we complement these cluster data with a sample of field galaxies. Prior to large-scale redshift surveys of galaxies at $z = 1$ in regions where HST data are available (e.g., Davis et al. 2003; Le Fèvre et al. 2004), we necessarily rely on photometric redshift estimates. We therefore selected a field for which a deep photometric data set with broad wavelength coverage and HST imaging through the F814W filter is available. The mosaided HST field containing the rich cluster Cl 0024 ($z = 0.395$) is well matched to this purpose, as the bulk of the faint population viewed is not associated with the foreground cluster. Ground-based BVRJK photometry plus F814W HST/WFPC2 imaging are available (Kneib et al. 2003), and the projected physical extent is $\sim 170$ Mpc$^2$ at $z = 1$, corresponding to a volume of $5 \times 10^5$ Mpc$^3$ when integrated over a redshift interval $0.75 \leq z \leq 1.25$. Extensive spectroscopic studies of this field (Czoske et al. 2001; Treu et al. 2003; S. M. Moran et al. 2005, in preparation) provide several hundred spectroscopic redshifts that are useful.
in calibrating photometric redshift estimates based on the BVRILK-band photometry (see § 3.1.2).

In comparing morphological fractions at different redshifts, in addition to k-corrections and adopting a fixed luminosity limit of \( M_V^* + 1 \), the question of luminosity evolution in the population needs to be considered. Interpolating between the redshift-dependent B- and R-band luminosity functions, we estimate that evolution of \( M_V^* \) between \( z = 1 \) and \( z = 0 \) is 1 mag (Brown et al. 2001; Chen et al. 2003; Norberg et al. 2002; Poli et al. 2003). This amount of evolution in the rest-frame V band is also consistent with passive evolution of an old stellar population (e.g., Treu & Stiavelli 1999). Although there is some uncertainty in this estimate, we conclude that it is better to apply this adjustment rather than to ignore the effect altogether. We therefore subtract 1 mag of evolution from \( M_V^* \) at \( z = 0 \) (Brown et al. 2001) to define a luminosity limit 1 mag fainter than \( M_V^* \) at \( z = 1 \), i.e., \( M_V \leq -21.2 \).

### 2.2. Space-based Observations

A wide-field, sparse-sampled HST/WFPC2 mosaic of Cl0024 (\( z = 0.395 \)) was acquired during Cycle 8 (PI: R. S. Ellis; GO: 8559), comprising 38 independent pointings observed through the F814W filter for two orbits each. Treu et al. (2003) describe the reduction of these data; here we summarize key details of the reduced data: the pixel scale is 0.05 arcsec; the estimated 80% completeness limit is \( I_{814} \ga 25 \); and the total combined field of view of the 39 pointings (including the cluster center, e.g., Smail et al. 1997) is 0.05 deg², excluding the PC chip from each pointing. The primary motivation of these observations was a panoramic study of the rich cluster Cl 0024 (Treu et al. 2003; Kneib et al. 2003). However, as discussed, these data provide morphological information on a large sample of field galaxies at \( z \approx 1 \) (§ 3.2). The limiting magnitude of these data corresponds to \( M_V \approx -20 \) at \( z = 1 \), i.e., sufficiently deep to provide early-/late-type morphological classification in a manner consistent with that of earlier work (see § 3.2 for more details of the classification process, including estimation of uncertainties).

The high-redshift cluster data (Table 1) were reduced using the WFIXUP, WMOSAIC, IMALIGN, IMCOMBINE, and COSMICRAYS tasks in IRAF. The reduced frames have a pixel scale of 0.07 arcsec, and the mean FWHM of stellar profiles is 0.17 arcsec. As this pixel scale is twice that of the field galaxy data described above, we block-averaged the field data for the purpose of morphological classification. Although this results in a slight undersampling of the WFPC2 point-spread function, the larger pixels assist in the identification of faint morphological features. Although these cluster data are deeper than the corresponding field images (see Table 1), both are sufficiently deep for the morphological classification exercise (§ 3.2).

