THE MORPHOLOGICAL CONTENT OF 10 EDisCS CLUSTERS AT 0.5 < z < 0.8\textsuperscript{1,2}

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Received 2006 November 13; accepted 2007 January 25

ABSTRACT

We describe Hubble Space Telescope (HST) imaging of 10 of the 20 ESO Distant Cluster Survey (EDisCS) fields. Each \textasciitilde{}40 arcmin\textsuperscript{2} field was imaged in the F814W filter with the Advanced Camera for Surveys Wide Field Camera. Based on these data, we present visual morphological classifications for the \textasciitilde{}920 sources per field that are brighter than $I_{\text{lim}} = 23$ mag. We use these classifications to quantify the morphological content of 10 intermediate-redshift (0.5 < z < 0.8) galaxy clusters within the HST survey region. The EDisCS results, combined with previously published data from seven higher redshift clusters, show no statistically significant evidence for evolution in the mean fractions of elliptical, S0, and late-type (Sp+Irr) galaxies in clusters over the redshift range 0.5 < z < 1.2. In contrast, existing studies of lower redshift clusters have revealed a factor of \textasciitilde{}2 increase in the typical S0 fraction between z = 0.4 and 0, accompanied by a commensurate decrease in the Sp+Irr fraction and no evolution in the elliptical fraction. The EDisCS clusters demonstrate that cluster morphological fractions plateau beyond z \textasciitilde{} 0.4. They also exhibit a mild correlation between morphological content and cluster velocity dispersion, highlighting the importance of careful sample selection in evaluating evolution. We discuss these findings in the context of a recently proposed scenario in which the fractions of passive (E, S0) and star-forming (Sp, Irr) galaxies are determined primarily by the growth history of clusters.

Subject headings: galaxies: clusters: general — galaxies: evolution — galaxies: formation

Online material: machine-readable table

1. INTRODUCTION

Although the morphology-density relation is observationally well established, it is still unclear why the incidence of early type (E+S0) galaxies is higher in overdense regions of the universe. The options are often couched in terms of “nature” versus “nurture.” These scenarios describe different paths to qualitatively similar relations between morphology and environment, and are therefore difficult to disentangle. In the nature scenario, galaxies that end up in high-density environments at low redshift are more likely to have experienced initial conditions leading to an early-type morphology on formation. In the nurture scenario, all galaxies, regardless of their local densities at low redshift, have identical probabilities of having formed as early types. The morphology-density relation is then the result of subsequent morphological alterations as galaxies enter increasingly higher density environments as structure grows. Many mechanisms that could produce the required morphological transformations have been suggested, including mergers and galaxy-galaxy interactions (Toomre & Toomre 1972; Icke 1985; Lavery & Henry 1988; Milos 2004), harassment (Richstone 1976; Moore et al. 1998), gas stripping (Gunn & Gott 1972; Abadi et al. 1999; Quilis et al. 2000), strangulation (Larson et al. 1980; Bekki et al. 2002), and cluster tidal forces (Byrd & Valtonen 1990).

The observed evolution of the morphology-density relation provides an important constraint on models of its origin. Observations of the high-density regions of cluster cores show that while the elliptical fraction has not evolved, the S0 (Sp+Irr) fraction has grown (diminished) by a factor of \textasciitilde{}2 over the last 5 Gyr (Dressler et al. 1997; Fasano et al. 2000). However, over the same time interval, no evolution is observed at lower densities (Treu et al. 2003; Smith et al. 2005). The morphology-density relation at larger lookback times (z > 0.5) has just begun to be explored. Smith et al. (2005) used Hubble Space Telescope (HST) Wide-Field Planetary Camera 2 (WFPC2) data for six clusters at 0.75 < z < 1.25 to estimate the early-type fraction as a function of local galaxy surface density. They extended their measurements to low densities (\textasciitilde{}1 Mpc\textsuperscript{−1}) by including field galaxies in HST WFPC2 images of the cluster CL0024 at z = 0.395. Comparing their results to similar studies at lower redshifts (Dressler 1980b; Dressler et al. 1997; Treu et al. 2003), they found that the early-type fraction has increased steadily since z \textasciitilde{} 1 in the densest regions.
(~1000 Mpc−2), has increased only since z ∼ 0.5 in moderate-density regions (~100 Mpc−2), and has remained constant since z ∼ 1 in the lowest density regions (<10 Mpc−2). Postman et al. (2005) find compatible results in their study of the morphology-density relation using HST Advanced Camera for Surveys (ACS) imaging of seven z ∼ 1 clusters. Smith et al. (2005) suggest a nurture scenario to explain the observed evolution in the morphology-density relation. If structure growth is hierarchical, the densest regions at any redshift collapsed the earliest. Thus, if environmental processes can modify a universal initial mix of morphologies through a transformation from late to early types, these processes would have had a longer time to operate in increasingly dense regions. In addition, the efficiency of such transformations could be density-dependent.

To discover whether environmental processes, rather than initial conditions, drive the differential evolution of the morphology-density relation, we must first demonstrate that nature scenarios cannot reproduce the observations. If we find that environmental factors are indeed important, it is critical to identify the responsible mechanisms. The current data are insufficient to discriminate among the alternative models. For this, we require a full mapping between galaxy properties and environment. Toward this goal, we present the morphological fractions in 10 rich clusters at 0.5 < z < 0.8, drawn from the ESO Distant Cluster Survey (EDisCS; White et al. 2005).16 Because strong evolution has been observed in high-density regions, clusters are a critical environment to probe. The redshift range of our study bridges a gap between those of Dressler (1980a), Fasano et al. (2000), and Dressler et al. (1997) and to provide the corresponding content in each cluster. Our results are presented in White et al. (2005) and form the basis of the weak-shear analysis presented by Clowe et al. (2006). Additional near-infrared imaging was obtained with SOFI at the New Technology Telescope (NTT) in Ks for the z ∼ 0.5 candidates and in JKs for the z ∼ 0.8 candidates (A. Aragón-Salamanca et al. 2007, in preparation). The near-infrared imaging covers approximately 6′ × 4.2′ in the fields of the intermediate-redshift clusters and 5.4′ × 4.2′ in the fields of the high-redshift clusters. The optical and near-infrared imaging were used to measure photometric redshifts, as described in R. Pelló et al. (2007, in preparation).

