THE EVOLUTION OF EARLY-TYPE RED GALAXIES WITH THE GEMS SURVEY: LUMINOSITY-SIZE AND STELLAR MASS–SIZE RELATIONS SINCE $z = 1^{1}$

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Received 2004 November 26; accepted 2005 June 16

ABSTRACT

We combine imaging from the Hubble Space Telescope Advanced Camera for Surveys, as part of the GEMS (Galaxy Evolution from Morphologies and SEDs) survey, with redshifts and rest-frame quantities from COMBO-17 to study the evolution of morphologically early-type galaxies with red colors since $z = 1$. From $0.5 \times 0.5$ imaging, we draw a large sample of 728 galaxies with centrally concentrated radial profiles (i.e., $n \geq 2.5$ from Sérsic fits) and rest-frame ($U-V$) colors on the red sequence. We explore how the correlations of rest-frame $V$-band luminosity and of stellar mass with intrinsic half-light size change over the last half of cosmic time. By appropriate comparison with the well-defined local relations from the Sloan Digital Sky Survey, we find that the luminosity-size and stellar mass--size relations evolve in a manner that is consistent with the passive aging of ancient stellar populations. By itself, this result is consistent with a completely passive evolution of the red early-type galaxy population. If instead, as demonstrated by a number of recent surveys, the early-type galaxy population builds up in mass by roughly a factor of 2 since $z \sim 1$, our results imply that new additions to the early-type galaxy population follow similar luminosity-size and stellar mass--size correlations, compared to the older subset of early-type galaxies. Adding early-type galaxies to the red sequence through the fading of previously prominent disks appears to be consistent with the data. Through comparison with models, the role of dissipationless merging is limited to $< 1$ major merger on average since $z = 1$ for the most massive galaxies. Predictions from models of gas-rich mergers are not yet mature enough to allow a detailed comparison to our observations. We find tentative evidence that the amount of luminosity evolution depends on galaxy stellar mass, such that the least massive galaxies show stronger luminosity evolution compared to more massive early types. This could reflect a different origin of low-mass early-type galaxies and/or younger stellar populations; the present data are insufficient to discriminate between these possibilities.

Subject headings: galaxies: evolution — galaxies: fundamental parameters (luminosities, stellar masses, radii) — galaxies: general — surveys

1. INTRODUCTION

The formation and evolution of massive, early-type galaxies constitutes a long-standing and crucial problem in cosmology. In all hierarchical models, e.g., a $\Lambda$-dominated cold dark matter ($\Lambda$CDM) cosmology, the massive early-type galaxies seen now are expected to have formed through mergers of smaller galaxies over time (White & Frenk 1991; Cole et al. 2000). Yet, within these models it is difficult to predict robustly at what point during this assembly most stars formed. In order to constrain the star formation (SF) and assembly histories of the early-type galaxy population, it is necessary to explore the evolution of their number density and various scaling relations, such as the fundamental plane (van Dokkum & Franx 1996; Kelson et al. 2000; van Dokkum et al. 2001; Treu et al. 2002; Wuyts et al. 2004; van der Wel et al. 2004), the luminosity-size relation (Barrientos et al. 1996; Bahre et al. 1996; Schade et al. 1997, 1999; Barger et al. 1998; Ziegler et al. 1999), and the stellar mass--size relation (Trujillo et al. 2004b). To this end, we use the GEMS (Galaxy Evolution from Morphology and SEDs; Rix et al. 2004) survey in conjunction with COMBO-17 (Classifying Objects by Medium-Band Observations in 17 Filters; Wolf et al. 2003, 2004) to construct the largest sample to date of distant ($0 < z \leq 1$) early-type galaxies with Hubble Space Telescope (HST) imaging to explore the evolution of luminosity and stellar mass as functions of galaxy size.