### 2.3. Ground-based Observations

Panoramic optical data of Cl 0024 were acquired with the 3.6 m Canada-France-Hawaii Telescope using the CFH12k camera (Cuillandre et al. 2000) through the BVRI filters. These data are described by Czoske (2002) and Treu et al. (2003). The sensitivity limit and image quality achieved in each passband are given in Table 2. The optical data are complemented by wide-field J- and Ks-band (hereafter K band) imaging obtained with the WIRC camera (Wilson et al. 2003) at the Hale 200" telescope on 2002 October 29–30. These near-infrared (NIR) observations comprise a 3\( \times \)3 mosaic of WIRC pointings, providing a contiguous observed area of \( \sim 26\times26' \) centered on the cluster. Further details of these observations and the data reduction are described by Kneib et al. (2003). Here we note that independent checks on the absolute photometric calibration using unsaturated sources in the 2MASS point source and extended source catalogs, together with examination of the sources that fall in the overlap regions between the nine pointings, confirm that the absolute and relative calibration of both the J- and K-band data are accurate to 10%. We incorporate these uncertainties into the spectral template fitting described in § 3. All of the ground-based data were registered onto Czoske et al.'s (2001) astrometric grid, which is accurate to \( \pm 0.2" \).

An important question is whether the depth of this multiband data is adequate for reliable photometric redshift studies at \( z = 1 \) described in § 3.1.2. We compare the depth of the ground-based data as a function of wavelength to spectral templates derived from observations of local galaxies (Coleman et al. 1980, hereafter CWW80). We redshifted the CWW80 templates to \( z = 1 \), normalized them to \( M_V = -21.2 \) (see § 2.1), and compared them with detection limits listed in Table 2 (note that the J-band detection limit is shown at 5σ significance because this is the detection filter adopted in § 3.1.2). Figure 1 confirms that the ground-based data are sufficiently deep to provide strong signal-to-noise ratio detections across the full wavelength range from B to K bands for all but the reddest spectral types. The slight shortfall in sensitivity in the bluest filters is not a significant concern because we have ignored spectral evolution when constructing Figure 1. Indeed, only 3% of the galaxies at \( z \approx 1 \) in the final photometric redshift catalog are undetected in the B band.

### 3. ANALYSIS

In this section we describe how we construct samples of cluster and field galaxies at \( z = 1 \) and measure the projected density \( \Sigma \) at the location of each galaxy (§ 3.1). In § 3.2 we describe the morphological classification.
m mosaic is of key importance here, since it provides a reasonable match to the rest-frame $V$ band at $0.75 \leq z \leq 1.25$. We analyze this data with SExtractor (Bertin & Arnouts 1996) excluding all sources that lie close to diffraction spikes around bright stars, adjacent to a small number of remaining cosmetic defects on the final reduced mosaic and within $10''$ of the edge of the field of view. Monte Carlo simulations were used to determine the completeness limits of the $J$-band catalog. Scaled artificial point sources that match the seeing were inserted at random positions into the $J$-band mosaic and examined using the same SExtractor configuration as above. The 80% completeness limit (equivalent to a 5σ detection limit) was determined to be $J(5\sigma) = 21.1$. We then performed aperture photometry for all of the $J$-detected sources using a $2''$ diameter aperture on the seeing matched $BVRIJK$-band frames. Finally, we removed several hundred stars from the multicolor catalog based on their profile shapes to yield a final catalog of 4376 sources. Using HYPERZ\(^9\) (Bolzonella et al. 2000), we then fitted synthetic spectral templates (Bruzual & Charlot 1993) to all 4376 galaxies in the $BVRIJK$ photometric catalog, allowing no dust extinction. This scheme was selected after experimenting with and without dust extinction, and with alternative templates (e.g., CWW80) it was found to produce the most accurate results, as determined from the tests described below.

The resulting photometric redshift distribution in Figure 2 shows that the foreground cluster, Cl 0024 ($z = 0.4$), is well recovered in the photometric redshift analysis. The photometric redshift reliability at higher redshifts can be gauged by comparing with the extensive spectroscopic catalog of S. M. Moran et al. (2005, in preparation; see also Czoske et al. 2001; Treu et al. 2003). The overlap between the photometric and spectroscopic catalogs extends only to $z = 1$ because the wavelength coverage of the spectroscopic observations ($\lambda \lesssim 0.75$ $\mu$m; e.g., Treu et al. 2003) was designed to locate cluster members at $z \approx 0.4$. Nonetheless, in the region of overlap the mean photometric redshift error is $\Delta z_{\text{phot}} = 0.01$, where $\Delta z_{\text{phot}} = (z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{spec}})$ is the rms scatter, defined as $\sigma_{\Delta z}^2 \equiv (N - 1)^{-1}\Sigma_{\Delta z}/1 + z_{\text{spec}})^2$, where $N$ is the number of galaxies, is also small: $\sigma_{\Delta z} = 0.1$. We also find that the quality of the photometric redshifts is remarkably uniform across the entire interval $0.25 < z < 1$, with $[(\Delta z_{\text{phot}})] < 0.01$ and a catastrophic error rate of $\lesssim$1%, where catastrophic errors are defined as sources for which $|z_{\text{spec}} - z_{\text{phot}}| > 0.5$. The results of these tests are consistent with the nominal performance of HYPERZ (Bolzonella et al. 2000).