An initial phase of spectroscopy consisted of relatively short exposures of a single slit mask per cluster. One cluster with an estimated redshift of z ∼ 0.8 was revealed as a superposition of weak groups and was rejected from the sample. These spectra revealed that the remaining 19 clusters have redshifts in the range 0.4 ≤ z ≤ 1. Deeper spectroscopic exposures (~2 hr each for galaxies with 18.6 ≤ I(r = 1″) ≤ 22 mag in intermediate-redshift clusters; ~4 hr each for galaxies with 19.5 ≤ I(r = 1″) ≤ 23 mag in high-redshift clusters) of 3–5 masks per field were then taken and are of sufficient quality to provide information about the stellar populations and internal dynamics of the target galaxies. The spectroscopic observations are described in Halliday et al. (2004) and B. Milvang-Jensen et al. (2007, in preparation).

The ground-based EDisCS imaging and spectroscopy go a long way toward characterizing both the clusters themselves and the galaxies within them. At the high redshifts of the EDisCS sample, however, only HST can provide the spatial resolution necessary to provide robust morphologies. Motivated by the issues discussed in §1, we obtained HST imaging for the 10 highest redshift EDisCS clusters, listed in Table 1 along with their basic physical parameters. Cluster 9 (el1232-1250) was drawn from the EDisCS intermediate-redshift sample, and the remainder were drawn from the high-redshift sample.

### 3. HST ACS DATA

The HST observations were designed to coincide as closely as possible with the coverage of the ground-based optical imaging and spectroscopy, within guide-star constraints. The ground-based optical data cover a 6.5′ × 6.5′ region around each cluster, with the cluster center displaced by 1′ from the center of the region. For reference, the ACS Wide Field Camera has a field of view of roughly 3.5′ × 3.5′. Balancing scientific motives for going deep over the entire field against a limited number of available orbits, we tiled each 6.5′ × 6.5′ field in four pointings, with one additional deep pointing on the cluster center (taken as the location of the

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16 See http://www.mpa-garching.mpg.de/galform/ediscs/index.shtml.
BCG). The resulting exposure time per pixel is 2040 s, except for the central 3.5′ × 3.5′, which has an exposure time per pixel of 10,200 s. The deep central pointing probes to lower surface brightness, fainter magnitudes, and larger galactic radii in the region of the cluster containing the most galaxies. The centers of the structures ultimately chosen for spectroscopic follow-up in the c11103-1245b and c11227-1138 fields are somewhat offset from those anticipated at the time the HST observations were taken. All exposures were taken under LOW SKY conditions to maximize our surface brightness sensitivity.

The ACS calibration pipeline, CALACS version 4.3 (2003 June 6) debiased, dark-subtracted, and flat-fielded our ACS images “on the fly” when they were requested from the HST archives. Known bad pixels and saturated data were also flagged in accompanying data quality (DQ) arrays. Approximate world coordinate system (WCS) headers were provided. The resulting images were returned by the archive with the FLT suffix. In addition, images that were cosmic-ray split were combined and returned with a CRJ suffix.

To produce a mosaic, we required precise offsets between the 32 FLT images retrieved for each cluster. The approximate WCS headers provided were sufficient for this purpose. We found that the offsets between cosmic-ray split images were negligible. We therefore computed the necessary shifts between pointings using the higher signal-to-noise CRJ images. The shifts could not be computed using the retrieved CRJ files because they had not been undistorted. We therefore drizzled each CRJ image separately, using the approximate WCS headers provided. Because each undistorted CRJ image overlaps the central pointing, one of the images centered on the cluster center was chosen as the reference image. Shifts between the reference image and each undistorted CRJ image were then computed using cross-correlation.

Combination of the FLT images using the resulting shifts was accomplished using MultiDrizzle, a Python code written by Anton Koekemoer to run under PyRAF, the Python-based interface to the Image Reduction and Analysis Facility (IRAF). MultiDrizzle automatically removes cosmic rays and combines dithered images using PyDrizzle, which has been developed by the Science Software Branch at the Space Telescope Science Institute. For each of the 32 FLT images per cluster, MultiDrizzle included negative bad pixels in the data quality array, subtracted the sky, and separately drizzled and undistorted each image. Next it created a median image from these separately drizzled images using shifts computed from the headers along with the user-supplied refinement shifts described above. This median image, relatively free of cosmic rays, was compared to the input images to identify cosmic rays. The median image was then redistorted to create cosmic-ray masks. These masks were used in the final image combination step using drizzle and the lanczos3 kernel, which provided optimal noise properties.

4. GALAXY MORPHOLOGIES

We visually classified all galaxies brighter than $I_{auto} = 23$ mag. Here $I_{auto}$ is the SExtractor (Bertin & Arnouts 1996) AUTO magnitude measured on the I-band VLT images and is an estimate of the total magnitude of a galaxy in the Vega system. This magnitude does not include an aperture correction, nor has it been corrected for Galactic extinction. The limit was set both to ensure robust classifications and to provide a tractable sample of $\sim$9200 galaxies.

Our classifications are most useful if they conform to systems adopted by previous studies. For this reason, each classifier trained on the HST WFPC2 images and visual morphological catalogs of the 0.3 < $z$ < 0.5 MORPHS clusters, using the same procedure described in Smail et al. (1997). For uniformity, each classifier used the same IRAF script to examine and classify EDisCS galaxies. This script displays two side-by-side versions of a 200 × 200 square pixel cutout centered on each galaxy meeting the magnitude limit described above. One version is on a log scale between $−0.1$–$2$ DN s$^{−1}$, while the other is on a log scale between $−0.1$–$25$ DN s$^{−1}$. Together, these displays allow classifiers to inspect the galaxies from their high surface brightness cores to their low surface brightness outer features. In general, we found that the depth and quality of the EDisCS ACS data were similar to or better than the MORPHS WFPC2 data for lower redshift clusters.