Most initial studies of $z \leq 1$ early-type galaxies focused on galaxies in some of the richest clusters at each epoch (e.g., van Dokkum & Franx 1996; van Dokkum et al. 1998; Kelson et al. 2000), and found that the mass-to-light ($M/L$) ratios of massive galaxies in this environment changed as expected for passive fading of a population formed exclusively at very early epochs. In recent years, greatly expanded studies of “red” galaxies in random cosmological volumes have been carried out, extending to redshifts of at least $z \sim 2$ (Chen et al. 2003; Rusin et al. 191
amounting to a factor of only through fading since the age distribution of the stars in these galaxies does not by itself speak to their dynamical assembly.

While the optical colors of massive red early-type galaxies would indeed be consistent with a population that has evolved only through fading since \( z \sim 2 \), other data indicate that more must have happened. In particular, the comoving total stellar mass density in red-sequence galaxies is lower at earlier epochs, amounting to a factor of \( \sim 2 \) buildup since \( z \sim 1 \) (Chen et al. 2003; Bell et al. 2004b; Cross et al. 2004). Several factors are expected to contribute to this evolution: (1) in galaxies with vanishing and disappearing SF, the disk will fade and the bulge gain prominence in comparison; (2) spheroidal components may newly form from gas-rich disk mergers or from internal disk instabilities; or (3), galaxies within the red sequence could undergo dissipationless merging, changing their masses and structures while leaving their stellar populations unchanged. All processes are expected to continue to the present epoch in a hierarchical universe (e.g., Cole et al. 2000; Steinmetz & Navarro 2002; Khochfar & Burkert 2003). The relative importance of the effects is expected to be a strong function of galaxy mass: gas-rich mergers, disk instabilities, and disk fading are expected to contribute strongly at low masses, whereas dissipationless mergers may dominate for high-mass galaxies (Khochfar & Burkert 2003).

The aging of a stellar population not only implies redder colors but also dimming. We exploit this to apply an independent test for the population evolution of massive galaxies. This test uses the morphological and structural information for a large sample of early-type, red galaxies to \( z \sim 1 \), which we draw from the COMBO-17 redshift and spectral energy distribution (SED) survey (Wolf et al. 2003, 2004) and the GEMS \( HST \) imaging survey (Rix et al. 2004). By constructing the luminosity-size \((L_{V}/r_{50})\) and stellar mass-size \((M_{*}/r_{50})\) relations for subsamples of morphologically selected early-type, red galaxies at different redshifts, one can test the hypothesis of passive evolution and provide constraints for other evolutionary scenarios. In practice, the concentration of the light profile, specified by the Sérsic index \( n \geq 2.5 \) is used as a quantitative proxy for morphology.

For the most strict version of passive evolution (no new stars; no merging) the prediction is clear: the \( M_{*}/r_{50} \) relation will remain unchanged \(^{12} \) and the \( L_{V}/r_{50} \) relation should change in the sense that galaxies of a given size would have been brighter by about 1 mag in \( V \) band at \( z = 1 \), if the observed color evolution (Bell et al. 2004b) is a guide to the stellar \( M/L (M_{*}/L) \) ratio evolution. The predictions for the evolution of these relations in the presence of merging are maturing rapidly. Gas-free dissipationless mergers (see, e.g., Naab & Burkert 2003; Dantas et al. 2003; Nipoti et al. 2003) will slowly move galaxies away from the \( L_{V}/r_{50} \) and \( M_{*}/r_{50} \) relations (Nipoti et al. 2003); we discuss this issue in detail later. Existing constraints from the color-magnitude relation (CMR) or fundamental plane (FP) limit the amount of dissipationless merging that can occur to a factor of a few in terms of mass growth in this merging mode, if roughly equal mass mergers dominate the mass growth (Bower et al. 1998; Dantas et al. 2003; Nipoti et al. 2003; González-García & van Albada 2003; Evstigneeva et al. 2004). Predictions for gas-rich mergers are less mature, and it is not clear what to expect for the evolution of the \( L_{V}/r_{50} \) and \( M_{*}/r_{50} \) relations in this case.