Given our inability to test explicitly the quality of the photometric redshift estimates beyond $z = 1$ with the current data set, we considered limiting our analysis to $0.75 \leq z \leq 1$. However, when we tried this option, we found no systematic difference between the results based on this redshift cut and the broader cut adopted thus far. The main difference between results based on the two cuts was the poorer statistical precision achieved with the smaller sample. This probably indicates that the dominant source of uncertainty in this study, especially at low $\Sigma$, is statistical arising from the modest volume probed by the data. While it would be preferable to test the photometric redshifts beyond $z = 1$, we conclude that the absence of such a test does not introduce significant additional uncertainty into the analysis. We therefore adopt a redshift interval of $0.75 \leq z \leq 1.25$ for the low-density environments. Down to a luminosity $M_V \leq -21.2$ (see § 2.1) the combined photometric/spectroscopic catalog then yields a sample of 843 galaxies.

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\(^9\) See http://webast.ast.obs-mip.fr/hyperz.
Determining the optimal redshift bin, $\delta z$, for estimating the galaxy density is a trade-off between two effects. To avoid spurious associations $\delta z$ should ideally be as small as possible. However, given the use of photometric redshifts, it is pointless making the bin smaller than the typical error in estimated redshift. After some experimenting, at each field galaxy position, the 10 nearest neighbors within a redshift slice ($\delta z = \pm 0.1$) centered on the best-fit photometric redshift (or spectroscopic redshift where available) were located. The corresponding area was then computed as described above (§ 3.1.1). Two corrections were subsequently applied. First, a field correction was calculated in the redshift slice relevant to each galaxy in the sample: the projected number density, $\langle n_{z=0.1} \rangle$, of galaxies across the entire field of view within $\delta z = \pm 0.1$ of the galaxy in question. This mean was then taken as representing the field contamination and was subtracted from the raw measurement of $\Sigma$ for each galaxy. The second correction takes account of uncertainties in the photometric redshifts. For simplicity we assume that these uncertainties are normally distributed. Since the measured scatter [$\sigma_z (1 + z) \simeq 0.2$] is somewhat larger than the width $\delta z = \pm 0.1$ of the interval employed for the density measurement, the local density measurements are therefore underestimated by a factor of $\sim 2$. We therefore multiplied the estimates of $\Sigma$ by this factor to arrive at the corrected values: $\Sigma = 2(10 / \langle n_{z=0.1} \rangle)$). Note that the morphology-density relation is very flat at the densities probed by these data ($\Sigma \lesssim 50$ Mpc$^{-2}$; Fig. 3); therefore, these corrections for field contamination and photometric redshift uncertainties have negligible effects on the final results.

3.2. Morphological Classification

The total number of $z \approx 1$ galaxies for which detailed morphological information is available is 1257. This comprises all 957 members of the high-density cluster catalog (§ 3.1.1) and 300 members out of the total of 843 galaxies in the low-density field catalog (§ 3.1.2) that lie on the sparse-sampled $HST$ mosaic of Cl 0024 ($\theta 25$; see also Fig. 1 of Treu et al. 2003). To guard against the possibility that the sparse sampling strategy may bias our results because of the serendipitous inclusion/exclusion of regions of atypical local galaxy density, we verified that the distribution of $\Sigma$ values for the morphologically identified and unidentified galaxies are consistent within the counting errors. The sparse sampling strategy therefore should not bias our results.

Postage stamp images ($5'' \times 5''$) of all 1257 galaxies were extracted, and classification was performed using a scheme comprising stellar/compact, early-type (E/S0), late-type (Sa and later), and faint categories, patterned after that employed by Treu et al. (2003) but with broader classes designed to take account of the lower signal-to-noise ratio of the most distant galaxies targeted by this study. One of us (G. P. S.) classified all 1257 galaxies, and a control sample comprising a subset of roughly one-third of the total sample was cross-classified by three of the authors (G. P. S., T. T., and R. S. E.). The majority of the differences in the latter test arose from difficulties in classifying unambiguously bulge-dominated galaxies as either E/S0 (i.e., early types) or Sa (i.e., late types in our scheme). We use these three independent morphological catalogs to estimate the uncertainty in the early-type fraction ($6\%$) and add this in quadrature to the statistical errors when presenting our final results in § 4.1.