Classifications were performed by five of the authors (A. A., J. J. D., V. D., P. J., and B. P.). Each classified the galaxies in three to six clusters. For a given galaxy, the final Hubble type was based on the classifications of two or more of the authors. First, the Revised Hubble Type was translated into a T-type according to the scheme presented in Table 2. Classifications appended by one question mark were given half weight; those appended by two question marks were given one-quarter weight.

If a classifier specified two types separated by a slash, the first
The main results of this work are sensitive to how accurately galaxies can be placed into the broad categories of elliptical (E), S0, and late (Sp+Irr). Although accuracy in this case is difficult to quantify, we can test how consistently galaxies are placed in the same bin by different classifiers. Using ~900 galaxies down to $I_{\text{auto}} = 23$ mag in cl1216-1201, all of which were assigned a Hubble type by all classifiers, we computed the raw fractions for each classifier, uncorrected for the presence of foreground and background galaxies. The root mean variance for any morphological fraction is $\pm 0.10$, which is comparable to the error computed from Poisson statistics.

There is some controversy surrounding the ability of morphologists to distinguish between E and S0 galaxies, especially at high redshifts. For this reason, some previous investigators chose to lump E and S0 galaxies together into an early-type class. For easy comparison with these works, in the following we have plotted the surface brightness profile. Likewise, the B/T fractions for visually classified ellipticals appear to be skewed to higher values than visually classified ellipticals. Although in some individual cases it is difficult for visual classifiers to differentiate between E’s and S0’s, it is clear that, in a statistical sense, objects visually classified as E’s and S0’s form two distinct populations with objectively measurable physical differences. More sophisticated

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**Table 2: Notes on Parameters in Morphological Catalogs**

| Heading                  | Description                                                                 |
|--------------------------|-----------------------------------------------------------------------------|
| ID                       | EDisCS ID                                                                   |
| RA                       | Right ascension in decimal degrees (J2000.0)                                 |
| DEC                      | Declination in decimal degrees (J2000.0)                                     |
| $I_{\text{auto}}$        | Total $I$ magnitude; SExtractor MAG\_AUTO parameter measured from ground-based $I$-band images |
| Type                     | Star=−7, nonstellar but too compact to see structure=−6, E=−5, S0=−2, Sa=1, Sb=3, Sc=5, Sd=7, Sm=9, Irr=11, no HST data corresponding to ground-based object=111, unclassifiable=66 |
| S0 disk flag             | If any of the classifiers noted that the B/D ratio is small but the disk is featureless, this flag is 1. |
| Bar flag                 | If any of the classifiers noted the presence of a bar, this flag is 1.        |
| Edge-on flag             | If any of the classifiers noted that this galaxy is edge-on, this flag is 1. |
| Small flag               | If any of the classifiers noted that this galaxy is small, this flag is 1.   |
| LSB flag                 | If any of the classifiers noted that this galaxy is low-surface-brightness, this flag is 1. |
| Defect flag              | If any of the classifiers noted that the image of this galaxy was defective, due for example to cosmic rays or incomplete coverage, this flag is 1. |
| Dust flag                | If any of the classifiers noted the presence of dust in the galaxy, this flag is 1. |
| Disturbance flag         | If any of the classifiers noted that this galaxy is disturbed, this flag is 1. |
| Comments                 | Additional comments by any of the classifiers                                |

*Note.—The morphological catalogs are published in the electronic edition of the *Astrophysical Journal.*
5. ANALYSIS

The goal of this paper is to quantify the morphological content of the EDisCS clusters. In particular, we discuss the overall fractions of E, S0, and late-type galaxies in our clusters and compare them to the fractions found in clusters spanning a range of redshifts. Following Dressler et al. (1997) we do not include galaxies that were unclassifiable (types 6 and 66 in Table 2) in our analysis. To facilitate a fair comparison with other samples, we compute the morphological fractions as consistently as possible with previous work. In the following subsections, we describe the key elements of our analysis.

5.1. Magnitude Range

Early types preferentially occupy the bright end of the galaxy luminosity function, while late types dominate the faint end (e.g., Blanton et al. 2001; Goto et al. 2002; Zucca et al. 2006). Thus, morphological fractions depend on the range of absolute magnitudes sampled. Morphological fractions in the MORPHS clusters were determined using apparent magnitude cuts in $I_{814}$ designed to correspond to a $V$-band absolute magnitude of $M_V = -20$ mag (Dressler et al. 1997), but in actuality corresponding to $M_V = -19$ mag due to a transcription error (Fasano et al. 2000). However, Fasano et al. (2000) reanalyzed the MORPHS data with the intended limiting absolute magnitude and additionally analyzed nine clusters with $0.1 < z < 0.25$ in the same manner, providing an ideal comparison sample for the EDisCS clusters. We therefore adopt an absolute magnitude limit of $M_V = -20$ mag. For a given cluster, the limiting apparent magnitude in the $I$-band is then given by

$$I_{\text{auto,lim}} = M_V + 5 \log_{10}(d_{L, \text{pc}}) - 5 - (M_V - M_I) + k_I,$$

where $d_{L, \text{pc}}$ is the luminosity distance of the cluster in parsecs (calculated in either the classic or WMAP cosmology, as indicated),

![Image of two-dimensional profile fits](image-url)
$M_V - M_I$ is the rest-frame color, and $k_i$ is the $I$-band $k$-correction. We adopt the rest-frame color and Cousins $I$-band $k$-corrections for an elliptical galaxy, as presented in Poggianti (1997). Equation (3) results in values of $I_{auto,lim}$ ranging from 21.3 to 23.3 mag, the faintest values being slightly fainter than the limit of our visual classifications. Given the errors in the $k$-corrections relative to these differences, we adopt $I_{auto,lim} = 23$ mag in these instances. This occurs for cl1216-1201 when using the WMAP cosmology and for cl1054-1245, cl1216-1201, and cl1354-1230 when using the classic cosmology.