As shown persuasively by Simard et al. (1999), any such test for passive or other physical evolution requires careful accounting for redshift-dependent selection effects. We will address this issue extensively, as the systematics of the sample selection become increasingly important over diminishing statistical errors for larger samples. Also, all existing surveys that are deep enough to reach \( z \sim 1 \) cover such a small area that their volumes at low redshifts (\( z \leq 0.2 \)) become too small. Therefore, we will combine the COMBO-17/GEMS data at \( z \geq 0.2 \) with the present-day \( L_{V}/r_{50} \) and stellar \( M_{*}/r_{50} \) relations for early-type galaxies (Shen et al. 2003) from the Sloan Digital Sky Survey (SDSS; York et al. 2000). Both for Shen et al. (2003) and the \( 0.2 < z < 1 \) sample presented here, \( M_{*}/L \) ratios are estimated from the spectra and SEDs.

In this paper we bring to bear the largest sample of morphologically and color-selected early-type galaxies with \( HST \) imaging for a comprehensive analysis of the evolution of the \( L_{V}/r_{50} \) and \( M_{*}/r_{50} \) relations. Measuring the evolution of relationships between these fundamental galaxy properties over \( 0 < z < 1 \) can place further constraints on galaxy formation and evolution models. Specifically, we have two goals: (1) to quantify the expected luminosity evolution of galaxies of a given size due to the simple aging of their ancient stars with the best accounting of selection effects to date; and (2) to test whether stellar mass evolution occurs at different fixed galaxy sizes, which may provide constraints on the merging history of these systems of old stars. The outline of this paper follows. We describe our early-type galaxy data in §2, including relevant discussions of the GEMS imaging survey, the rest-frame quantities from COMBO-17, the early-type sample selection, and our galaxy size measurements. In §3 we explore the evolution of the luminosity and stellar mass scaling relations of early-type galaxies with \( z \leq 1 \). We discuss our results in §4 and give our conclusions in §5. For rest-frame luminosities, stellar masses, and physical sizes we assume a flat, \( \Lambda \)-dominated cosmology with \( \Omega_{m} = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( H_{0} = 100 \) km s\(^{-1}\) Mpc\(^{-1}\). When estimating expected passive stellar population evolution, we adopt a flat universe with the \textit{Wilkinson Microwave Anisotropy Probe} parameters \( H_{0} = 72 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( \Omega_{m} = 0.27 \); Spergel et al. 2003), which give a Hubble time of 13.5 Gyr, to account for \( M_{*}/L \) ratio and color evolution in the most realistic way possible at this time.

2. EARLY-TYPE GALAXY DATA

We select a well-defined sample of early-type galaxies with \( HST \) imaging from GEMS, and high-precision photometric redshifts and rest-frame luminosities from COMBO-17. In this section we discuss briefly the high-resolution imaging and the aspects of the COMBO-17 data relevant to this study. Furthermore, we outline the early-type sample selection and its completeness, and we describe the galaxy size measurements from the \( HST \) data.

2.1. High-Resolution Imaging

The GEMS survey has obtained a large, two-passband (F606W and F850LP) Advanced Camera for Surveys (ACS) image mosaic over an area of \( 28^\prime \times 28^\prime \), encompassing the Extended Chandra Deep Field–South (ECDF-S). This is the largest contiguous color map of the cosmos obtained with \( HST \) and consists of a grid of 78 mostly overlapping images taken with the ACS wide-field camera during 2002 November. The full details of the imaging grid, observations, data reduction, calibration, and data quality

\(^{12}\) This is true neglecting the possible change in effective radius that might occur in a galaxy with a substantive age gradient. Stellar mass loss in an aging stellar population would lead also to slow changes in the \( M_{*}/r_{50} \) relation.
assumption will be presented in J. Caldwell et al. (2005, in preparation, hereafter C05). An overview of the GEMS survey experimental design is given in Rix et al. (2004). The foremost goal of GEMS is to quantify the internal structural evolution of galaxies using statistically significant samples of galaxies at known redshifts. To this end we selected the ECDFS-S field with an existing redshift data set from COMBO-17. Furthermore, a fraction of GEMS overlaps with the GOODS (Great Observatories Origins Deep Survey; Giavalisco et al. 2004), Ultra Deep Field (UDF), and UDF parallels (Bouwens et al. 2004) programs, thus providing a wealth of deeper, multiwavelength data.