In § 3.1 we corrected measurements of $\Sigma$ to remove statistically contamination of the galaxy catalogs by field galaxies. It also important to ensure that estimates of the early-type fraction, $f_{E+S0}$, do not suffer from the effects of such contamination. We therefore used the morphological data derived from the $HST$ Medium Deep Survey (Abraham et al. 1996) to estimate the impact of contamination on $f_{E+S0}$. In the cluster fields we found...
that the high number density of galaxies (due to the presence of the clusters), coupled with the uncertainties on the morphological data, result in the corrections to \( f_{E+S0} \) being negligible. This is also true in the low-density environments; however, in this case it is due to the absence of a measurable contrast in morphological fractions between the sample and the contaminants, which also acts to eliminate the statistical significance of this negligible correction. We therefore decided not to apply any corrections to \( f_{E+S0} \) for field contamination.

4. RESULTS

4.1. The Morphology-Density Relation at \( z = 1 \)

We now combine measurements of projected galaxy number density and the morphological classifications to construct the morphology-density relation at \( z = 1 \) (Fig. 3). For simplicity we summarize this relation in terms of the early-type fraction, \( f_{E+S0} \), as a function of redshift and environmental density.

Our data span 3 orders of magnitude in projected density from the “field,” \( \Sigma < 10 \, \text{Mpc}^{-2} \), to cluster cores, \( \Sigma \approx 1000 \, \text{Mpc}^{-2} \). The three highest density points are derived from the pointed cluster observations (§ 3.1.1); the two lowest density points are derived from our analysis of the field viewed in the Cl 0024 mosaicked image (§ 3.1.2). The bin widths (horizontal error bars) were chosen after some experimentation to give a minimum of 100 galaxies per bin; we found that below this threshold the results were very noisy and strongly dependent on bin width. Vertical error bars combine binomial uncertainties (Gehrels 1986) with two further contributions added in quadrature. First, we quantify the cluster-to-cluster scatter by recomputing the high-density points, each time excluding one of the clusters (see Table 1). The rms scatter between these measurements of \( f_{E+S0} \) is \( \approx 0.03 \), i.e., comparable with or smaller than the typical binomial uncertainty. We also include the effect of morphological misclassifications as noted in § 3.2.

Figure 3 clearly shows that morphological segregation was already present at \( z = 1 \). The early-type fraction \( f_{E+S0} \) monotonically increases with projected density \( \Sigma \). Previous studies of the fraction of early-type galaxies at early times concentrated on individual galaxy clusters (e.g., van Dokkum et al. 2000, 2001; Lubin et al. 2002). These authors found fractions consistent with those presented here when allowance is made for the fact that averages were taken over larger areas (the entire WFPC2 field in most cases), thereby sampling a range of projected densities. Taking MS 1054–0321 as an example, van Dokkum et al. (2000) found \( f_{E+S0} \approx 0.5 \pm 0.1 \) at a mean density of \( \Sigma \approx 50 \), which is consistent with the results presented in Figure 3.

4.2. Evolution of the Morphology-Density Relation

Figure 3 also presents histograms of \( f_{E+S0} \) as a function of projected density for the local and intermediate samples, \( z \approx 0 \) and \( z \approx 0.5 \). The former is based on Dressler et al.’s (1997) reanalysis of Dressler’s (1980) data. The latter combines Dressler et al.’s (1997) study of the core regions of 10 clusters at \( 0.37 \leq z \leq 0.56 \) with Treu et al.’s (2003) panoramic study of Cl 0024 (\( z = 0.4 \)). In combining these two data sets, we rebinned Dressler et al.’s data to be consistent with the Treu et al. data and took a simple average in the region where the two data sets overlap, i.e., \( \Sigma \geq 30 \, \text{Mpc}^{-2} \).

Although we detect a morphology-density relation at \( z = 1 \), it is not as prominent as in the local universe. We quantify this evolution by fitting a straight line of the form \( f_{E+S0} \propto \beta \log \Sigma \) to both the \( z = 0 \) and \( z = 1 \) data. We obtain \( \beta(z = 0) = 0.26 \pm 0.01 \) and \( \beta(z = 1) = 0.08 \pm 0.02 \). The morphology-density relation, as summarized by the early-type fraction, is therefore \( \approx 3 \) times steeper locally than at \( z = 1 \).

We also compare our \( z \approx 1 \) results with those at \( z = 0.5 \) and find, perhaps surprisingly, that there has been little evolution...
between $z = 1$ and $z = 0.5$, except in the densest bin, i.e., $\Sigma \simeq 1000$ Mpc$^{-2}$. Fitting our simple model to the $z = 0.5$ data, we obtain $\beta(z = 0.5) = 0.15 \pm 0.05$. If we exclude the highest density bin, the result changes only slightly: $\beta(z = 0.5) = 0.13 \pm 0.05$. Both of these values agree within the uncertainties with the slope found at $z = 1$.