5.2. Aperture

Clusters exhibit a radial gradient in their morphological fractions; the centers of clusters contain a larger fraction of ellipticals than the outskirts (e.g., Melnick & Sargent 1977; Goto et al. 2004; Thomas & Katgert 2006). Thus, in comparing the overall morphological fractions across clusters, one must choose a consistent aperture. The MOPHIS project has set the standard for the aperture within which to compute morphological fractions. Most studies of the morphological fractions of galaxy clusters at other redshifts have used a similarly sized aperture. So that we may assess the level of evolution between the morphological studies presented in the literature and those conducted with EDisCS data, we adhere to this precedent and adopt a circular aperture of radius 600 kpc (classic cosmology).

Since the radial density profiles of clusters vary, the average galaxy density within a fixed metric aperture will also vary. We therefore also calculated the morphological fractions within an aperture that scales with $R_{200}$, the radius within which the average mass density is equal to 200 times the critical density. The derived $R_{200}$-values were computed using equation (8) in Finn et al. (2005) and are listed in Table 1 for both the classic and WMAP cosmologies. Unfortunately, our imaging data is complete out to $R_{200}$ for only cl1040-1155, cl1054-1146, cl1054-1245, and cl1354-1230. We therefore use a radius of 0.6 $R_{200}$, which keeps the analysis area within the imaging region for all clusters except for cl1227-1138 and cl1232-1250. The fraction of the analysis region which is not included in these two clusters is very small, and the resulting effect on the morphological fractions is likely minimal.

5.3. Background Subtraction

Galaxies within the magnitude range and distance from the cluster center described in §5.1 and 5.2 lie at a variety of redshifts. We wish to determine the proportions of E, S0, and late-type galaxies among cluster members only. Because the morphological mix of field galaxies differs substantially from that of cluster populations, morphological fractions computed without regard to field contamination will underestimate the fraction of early types and overestimate the fraction of late types in clusters. We use four methods, described in detail below, to account for the presence of cluster nonmembers, checking for consistency among the resulting morphological fractions.

5.3.1. Spectroscopic Redshifts

As described in §2, the EDisCS program includes an extensive spectroscopic survey. For each cluster, redshifts were obtained for 6–86 galaxies which both meet our apparent magnitude limit and lie within 0.6 $R_{200}$ (WMAP cosmology). We use this spectroscopic sample to constrain the morphological fractions in each cluster in two ways. First, we calculate hard limits on the morphological fractions using both the spectroscopic sample and the purely photometric sample, consisting of galaxies that were either not targeted for spectroscopy, or for which spectroscopy failed to yield a redshift. This calculation does not require that the spectroscopic sample be complete. Second, we estimate the morphological fractions using only the spectroscopic sample after applying small completeness corrections.

The upper and lower hard limits on the fraction of galaxies of type $i$ are given by:

$$f_{\text{min}}(i) = \frac{N_{s}^m(i) + N_{p}^m(i)}{N_{s}^m + N_{p}^m},$$

and

$$f_{\text{max}}(i) = \frac{N_{s}^m(i) + N_{p}^m(i)}{N_{s}^m + N_{p}^m(i)}.$$
the spectroscopic flux limit. Most (\(\gtrsim 80\%\)) of these are late-type galaxies. Thus, it is possible that our direct spectroscopic estimates are biased slightly toward low late-type fractions. In Figure 2, we compare the morphological fractions derived from different methods, and find that for cl1054-1245, cl1216-1201, and cl1232-1250, the spectroscopic method does yield lower late-type fractions than the photometric redshift or statistical background subtraction methods. However, all methods produce late-type fractions that are consistent with one another, within the errors. For cl1354-1230, the spectroscopic method results in a late-type fraction between the photometric redshift method and the statistical background method.

5.3.2. Photometric Redshifts

Our optical and near-infrared imaging allows the derivation of photometric redshifts, as described in R. Pelló et al. (2007, in preparation). Briefly, two estimates of the redshift probability distribution [\(P(z)\)] were computed for each galaxy. Two independent codes were employed, one described in Rudnick et al. (2001) and Rudnick et al. (2003) and Hyperz, described in Bolzonella et al. (2000). An estimate of \(P(z)\) can be integrated over a suitable interval \(\Delta z\) (in this case \(\pm 0.1\)) around the cluster redshift to obtain the probability \(P_{\text{clus}}\) that the galaxy is a member of the cluster. We used our large spectroscopic sample to determine \(P_{\text{thresh}}\), the minimum value of \(P_{\text{clus}}\) required for a galaxy to be considered a cluster member. Membership information derived from each of our two estimates of \(P(z)\) was then combined to determine cluster membership. That is, both estimates were required to be consistent with cluster membership in order for a galaxy to be considered a cluster member.

We used the subset (vast majority) of our spectroscopic sample with both optical and near-infrared imaging to estimate (1) the fraction of spectroscopically confirmed cluster members excluded by our photometric redshifts as a function of morphology and (2) the fraction of spectroscopic nonmembers that are photometric members as a function of morphology. Since \(P_{\text{thresh}}\) was calibrated to include as many cluster members as possible rather than to exclude all nonmembers, the former fraction tends to be significantly smaller than the latter. Given these fractions, we calculated \(N_{\text{m}}(i)\), the expected number of cluster members of type \(i\) that were missed by the photometric redshifts; and \(N_{\text{v}}(i)\), the expected number of nonmembers among galaxies of type \(i\) that contaminate the photometric redshift member sample. We then used this information to compute the corrected number of observed cluster members of type \(i\) [\(N_{\text{photoc}}(i)\)], and finally, the corrected fraction of cluster members of type \(i\) [\(f_{\text{photoc}}(i)\)]:

\[
N_{\text{photoc}}(i) = N_{\text{obs}}(i) + N_{\text{m}}(i) - N_{\text{v}}(i) \tag{9}
\]

\[
N_{\text{photoc}}(\text{tot}) = N_{\text{photoc}}(E) + N_{\text{photoc}}(S0) + N_{\text{photoc}}(Sp + Irr) \tag{10}
\]

\[
f_{\text{photoc}}(i) = N_{\text{photoc}}(i)/N_{\text{photoc}}(\text{tot}) \tag{11}
\]

As in 5.3.1, errors were computed using the Gehrels (1986) approximation using \(N_{\text{photoc}}(i)\) and \(N_{\text{photoc}}(\text{tot})\). The morphological fractions computed using equation (11) are shown as hollow circles in Figure 2.