Hereafter, we concentrate our analysis on measuring galaxy sizes from the longest rest-frame wavelength possible at which galaxy profiles appear most uniform and the contamination from star-forming regions in disk galaxies is minimized. Therefore, we measure sizes by fitting simple models to the two-dimensional galaxy imaging in the F850LP filter.

For each pointing in the GEMS mosaic we have individual F850LP images, which are multidrizzle combinations of three dithered exposures (720–762 s each; see C05 for details). Briefly, the exposures were processed individually prior to combining (i.e., bias and dark current correction, flat-fielding). The final frames are free of most cosmic rays and remapped onto a fine 0′′03 pixel−1 scale. The full suite of 78 F850LP images are quite flat with background differences between images considerably less than 0.2 ADU, and the local galaxy background measurements across each frame have a typical rms of 0.2 ADU. In addition, we have a variance image (necessary for source detection) with the same scale for each frame. The images are flux-calibrated for photometric uniformity over the large mosaic of ACS frames, which assures unbiased galaxy size measurements. We calibrate the astrometry of each image to the ground-based epoch J2000.0 system of COMBO-17, which allows precise image/redshift cross correlation. The reduced frames have angular resolution of 0′′077 FWHM, corresponding to a physical scale of 700 pc at z ∼ 0.75, comparable to the resolution of Coma galaxy cluster observations with 1″ seeing.

The final GEMS source catalog contains 41,681 unique objects detected in the F850LP imaging. For source detection we employ SExtractor (Bertin & Arnouts 1996) in a two-step strategy discussed in detail in Rix et al. (2004). Briefly, first we use a conservative (“cold”) detection and deblending configuration that avoids spurious deblending of large galaxies with strong features, yet is incomplete for faint, low surface brightness objects found in COMBO-17. Next we use a “hot” configuration to detect 99% of known COMBO-17 sources down to a total apparent magnitude of Rtot = 24 (Vega), the limit at which the redshift performance drops dramatically. The exact configuration parameters are given in Rix et al. (2004). In each case, separate catalogs for each GEMS pointing are constructed from the combined F850LP image and a weight map (σ/μ)−1. The use of weight maps reduces the number of spurious detections in low signal-to-noise ratio (S/N) areas of each image (e.g., near image edges).

For each field we combine all “cold” sources plus the subset of “hot” sources residing outside of the isophotal area of any cold detections, and then we remove duplicate sources to produce the final catalog with the following properties: (1) contains 99% of all objects in the Rtot ≤ 24 mag COMBO-17 sample; (2) avoids spurious deblending of large, bright galaxies exhibiting strong substructure in HST images from spiral features, etc.; and (3) provides a homogeneous, flux and surface brightness–limited catalog of all sources in the F850LP ACS mosaic, regardless of COMBO-17 or other external information. Through detailed simulations (B. Häußler et al. 2005, in preparation, hereafter H05), we have detection completeness maps for r1/4 spheroids (see Fig. 5) and exponential disks. The GEMS SExtractor source catalog will be published and described in complete detail in C05.

2.2. Rest-Frame Quantities from COMBO-17

COMBO-17 is a deep photometric survey comprised of five (three completed) disjoint fields, each ~0.25 square degrees in size, with flux measurements in five broad and 12 medium passbands (between 3500 and 9000 Å). This survey provides data for ~25,000 galaxies with Rtot < 24 mag in the range 0.2 < z < 1.2. The COMBO-17 data, associated uncertainties, sample selection, and completeness are discussed in detail in Wolf et al. (2004).