A simpler way to present our results is the run of $f_{E+S0}$ as a function of look-back time for low ($\Sigma \leq 10$ Mpc$^{-2}$), intermediate ($\Sigma = 100$ Mpc$^{-2}$), and high ($\Sigma = 1000$ Mpc$^{-2}$) densities (see Fig. 3). This elucidates more clearly the timing of environmental evolution. Little evolution is seen in the early-type fraction in low-density environments over $0 < z < 1$. Evolution at intermediate densities occurred remarkably recently (i.e., in the last 5 Gyr) with little evidence for any change at earlier times. In the highest density regions, there has been a monotonic rise with cosmic times.

5. DISCUSSION

We first consider why the fraction of early-type galaxies increases first in the higher density environments, then in intermediate-density environments, and finally—if it does at all—in the lowest density environments. Qualitatively, this can be understood in the scenario of hierarchical structure formation. At a given epoch, the densest regions are those that started collapsing earliest; in terms of age since collapse, the densest regions are therefore the oldest. If we assume that the original morphological mix is universal and then late-type galaxies are transformed into early-type galaxies by environmental processes, then the densest regions have had more time to increase their early-type fraction. Clearly, the rate of transformation could also be a function of density; for example, dense clusters are likely to be more efficient than poor groups at inducing ram pressure stripping, and therefore the metamorphosis could be accelerated once some threshold conditions are met. In summary, the broad picture presented by our results is in qualitative agreement with the hierarchical paradigm. We now turn to more quantitative possible explanations for our results. We begin with a brief review of the evolution of early-type galaxies in clusters.

For some years now, evidence spanning the range $0 < z < 1$ has suggested that cluster early-type galaxies represent a very homogeneous, slowly evolving population. This is based in part on the low intrinsic scatter ($\sim 0.08$ mag) observed in the local color-magnitude relation (Bower et al. 1992) and that tracked to $z \simeq 1$ (Ellis et al. 1997; Stanford et al. 1998). The mass-to-light ratios deduced from the fundamental plane provide a second indicator, both at low redshift (e.g., Lucey et al. 1991; Faber et al. 1998) and intermediate redshifts (e.g., van Dokkum & Franx 1996; Bender et al. 1998; van Dokkum et al. 1999; Kelson et al. 2000). Both results have supported the widely held view that the stars in some cluster early-type galaxies formed at high redshift (i.e., $z > 2$).

This does not necessarily mean that all local early-type galaxies evolved from those seen at earlier times. Conceivably some formed subsequent to $z \simeq 0.5$–1 but nonetheless found their way onto the present-day fundamental plane and color-magnitude relations (Bower et al. 1998). This is particularly likely for the lenticular galaxies that may have been transformed relatively recently from star-forming galaxies (Dressler et al. 1997). However, the physical processes that govern how star-forming disk galaxies are transformed into quiescent lenticulars remains an important outstanding question (e.g., Kodama & Smail 2001; Treu et al. 2003).

Motivated by our new results, we now explore what new clues we can deduce about the evolution of cluster early-type galaxies. Specifically, we use several evolutionary scenarios to attempt to set a limit on the fraction of lenticular galaxies $f_{S0}$ in clusters at $z = 1$. Note that we restrict our attention to the high-density regions; this is because measurements of $f_{S0}$ are not available at lower redshift for the intermediate- and low-density regimes. The crux of our model is to use our measurement of $f_{E+S0}$ at $z = 1$, in combination with the elliptical galaxy fraction $f_E$ at $z = 0.5$ (Dressler et al. 1997; Treu et al. 2003; § 4.2) and simple model assumptions to estimate $f_{S0}$ at $z = 1$. We write the following expression for the lenticular fraction at $z = 1$:

$$f_{S0, z=1} = f_{E+S0, z=1} - f_{E, z=0.5} \frac{N_{E,z=0.5}}{N_{E,z=1}} \frac{\Delta N_E}{N_{E,z=1}} - f_{E, z=0.5} \frac{\Delta N_E}{N_{E,z=1}}$$

(1)

From the early-type fraction at $z = 1$ ($f_{E+S0, z=1}$), we subtract the elliptical fraction at $z = 0.5$, renormalized to account for changes in the total number of galaxies due to evolutionary processes such as infall and galaxy-galaxy mergers. We also add a term to account for changes in the number of elliptical galaxies due to these evolutionary processes; we divide the change in the number of ellipticals ($\Delta N_E = N_{E,z=0.5} - N_{E,z=1}$) by the total number of galaxies at $z = 1$. Equation (1) is also derived from first principles in the Appendix.