As described in § 2, the area of each cluster with near-infrared imaging is somewhat smaller than that imaged in the optical. In the classic cosmology, an analysis radius of 600 kpc extends beyond the near-infrared imaging for cl1227-1138. As a result, 19 out of 49 galaxies meeting the magnitude and aperture requirements for inclusion in the morphological analysis lack near-infrared data.
Using the WMAP cosmology and an analysis radius of 0.6 $R_{200}$, a similar problem occurs for both cl1227-1138 (21 out of 50 galaxies lack near-infrared data) and cl1232-1250 (14 out of 222 galaxies lack near-infrared data). Because the $P(z)$ distributions for photometric redshifts computed without near-infrared data are broad, they have low $P_{\text{clust}}$ values and are somewhat more likely to be rejected than galaxies with photometric redshifts computed using the full filter set. Figure 2 shows that this effect does not appear to have systematically skewed the morphological fractions for cl1227-1138 and cl1232-1250 compared to the other methods employed.

5.3.3. Statistical Background Subtraction

In the absence of spectroscopic or photometric redshift information for each galaxy, we can still estimate the morphological fractions by statistically correcting the number of observed galaxies of a given type to account for sources that lie in the field:

\[
N_{\text{field}} = \Sigma_{\text{field}} A, \tag{12}
\]

\[
N_{\text{stat}}(i) = N_{\text{obs}}(i) - N_{\text{field}} P(i) \tag{13}
\]

\[
N_{\text{stat(tot)}} = N_{\text{obs(tot)}} - N_{\text{field}} \tag{14}
\]

\[
f_{\text{stat}}(i) = \frac{N_{\text{stat(i)}}}{N_{\text{stat(tot)}}}. \tag{15}
\]

Here $A$ is the area of the aperture described in § 5.2; $N_{\text{obs(tot)}}$ is the total number of galaxies meeting the magnitude criterion (§ 5.1) within that aperture; $N_{\text{obs}}(i)$ is the number of these galaxies which have morphology $i$; $N_{\text{field}}$ is the number of the observed galaxies that are expected to be field members; and $N_{\text{stat(tot)}}$ and $N_{\text{stat}}(i)$ are the background-subtracted number of galaxies in the aperture and the number of type $i$, respectively. The surface density of field galaxies, $\Sigma_{\text{field}}$, is determined by integrating the $I$-band differential number counts in Table 1 of Postman et al. (1998) down to the redshift-dependent $I$-band apparent magnitude limit adopted for each cluster, as described in § 5.1. We computed $P(i)$, the fraction of field galaxies of each morphological type, using data from the Medium Deep Survey (MDS; Griffiths et al. 1994), a Hubble Telescope Key Project that cataloged the morphologies of intermediate-redshift field galaxies down to $I_{90} \sim 22$ mag. In particular, we used the classifications of Richard Ellis listed in Table 1 of Abraham et al. (1996). The magnitude limits, $I_{90}$, of our morphological analysis vary from cluster to cluster and with cosmology but generally range from 21.3 to 23 mag. The values of $P(i)$ are a function of $I_{90}$, decreasing to faint magnitudes for early-type galaxies and increasing to faint magnitudes for late types. For those clusters with $I_{90} > 22$ mag, we adopt the values of $P(i)$ down to $I_{90} = 22$ mag. Based on the behavior of $P(i)$ versus $I_{90}$, this procedure likely overestimates $P(E)$, $P(S0)$, and $P(\text{Sp})$ and underestimates $P(\text{S}p+\text{Irr})$ and $P(\text{Irr})$. These trends translate into underestimates of the $E$, $S0$, and Sp morphological fractions and overestimates of the Sp$+\text{Irr}$ and Irr fractions. These misestimates will be most severe for cl1054-1245, cl1216-1201, and cl1354-1230, which have the faintest values of $I_{90}$. The morphological fractions computed using statistical background subtraction and equation (15) are shown as open triangles in Figure 2. Examination of this figure does not reveal any obvious biases with respect to other methods that could be attributable to our $P(i)$ estimates.

As in §§ 5.3.1 and 5.3.2, errors were computed using the Gehrels (1986) approximation and $N_{\text{stat}}(i)$ and $N_{\text{stat(tot)}}$.

6. RESULTS

We have estimated the morphological fractions of 10 EDIsCS clusters at $0.5 < z < 0.8$ using four different background-subtraction techniques (absolute limits from spectroscopic redshifts, direct estimates from spectroscopic redshifts, photometric redshifts, and statistical subtraction), within apertures of different radii (600 kpc and 0.6 $R_{200}$), and for two different cosmologies (the classic cosmology: $\Omega_0 = 1$, $\Lambda = 0$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, and the WMAP cosmology: $\Omega_0 = 0.3$, $\Lambda = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$). Figure 2 shows how the different methods compare for an aperture of 0.6 $R_{200}$ in the WMAP cosmology. The direct estimate methods are consistent with the absolute limits derived from our spectroscopy, and with one another. In addition, there is no systematic trend for one estimate to produce higher or lower fractions than any other. For each cluster we therefore adopt a single method: direct estimate from spectroscopy, photometric redshifts, or statistical background subtraction. The adopted method, which differs from cluster to cluster, is chosen in the following way. For a given cluster, median E, S0, and Sp$+\text{Irr}$ fractions are selected from among the estimates of all three methods. The method selected most often in this process is the one adopted for the cluster. The E, S0, and Sp$+\text{Irr}$ fractions estimated using the chosen method for each cluster are shown in Tables 3 and 4, and are the quantities plotted in Figures 3 through 5.

The morphological fractions in Figure 2 appear to be correlated with cluster number, which is determined by right ascension. Spearman and Kendall rank correlation tests show that marginal correlations are detected at the $\sim 2 \sigma$ level for the S0 and Sp$+\text{Irr}$ fractions. We find no correlation between cluster redshift and...
with cluster velocity dispersion, a possibility we revisit in § 6.2. Since there is no reason for any physical property of the cluster to correlate with cluster number, these correlations hint that the morphological fractions correlate with cluster velocity dispersion, a possibility we revisit in § 6.2.