The deep 17 passband data combined with stellar, active galactic nucleus, and nonevolving galaxy template spectra allow nearly all (98%) objects to be assigned redshifts and SED classifications. The redshift accuracies depend primarily on R-band aperture magnitude, with εz/(1 + z) ∼ 0.02 for Rap < 22 mag. When going fainter the errors reach εz/(1 + z) ∼ 0.05 at Rap = 23 mag (Wolf et al. 2004). Reliable redshift estimates allow the construction of rest-frame luminosities and colors. Depending on the redshift in question, rest-frame luminosities are determined either by interpolation or mild extrapolation. For this study we use the rest-frame V-band absolute magnitudes for the luminosity parameter, which are extrapolated for galaxies with z > 0.7. Nevertheless, the leverage of the COMBO-17 filter set continues to provide accurate V-band magnitudes to z = 1, with typical uncertainties of ~10% (z < 0.7) and ~15% (z > 0.7). We note that the quoted redshift accuracies correspond to ≤15% fractional distance errors for z > 0.2.

We cross correlate the positions of sources from the GEMS F850LP imaging with source coordinates from the COMBO-17 ECDFS-S catalog.13 We find 6152 galaxies with redshifts 0.2 ≤ z ≤ 1.0 and Rap ≤ 24 mag. This is our overall galaxy sample. We note that the COMBO-17 magnitude limit corresponds to the reliability of estimating redshifts, which is brighter than the limit to detect galaxies with high completeness both in COMBO-17 and GEMS. For red-selected galaxies, which are the primary concern of this paper, the completeness limit owing to redshift reliability depends somewhat on redshift: for 0.2 < z < 0.6 the mean 90% limit occurs at Rap = 23.5; while at larger redshifts (0.6 < z < 1.0) the sample is fully complete down to Rap = 24 mag. At redshifts above z = 1, COMBO-17 remains complete to the magnitude limit, yet this limit begins restricting the sample to only the very luminous (M_V < −21 + 5 log(h/0.7) at z ∼ 1) red galaxies. We therefore adopt a strict z = 1 cut for our analysis.

We use stellar mass M_∗ estimates based on direct modeling of the COMBO-17 SEDs (A. Borch et al. 2005, in preparation). The 17 passband COMBO-17 SEDs were compared with a library of galaxy template spectra obtained from the PEGASE code (see Focie & Rocca-Volmerange 1997, for a description of an earlier version of the code). From each galaxy’s SED we estimate directly its M_*/L ratio, and hence M_*/M_∗ uncertainties include contributions from redshift uncertainty. We use a Kroupa et al. (1993) stellar initial mass function (IMF), which produces M_*/L values comparable to those from a Kroupa (2001) IMF, and ~0.3 dex lower than from a Salpeter (1955) IMF. For red-selected galaxies, these stellar masses agree to within ±40% (0.11 dex), and show no average offset when compared to stellar masses based on the simple relation between (B − V) color and M_*/L from Bell et al. (2003), assuming the same IMF. The stellar mass estimates suffer from a number of random and systematic
uncertainties, such as uncertainties in galaxy age, bursts of SF in the last 1–2 Gyr, and variations in the relationship between dust reddening and extinction (see, e.g., Bell & de Jong 2001; Bell et al. 2003, for a more in-depth discussion of the relevant sources of uncertainties). Generally these uncertainties amount to ~0.3 dex; for the red-sequence galaxies studied here, it is likely that the stellar mass estimates are more accurate than this, as relatively old stellar populations are somewhat easier to model robustly with simplistic star formation history prescriptions.