We now employ a series of evolutionary scenarios from which we estimate values of $N_{E,z=0.5}/N_{E,z=1}$ and $\Delta N_E/N_{E,z=1}$ and thus, in combination with measurements of $f_{E+S0, z=1}$ and $f_{E, z=0.5}$, derive estimates of $f_{S0, z=1}$. The numerical details of each scenario are listed in the Appendix.

We first adopt a closed-box model in which we assume that all cluster elliptical galaxies are formed at high redshifts, say $z > 2$, and that the rising fraction of early-type galaxies (i.e., ellipticals and lenticulars) with cosmic time arises entirely as a result of lenticulars transformed from star-forming spirals. A key prediction of this model, and indeed the open-box models discussed below, is the existence of an epoch at which the early-type population in clusters is “pristine,” i.e., comprises solely ellipticals formed at high redshift. Any measure of the fraction of lenticular galaxies ($f_{S0}$) as a function of redshift would then yield important constraints on the timing and the physics of galaxy transformation in clusters.

For the closed-box model, at $z \leq 1$, elliptical galaxies are neither created nor destroyed ($\Delta N_E = 0$), and there is no overall number evolution ($N_{E,z=0.5} = N_{E,z=1}$). The lenticular fraction at $z = 1$ is therefore simply the difference between the early-type fraction at $z = 1$ ($f_{E+S0, z=1} = 0.7 \pm 0.1$) and the elliptical fraction at $z = 0.5$ ($f_{E, z=0.5} = 0.6 \pm 0.1$; Dressler et al. 1997; Treu et al. 2003). We therefore derive a crude upper limit of $f_{S0, z=1} \leq 0.1$. Given the uncertainties in the observational data, in this picture, we could be witnessing such a pristine population of cluster ellipticals at $z \simeq 1$. However, clusters are probably not closed boxes; numerical simulations demonstrate that material is continually accreted into clusters, generally along the filamentary structure. We therefore also explore several open-box models, with the aim of finding out whether additional evolutionary processes tend to increase or decrease the closed box estimate of $f_{S0, z=1}$.

First, we relax the assumption that there is no infall from the field; we retain the assumption that there is no number evolution in the elliptical galaxies ($\Delta N_E = 0$). If we assume that the cluster galaxy population has increased between $z = 1$ and $z = 0.5$ through the infall of spirals and lenticulars, then the infall rate is limited to 0.17; i.e., $N_{E,z=0.5}/N_{E,z=1} \leq 1.17$, otherwise $f_{S0, z=1}$ would be negative. Note that this scenario includes implicitly the possibility that the infalling spirals could...
be transformed into lenticulars at later times. This spirals-only infall scenario therefore supports the idea that $f_{50}$ is negligible at $z = 1$.

We now consider number evolution in the elliptical galaxies; this could occur through several processes; for example, some of the infalling population could already be ellipticals, spirals, and/or lenticulars could merge to form ellipticals either in the cluster core or in the infalling groups (e.g., van Dokkum et al. 1999), and ellipticals in the cluster cores could merge together to form a brightest cluster galaxy (hereafter BCG; e.g., Nipoti et al. 2003). Taking the possibility of infalling ellipticals first, we derive from inspection of Figure 3 an upper limit on the fraction of the infalling population that could be ellipticals of $f_{5} = 0.5$. We then find that as the infall fraction $N_{z=0.5}/N_{z=1}$ increases, the lenticular fraction at $z = 1$ gradually decreases from the closed-box value of $f_{50}(z = 1) = 0.1$. Indeed, adopting lower values of $f_{5}$ for the infalling population acts to decrease $f_{50}(z = 1)$ more rapidly as a function of $N_{z=0.5}/N_{z=1}$. In summary, including ellipticals in the infalling population leads to values of $f_{50}(z = 1)$ that are lower than the closed-box model. We illustrate this scenario in the Appendix using $N_{z=0.5}/N_{z=1} = 1.3$ and $f_{5} = 0.5$ for the infalling population.