6.1. Evolution of Cluster Morphological Content

To assess the degree of evolution in the morphological content of rich clusters, we searched the literature for similar analyses of clusters spanning a broad redshift range. The first comparison sample consists of z < 0.5 clusters with morphological fractions originally measured by different groups using a variety of methods, but reanalyzed in a uniform manner by Fasano et al. (2000, hereafter F00). The F00 sample includes 55 low-redshift clusters (Dressler 1980a; Dressler et al. 1997); the 10 MORPHs clusters at 0.37 < z < 0.5 (Dressler et al. 1997); three clusters at z ~ 0.3 plus A2218 and A1689 at z = 0.18 (Couch et al. 1998); and nine clusters at 0.1 < z < 0.25 (Fasano et al. 2000). Using this large sample of uniformly analyzed clusters at z < 0.5, Fasano et al. (2000) confirmed the MORPHs finding that the S0 fraction in clusters has doubled since z ~ 0.5, while the late-type fraction has decreased by a similar factor.

We also compare our results with that of Postman et al. (2005, hereafter P05). They computed the morphological fractions within the virial radii of seven clusters at 0.8 < z < 1.27. This is the only

| Cluster Number | E     | S0    | E+S0  | Sp+Irr | Sp+Irr | Sp+Irr |
|---------------|-------|-------|-------|--------|--------|--------|
| c11037        | 0.122 | 0.240 | 0.101 | 0.206  | 0.000  | 0.290  |
| c11040        | 0.339 | 0.000 | 0.037 | 0.098  | 0.126  | 0.000  |
| c11054-11     | 0.256 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11054-12     | 0.285 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11103        | 0.271 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11138        | 0.196 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11216        | 0.266 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11227        | 0.319 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11232        | 0.348 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |
| c11354        | 0.170 | 0.000 | 0.000 | 0.000  | 0.000  | 0.000  |

Notes.—R = 0.6 R200, Ω0 = 0.3, Λ = 0.7, H0 = 70 km s⁻¹ Mpc⁻¹. The morphological fractions for a given cluster were computed using the background subtraction method adopted for that cluster (see § 6).

Fig. 3.—Evolution of the E, S0, E+S0, and Sp+Irr fractions as traced by EDisCS clusters (filled circles) and F00 clusters (open circles). All fractions were computed within a radius of 600 kpc, using the classic cosmology. The lookback times were calculated with the WMAP cosmology.
large study of clusters at these redshifts in which S0 galaxies are separately classified. As previously discussed, the S0 population is an important one to track at high redshift.

In Figure 3, we show the evolution at $z < 0.8$ of the morphological fractions in rich clusters, using EDisCS data in conjunction with the F00 sample described above. All points were computed within 600 kpc, using the classic cosmology. We do not include within 600 kpc, using the classic cosmology. We do not include measurements made on the Postman sample in this plot because they were computed within $R_{200}$ using the WMAP cosmology. As discussed previously, the F00 sample shows a systematic decrease in the S0 fraction from 55% at $z = 0$ to 20% at $z \sim 0.5$. Where the redshift range of the EDisCS clusters overlaps with that of F00, the morphological fractions derived from the two samples are generally consistent. However, the longer redshift baseline afforded by the addition of the EDisCS data reveals that the S0 fraction is actually flat over the range $0.4 < z < 0.8$. This could mean that $z \sim 0.4$ is a special epoch after which the S0 fraction in cluster cores begins to grow. The coincidence of this special epoch with the redshift where the two samples overlap raises the question of whether the samples were analyzed in different ways. However, Section 5 describes our extensive attempts to control systematics in the EDisCS sample and to conform to the analysis presented by F00. Alternatively, it is possible that we are missing some S0-rich clusters at $z \sim 0.4$, which would reveal that the growth of the S0 fraction in clusters at $z < 0.4$ is slower than suggested by the present data. Indeed, the scatter in the morphological fractions at $z \sim 0.4$ is smaller than at either higher or lower redshifts.

The F00+EDisCS data are consistent with either a bend in the morphological fractions at $z \sim 0.4$ or a smooth continuation of the trends observed at $z < 0.5$, but with a flatter overall slope than suggested by the F00 data alone. More observations at $z \sim 0.4$ and $z > 0.8$ are required to distinguish between these two possibilities. As discussed above, P05 have analyzed the morphological fractions, including the S0 fraction, in clusters at $z > 0.8$. In Figure 4 we show the morphological fractions of the EDisCS and P05 clusters as functions of redshift. All estimates were made using the WMAP cosmology, but the EDisCS fractions were computed within $0.6 R_{200}$ (see § 5.2), while the P05 fractions were computed within $R_{200}$. P05 find that the E and E+S0 fractions decrease out to $0.6 R_{200}$, while the S0 fraction stays roughly constant and the Sp+Irr fraction increases. Between $0.6 R_{200}$ and $R_{200}$, all the fractions are flat. According to Table 4 of P05, the E, S0, early- and late-type fractions computed within $R_{200}$ are factors of approximately 0.79, 0.96, 0.85, and 1.15 times the fractions computed within $0.6 R_{200}$. However, no corrections have been made to the points shown in Figure 4.

Figure 4 shows that the strong evolution in morphological fractions seen at $z < 0.4$ does not continue at $z > 0.4$. Indeed, the E+S0 (Sp+Irr) fraction appears to be larger (smaller) in the higher redshift P05 sample compared to the EDisCS clusters. However, a Spearman rank correlation analysis shows that there is no statistically significant evidence for any evolution over the entire redshift interval $0.4 < z < 1.25$, or in the individual EDisCS and P05 samples. Additional clusters in this redshift range are necessary to reveal the presence of any weak correlation.