2.3. Early-Type Galaxy Selection

In very generic terms, the visual appearances of galaxies fall into two broad types: (1) early-type refers to a galaxy with spheroidal or bulge-dominated (centrally concentrated) morphology; and (2) late-type corresponds to a disk-dominated or irregular system. In the local universe, several classes from the familiar Hubble (1926) sequence are considered early-type in morphology—ellipticals (E), lenticulars (S0), and spirals with dominant bulges and small disks with tightly wound spiral arms (Sa). In addition to physical appearance, the optical colors of galaxies are broadly different—early types have typically red colors suggestive of a dominant population of old stars with little or no current SF; late types tend to be bluer in color as a result of ongoing SF and some fraction of young stars. This bimodal distribution of galaxies in color space is observed both locally (Strateva et al. 2001; Hogg et al. 2002; Blanton et al. 2003b; Baldry et al. 2004) and out to z ~ 1 (Bell et al. 2004b; Weiner et al. 2005). Furthermore, red galaxies at z ~ 0.7 contain the same predominance (~85% by optical luminosity density) of early-type galaxies (E/S0/Sa) as locally (Bell et al. 2004a), with a small contamination by edge-on disk galaxies with colors reddened by internal extinction. For this study we are interested in early-type galaxies with red colors, and thus we select our sample using both color and morphology.

2.3.1. Red Sequence

Red-color selection permits an objective and empirical first cut for defining early-type galaxies over the last half of cosmic history. We use the empirical fit to the CMR evolution (including local comparison points) from Bell et al. (2004b)\(^1\) to select red-sequence galaxies at a given redshift z with rest-frame colors redder than

\[
(U - V) = 1.05 - 0.31 z - 0.08(M_V - 5 \log_{10} h + 20).
\]

This color cut is 0.25 mag redder than the fit to the CMR evolution and similar in philosophy to the Butcher & Oemler (1984) criteria, except that we select red rather than blue galaxies. The color evolution of red-sequence galaxies selected with this definition is in good agreement with the expected evolution of a single-age stellar population anchored to z = 0. There are 1166 red-sequence objects with 0.2 < z < 1.0 and GEMS imaging.

To facilitate meaningful profile fitting, we visually inspect the F850LP images of the red-sequence sample. COMBO-17 is expected to misclassify a small number of red M-class stars as moderate-redshift red-sequence galaxies (Wolf et al. 2004). With the superior resolution of GEMS, we can directly detect 69 misclassified stars, which are shown in Figure 5 for completeness and are omitted from the analysis hereafter. We note that these stars are also separated cleanly from galaxies using a SExtractor CLASS_STAR ≥ 0.85 cut. In addition, we remove 50 red-sequence galaxies with poor S/N found near GEMS image edges or within interchip gaps. This leaves 1047 red-sequence galaxies with useful GEMS imaging. Last, we remove 84 galaxies with morphologies where reliable fits are not possible (14 with prominent dust lanes, 29 irregulars, and 41 peculiar/interacting). We are left with a final sample of 963 morphologically “normal” red galaxies with the following breakdown of coarse types: 699 E/S0, 162 Sa, and 102 late-type spirals (Sb–Sc). Owing to the subjective nature of visual classifications, we divide the sample morphologically using a quantitative method in the next section.

2.3.2. Quantitative Morphology

We refine our sample further by determining which red-sequence galaxies have early-type morphology using a quantifiable and repeatable method. The simple Sérsic (1968) model, which describes the radial surface brightness profile of a galaxy by \(\Sigma(r) \propto r^{-n/4}\), is the most widely used parametric function. The Sérsic index \(n\) describes how centrally concentrated a galaxy appears, with \(n = 4\) describing the familiar \(r^{1/4}\) profile of ellipticals (de Vaucouleurs 1948) and \(n = 1\) representing the exponential profile commonly seen in spiral disks. Studies with the SDSS have adopted empirical cutoffs around \(n = 2.5\) to separate morphologically early and late types (Blanton et al. 2003b; Shen et al. 2003; Hogg et al. 2004). In addition, using a sample of nearly 1500 GEMS galaxies in the thin redshift slice 0.65 ≤ z ≤ 0.75, Bell et al. (2004a) showed that an \(n = 2.5\) cut was reliable at distinguishing between visually classified early and late types. To remain consistent, we adopt \(n ≥ 2.5\) to denote early types in this study.