We now include galaxy-galaxy mergers as a mechanism for generating cluster elliptical galaxies, and for simplicity assume zero infall from the field. If 10 in every hundred cluster spirals at $z = 1$ merge pairwise to produce half that number of ellipticals by $z = 0.5$, then $N_{z=0.5}/N_{z=1} = 0.95$ and $\Delta N_{E}/N_{z=1} = 0.05$, which translates into $f_{50,2} = 0.18$. Note that increasing the merger rate causes the lenticular fraction at $z = 1$ to increase, suggesting that $f_{50,1} < 0.1$ may not be valid under this scenario. However, a more realistic picture probably includes both merging and infall; therefore, combining the merger scenario with an infall fraction of $N_{z=0.5}/N_{z=1} = 1.3$ and $f_{5} = 0.5$ for the infalling population gives a lenticular fraction at $z = 1$ of $f_{50,2} = 0.1$.

Under a galactic cannibalism scenario (e.g., Nipoti et al. 2003), the number of cluster elliptical galaxies reduces with time because of their ingestion into the BCG. If 5% of cluster ellipticals at $z = 1$ have been cannibalized by $z = 0.5$, then $N_{z=0.5}/N_{z=1} \approx 0.97$ and $\Delta N_{E}/N_{z=1} = -0.03$, which translates into $f_{50,2} = 0.09$. Note that increasing the cannibalism rate leads to further reductions in the $f_{50,2}$. Also, adding an illustrative 30% infall fraction to a cannibalism scenario yields an even lower lenticular fraction, $f_{50,2} = 0.04$. The cannibalism scenario therefore produces lenticular fractions at or below that of the closed-box model either with or without invoking infall from the field.

Finally, we consider differential luminosity evolution, in the sense that the number of galaxies in the cluster sample may decrease with time because of the fading of blue galaxies that would presumably have later morphological types. This is analogous with the Butcher-Oemler effect and may act to increase $f_{E+S0}$ over time. Following the approach developed above, we ask whether this effect would result in a lower or higher lenticular fraction at $z = 1$ than the closed-box model. Therefore, setting the last term in equation (1) equal to zero, it is straightforward to see that $f_{50,1}$ increases with decreasing $N_{z=0.5}/N_{z=1}$. For example, if $N_{z=0.5}/N_{z=1} = 0.8$, then $f_{50,2} = 0.22$ indeed, combining this scenario with the 30% infall model yields an almost identical result: $f_{50,2} = 0.23$. Differential luminosity evolution therefore deserves further investigation as part of testing our hypothesis that $f_{50}$ is negligible at $z = 1$.

In summary, we have used simple models to explore several scenarios for the evolution of early-type galaxies between $z = 1$ and $z = 0.5$, with the aim of constraining the fraction of lenticular galaxies in clusters at $z = 1$. While the scenarios considered are unlikely to represent an exhaustive study, it is interesting to note that in all except two scenarios the lenticular fraction at $z = 1$ is $f_{50} \leq 0.1$. This is comparable with the uncertainty on the observational data included in the calculations using equation (1). At $z = 1$, we may therefore be observing cluster galaxy populations at or very close to their pristine state, in a scenario where the bulk of the elliptical population formed at higher redshifts ($z > 2$).

Our suggestion that the lenticular fraction at $z = 1$ is negligible is clearly speculative. Additional data are required to test this interpretation; most importantly, a discriminator between elliptical and lenticular galaxies at high redshift is required. In addition to deep HST/ACS imaging for morphologies, resolved spectroscopy of early-type galaxies in clusters at $z \approx 1$ and beyond should help to discriminate between those galaxies that are dynamically hot (elliptical galaxies) and those that are cold, i.e., lenticular galaxies with systematic rotation. Already, promising exploratory studies have demonstrated the feasibility of making this distinction (van Dokkum & Stanford 2001; Iye et al. 2003).

6. CONCLUSIONS

We have used 52 individual HST/WFPC2 observations through the F814W filter, supplemented by panoramic ground-based imaging to measure the morphology-density relation of galaxies at $z = 1$. Our study adopts analysis methods similar to those developed at lower redshifts (e.g., Dressler 1980), and our principal achievement is to span, at $z \approx 1$, the full 3 orders of magnitude range in the projected number density of galaxies encompassed by the low-redshift studies. We choose to make a like-for-like comparison of the early-type fractions spanning field ($\Sigma \lesssim 10 \text{ Mpc}^{-2}$), group ($\Sigma \approx 100 \text{ Mpc}^{-2}$), and rich cluster ($\Sigma \approx 1000 \text{ Mpc}^{-2}$) environments.

We briefly summarize our findings as follows.

1. Morphological segregation remains a prominent feature of the galaxy population at $z = 1$, although the slope of the $f_{E+S0} - \log \Sigma$ relation is ~3 times shallower than observed locally.