How does the selection requirement for the EDisCS clusters to exhibit a red sequence affect the interpretation of Figures 3 and 4? If the red sequence takes time to build up, it may be expected that this requirement selects for clusters that are also dynamically evolved. In fact, the EDisCS sample includes clusters that are clearly nonspherical, as well as clusters that display significant substructure (see § 6.2). The red sequence requirement may also
be expected to select for clusters with high E and/or S0 fractions. Figure 3 demonstrates that the EDisCS clusters do not contain large E fractions compared to either the optically selected F00 sample at lower redshifts or the (primarily) X-ray–selected P05 sample at higher redshifts. Thus, either such a bias is weak, or it is shared by the comparison samples. Given the correlation between galaxy color and morphology, any clusters lacking a red sequence would likely have significantly different morphological fractions from the EDisCS, F00, and P05 samples, leading to increased scatter in Figures 3 and 4. While both the incidence of such clusters and their morphological content are currently impossible to quantify, in the next subsection we evaluate the dependence of morphological fractions on another cluster property: velocity dispersion.

6.2. Correlation between Morphological Fractions and Cluster Velocity Dispersion

In the previous subsection we argued that there is no systematic evolution in the morphological fractions within rich clusters at $0.4 < z < 1.25$. Figures 3 and 4 indicate that the scatter in these fractions is large. How much of this scatter is due to a correlation between morphological fractions and cluster mass? Such a correlation may be expected in either nature or nurture scenarios. In the former it is due to the fact that the most massive clusters collapsed at earlier times. In the latter it could be due to a higher efficiency of morphological transformations in more massive clusters.

P05 found that the E, S0, and E+S0 fractions within $R_{200}$ of seven $z \sim 1$ clusters increase with increasing bolometric cluster X-ray luminosity, although the correlations are significant only at the $\approx 3 \sigma$ level. However, they find no correlation between the E+S0 fraction and the X-ray temperature or the cluster velocity dispersion, perhaps because of small number statistics. In Figure 5 we plot the morphological fractions of the EDisCS and P05 samples against cluster velocity dispersion. From this figure it is apparent that clusters with larger velocity dispersions harbor a higher fraction of early type galaxies and fewer late type galaxies. Spearman and Kendall rank correlation tests show that these visual impressions are statistically significant at the $\approx 3 \sigma$ level.

While it is tempting to interpret this correlation as one between morphological content and cluster mass, the velocity dispersion of a cluster is directly related to its mass only if the cluster is virialized. The velocity dispersion may overpredict mass if the cluster is experiencing significant merging events. The degree of substructure in five of the clusters in this work (c1040-1155, c1054-1146, c1054-1245, c1216-1201, and c1232-1250) has been studied in detail by Halliday et al. (2004) using Dressler-Shectman tests (Dressler & Shectman 1988). They detect substructure in c1232-1250 and c1216-1201 with more than 95% confidence. For c1040-1155 and c1054-1245, not enough spectra were available to provide firm evidence for substructure. No evidence for substructure was found for c1054-1146. They note that the two clusters showing clear evidence of substructure also have the largest velocity dispersions in the EDisCS sample, and caution against using the velocity dispersions for these two clusters as a proxy for mass. Further analysis on the remaining EDisCS clusters is ongoing (B. Milvang-Jensen et al. 2007, in preparation).

What is the situation for the $z < 0.5$ sample, where evolution is observed? Velocity dispersions were available in the literature for 14 of the clusters in the F00 sample (Couch & Sharples 1987; Gudehus 1989; Girardi & Mezzetti 2001; De Propris et al. 2002; Bettoni et al. 2006). Figure 6 shows the morphological fractions for these 14 F00 clusters as a function of cluster velocity dispersion. Without a larger number of data points it is difficult to make a conclusive statement regarding the existence of a correlation. Spearman and Kendall rank correlation tests indicate that none...
of the morphological fractions are significantly correlated with cluster velocity dispersion. However, removal of two clusters (A389 and A3330) with unusually high S0 fractions for their velocity dispersions results in a $2\sigma$ detection of a correlation between S0 fraction and cluster velocity dispersion. Additional velocity dispersions for the F00 sample would greatly aid an assessment of any correlation, which is necessary for understanding the observed trends between morphology and redshift.

Comparing the x-axes of Figures 5 and 6, we see that the F00 sample at $z < 0.5$ includes some clusters with very high velocity dispersions ($\sigma > 1200$ km s$^{-1}$), while the $z > 0.5$ EDisCS+P05 sample does not. Figure 7 shows the cluster velocity dispersions of the EDisCS, F00, and P05 samples as a function of lookback time. The clusters with the highest velocity dispersions in these samples lie at low redshift. Unfortunately, velocity dispersions are unavailable for a significant fraction of the low-redshift sample. These are urgently needed to understand the extent to which sample selection is responsible for the apparent evolution in the morphological content of clusters.

7. DISCUSSION AND CONCLUSIONS

Using high-resolution imaging afforded by the ACS instrument on board the Hubble Space Telescope, we find no evidence for evolution in the morphological content of rich clusters with velocity dispersions in the range $\sigma = 200$–1200 km s$^{-1}$ over the redshift range $0.4 < z < 1.25$ (see Figs. 3 and 4). Although the scatter is significant, typical morphological fractions for clusters in this redshift range are 0.3, 0.15, and 0.55 for E, S0, and Sp+Irr galaxies, respectively. In contrast, studies of clusters at lower redshifts have shown that the elliptical fraction remains constant between $z = 0$ and $z \sim 0.5$, while the S0 fraction decreases by a
factor of \( \sim 2 \) and the Sp+Irr fraction increases by a similar amount over the same redshift range (e.g., F00). Our data show that the observed evolution in cluster S0 and Sp+Irr populations does not continue beyond \( z \sim 0.4 \), at least for the velocity dispersions probed in this study.

How do our results concerning the global evolution of galaxy morphologies within rich clusters translate into a statement regarding the evolution of the morphology-density relation? Although the centers of cluster cores are regions of high local galaxy density, our morphological fractions were computed within sizable apertures (see § 5.2), so the average environment we are probing is of moderate density. For example, the average galaxy surface density within a radius of 0.6 \( R_{200} \) \((\Omega_0 = 0.3, \Lambda = 0.7, H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}) \) for the EDisCS clusters used in this analysis ranges from \( \sim 40-175 \text{ Mpc}^{-2} \). The morphological fractions of the F00 and P05 clusters were likely computed using galaxies inhabiting environments of similar average density. These results may point to a lack of evolution in the morphology density relation between \( z = 0.8 \) and 0.4, with a subsequent increase in the S0 population and a decrease in the Sp+Irr population. Larger samples in this redshift range are needed to understand the scatter in the morphological fractions, and to rule out weak evolution. However, our current data are consistent with recent studies of the morphology-density relation at \( z \sim 1 \) (Smith et al. 2005; Postman et al. 2005).