2. The morphology-density relations at $z = 1$ and $z = 0.5$ are remarkably similar, with a significant difference only detected in the highest density bin. Most of the evolution producing the locally observed relation occurred in the redshift interval $0 < z < 0.5$.

3. At low densities, the early-type fraction is roughly constant at $f_{E+S0} = 0.4 \pm 0.1$ across the full redshift range ($0 < z < 1$).

These trends suggest to us a simple model whereby most cluster elliptical galaxies formed at high redshift ($z > 2$) with the bulk of the density-dependent growth arising from the environmental transformation of infalling disk galaxies into lenticulars, and possibly merging of cluster galaxies at later times. This is motivated by the suggestive agreement (within the uncertainties) between the early-type fraction at $z = 1$ in high-density regions with the elliptical fraction observed at $z = 0.5$. Within the observational uncertainties, the majority of the model scenarios that we have explored are consistent with a negligible lenticular fraction at $z = 1$, $f_{50} \leq 0.1$. It is therefore possible that all cluster early-type galaxies at $z = 1$ are ellipticals. To test this suggestion, resolved dynamical data are needed for a large sample of early-type cluster and field galaxies whose environmental densities can be measured.
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APPENDIX

DERIVATION OF EQUATION (1) AND TABULATION OF MODELS

Equation (1) describes how the fraction of lenticular galaxies at \( z = 1 \) (\( f_{S0, z=1} \)) can be estimated from two observable quantities: the fraction of early-type galaxies at \( z = 1 \) (\( f_{E, z=1} \)) and the fraction of elliptical galaxies at \( z = 0.5 \) (\( f_{E, z=0.5} \)). As explained in \$5\), the equation is quite intuitive; however, for completeness, we derive it here from first principals. First, we write the early-type fraction at \( z = 1 \) in terms of the elliptical and lenticular fractions at that redshift,

\[
f_{E, z=1} = f_{E, z=0.5} + f_{S0, z=1}.
\]

(A1)

Simple rearrangement, where \( N_{z=1} \) is the total number of cluster galaxies and \( N_{E, z=1} \) is the number of cluster ellipticals, both at \( z = 1 \), gives

\[
f_{S0, z=1} = f_{E, z=0.5} + f_{E, z=1} - \frac{N_{E, z=1}}{N_{z=1}}.
\]

(A2)

We now define \( \Delta N_{E} = N_{E, z=0.5} - N_{E, z=1} \) to be the change in the number of cluster ellipticals between \( z = 1 \) and \( z = 0.5 \), and we rewrite equation (A2) as

\[
f_{S0, z=1} = f_{E, z=0.5} + f_{E, z=1} - \frac{N_{E, z=0.5} - \Delta N_{E}}{N_{z=1}}.
\]

(A3)

Finally, we substitute \( N_{E, z=0.5} = f_{E, z=0.5} N_{z=0.5} \) to obtain equation (1) from \$5\),

\[
f_{S0, z=1} = f_{E, z=0.5} + f_{E, z=1} - \frac{N_{z=0.5} + \Delta N_{E}}{N_{z=1}}.
\]

(A4)

In Table 3 we list the values used in equation (1) from \$5\).

| Model Description | \( f_{S0, z=1} \) | \( f_{E, z=0.5} \) | \( f_{E, z=1} \) | \( \Delta N_{E} \) | \( N_{z=1} \) | \( x \) |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Closed-box model: | | | | | | |
| (A) No infall, no number evolution | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 1 \) | \( 0 \) | \( 0.1 \) |
| Open-box models: | | | | | | |
| (B) 17% infall of spirals and lenticulars | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 1.17 \) | \( 0 \) | \( 0.0 \) |
| (C) 30% infall of which half are ellipticals | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 1.3 \) | \( 0.15 \) | \( 0.07 \) |
| (D) 10% of the total population (assumed to be spirals) merge pairwise to form ellipticals | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 0.95 \) | \( 0.05 \) | \( 0.18 \) |
| (E) Model D plus model C | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 1.3 \) | \( 0.2 \) | \( 0.12 \) |
| (F) Cannibalism: 5% of ellipticals merge to form a BCG | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 0.97 \) | \( 0.03 \) | \( 0.09 \) |
| (G) Model F plus model C | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 1.3 \) | \( 0.12 \) | \( 0.04 \) |
| (H) 20% number evolution due to fading of blue galaxies | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 0.8 \) | \( 0 \) | \( 0.22 \) |
| (I) Model H plus model C | \( f_{S0, z=1} = 0.7 \) | \( 0.6 \times 0.8 \times 1.3 \) | \( 0.15 \) | \( 0.23 \) |
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