Several studies of nearby galaxies indicate that the observed relation between morphology and environment is a reflection of a more primary relation between star formation rate (SFR) and environment (Kaufmann et al. 2004; Christlein & Zabludoff 2005; Blanton et al. 2005). The star formation properties of cluster, group, and field galaxies in the EDisCS spectroscopic sample have been measured and compared to a low-redshift sample from the Sloan Digital Sky Survey by Poggianti et al. (2006, hereafter P06). Based on these data, P06 put forth a model in which passive galaxies devoid of ongoing star formation are made up of two separate populations: “primordial” galaxies whose stars all formed at \( z > 2.5 \) and galaxies whose star formation lasted until later times but was ultimately “quenched” due to entering a cluster-like environment \((>10^{14} M_\odot) \). In this model the primordial galaxies may be identified with the elliptical galaxies that make up \( \sim 30\% \) on average of the galaxy populations in clusters at \( z < 1 \), and perhaps some of the S0 galaxies (see below). This identification is consistent with both the lack of evolution in the elliptical fraction at \( z < 1 \) and with the old ages inferred for elliptical stellar populations. It is tempting to identify the quenched galaxies with S0’s. However, the fraction of quenched galaxies in the model increases at \( z < 0.8 \), while the S0 fraction only increases at \( z < 0.4 \). These timescales are consistent if it takes roughly a billion years for a galaxy to resemble an S0 after the cessation of star formation in a spiral galaxy (Dressler et al. 1999; Poggianti et al. 1999; Tran et al. 2003). However, the formation of the S0 population observed in clusters at \( 0.4 < z < 1 \) cannot be explained in this way. Perhaps these are primordial S0’s that assumed an S0 morphology upon or soon after formation at \( z > 2.5 \). If so, the S0 galaxies in clusters at \( z > 0.4 \) should be, on average, older and more massive than cluster S0’s at \( z < 0.4 \). Another possibility is that at least some late types may transform into S0’s in systems less massive than \( 10^{14} M_\odot \), perhaps by an entirely different mechanism than operates in \( >10^{14} M_\odot \) systems. The existence of S0’s in groups (e.g., Hickson et al. 1989) suggests that this may be the case.

If a significant fraction of S0 galaxies in nearby clusters were quenched, what did they look like beforehand? The parallel decline in the Sp+Irr fraction as the S0 fraction increases between \( z = 0.4 \) and 0 suggests that some subset of late-type galaxies transformed into S0’s subsequent to quenching. For the EDisCS clusters, we computed the fractions of Sp and Irr galaxies separately (see Tables 3 through 4). As with the other morphological fractions at \( z > 0.4 \), the Sp and Irr fractions do not vary systematically with redshift. Moreover, the Irr fractions in the EDisCS clusters are very small. We conclude that Sp galaxies and not Irr galaxies are the precursors of the quenched S0’s in local clusters.

In the P06 model, both nature and nurture (within clusters) play a role in the environmental dependence of star formation and therefore morphology. The nurture component within clusters is consistent with the observation that the relation between star formation and environment in nearby clusters is not solely a reflection of the relation between stellar age and environment, as would be expected in a pure nature scenario (Christlein & Zabludoff 2005). The P06 model is also compatible with observations which show that the SFR-density relation out to \( z \sim 1 \) extends to very low local densities, comparable to those found at the virial radius of clusters and even outside clusters (Lewis et al. 2002; Gómez et al. 2003; Cooper et al. 2006). The low-density relations could be set up by the dependence of galaxy properties on initial conditions, or perhaps a different mechanism creates S0 galaxies in low-density environments, or a combination of factors could be responsible.

Although the model forwarded by P06 is an attractive framework within which to view our observational results on the morphological content of rich clusters, it is not necessarily the only model that could explain all of the data accumulating on the evolution of galaxy properties with environment. Furthermore, it does not identify a mechanism responsible for the quenching, although it does specify a timescale (3 Gyr) and a mass scale \((10^{14} M_\odot) \) of a workable mechanism.

In addition to analyzing the evolution of the morphological content in galaxy clusters out to \( z = 1.25 \), we have also studied the dependence of the morphological content on the cluster velocity dispersion (see Figs. 5 and 6). We find that the early- and late-type fractions in the EDisCS and P05 cluster samples correlate with cluster velocity dispersion at a statistically significant level. This correlation highlights the importance of understanding global cluster properties in samples where evolution is observed, such as the F00 sample. Unfortunately, only limited velocity dispersion information is available for the F00 clusters. The existing information for 14 clusters indicates that they have a higher average velocity dispersion than either the EDisCS or P05 clusters. In addition, the morphological fractions of these 14 clusters do not correlate strongly with cluster velocity dispersion. It is possible that additional velocity dispersions for the F00 sample will reveal an underlying trend, that additional studies at high redshift will prove the trend observed in the higher redshift EDisCS+P05 sample to be spurious, or that the relation between morphological fraction and cluster velocity dispersion is itself a function of redshift. Larger cluster samples with robust velocity dispersions and morphologies are needed to determine which of these options is most likely. If the morphology-density relation is driven by environmental processes in clusters, such measurements are essential for determining how the efficiency of these transformations depends on cluster velocity dispersion, which, as discussed in § 6.2, is related to both the cluster mass and its dynamical state.

We greatly appreciate the timely and cheerful assistance of Galina Soutchkova in planning the HST observations. We also thank the referee, Manolis Plionis, for feedback which improved the paper. V. D. acknowledges funding from the Graduate Student Researchers Program. This work was supported by NASA...
grant HST-GO-09476.01. J. J. D. was partially supported by the Alfred P. Sloan Foundation. The Medium Deep Survey catalog is based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The Medium-Deep Survey analysis was funded by the HST WFPC2 Team and STScI grants GO2684, GO6951, GO7536, and GO8384 to Richard Griffiths and Kavan Ratnatunga at Carnegie Mellon University.

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