We note that the \(n = 2.5\) cut is a crude concentration cut that takes no account of the real diversity of galaxy forms seen in nature. In particular, this cut does not account explicitly for dynamically distinct bulge and disk components, and we reserve a detailed fitting of the photobulge and photodisk components to future papers. Nevertheless, it is unclear whether bulge/disk decompositions will be any more robust or physical than the simple \(n = 2.5\) cut. We note two additional sources of concern with the \(n ≥ 2.5\) selection. First, \((1 + z)^{2}d\) dimming of disks may cause a systematic bias such that large disks at high redshift may be too faint to detect and, thus, appear as bulge-dominated galaxies (larger n values). Second, a correlation exists between \(n\) and absolute B-band magnitude for visually selected ellipticals (e.g., Trujillo et al. 2004a). Therefore, a strict \(n = 2.5\) cut is effectively a luminosity cut of roughly \(M_B = -17 + 5 \log_{10} h\). This magnitude limit is below our redshift reliability cutoff at all redshifts except for the \(z ≤ 0.3\) interval, at which the drop in numbers of galaxies fainter than \(-17.5 + 5 \log_{10} h\) may be explained by this effect. Ultimately, we accept these caveats with the understanding that we have a repeatable and empirically motivated early-type galaxy sample.

In the Appendix we describe our method for fitting a Sérsic model to each galaxy’s two-dimensional luminosity profile from the F850LP imaging. Briefly, we use the fitting code GIM2D (Galaxy Image 2D; Simard et al. 2002) to fit the sample of 963 red-sequence galaxies and find that 96% (928) are fit successfully. The majority of fitting failures are the result of GIM2D reaching the Sérsic parameter limit of \(n = 8\). We estimate uncertainties of \(dn/n ~ 0.25\). Our final sample contains 728 red galaxies out to \(z = 1\) with \(n ≥ 2.5\).

In general, using an \(n = 2.5\) cut does a good job separating red-selected galaxies into morphologically early and late types.

\(^{14}\) This cut is slightly bluer than that given by Bell et al. (2004b). Owing partially to uncertainties in photometric calibration and galactic foreground extinction, the red sequence has slightly different colors in the three COMBO-17 fields, and the cut we use here is more appropriate for the ECDF-S.
We find only 3% of the red $n \geq 2.5$ sample have late-type (Sb–Sd) visual morphologies, while 14% of the visually early types (E–Sa) have $n < 2.5$; this is typical of what was found in the comparison of by eye and Sérsic classifications at $z \sim 0.7$ by Bell et al. (2004a). We show in Figures 1–3 that representative examples of the red GEMS galaxies with $n \geq 2.5$ are visually early-type in appearance. For contrast, in Figure 4 we display a handful of the red-sequence galaxies with $n < 2.5$ that correspond to edge-on disks.

2.4. Effective Size Measurements

2.4.1. Galaxy Sizes

The main focus of this work is the measurement and analysis of galaxy sizes as a function of redshift. GIM2D calculates the half-light semimajor axis length $a_{50}$ by integrating the best-fit Sérsic model flux to infinity. For meaningful comparison with SDSS results we adopt a circular half-light radius, or geometric mean, given by $r_{50} = a_{50}(1 - e)^{1/2}$, where $e$ is the best-fit model ellipticity. We have applied a robust method for determining the systematic and random uncertainties of each model parameter by measuring their random offset and variance with respect to known values using a large sample of artificial galaxies analyzed in the same manner as the GEMS data (H05). This method has proven successful in other galaxy fitting work (e.g., Tran et al. 2003; MacArthur et al. 2003). We find that $r_{50}$ has typical random uncertainties of $\sim 35\%$ with no systematic error. In addition, we find that GIM2D $r_{50}$ measurements are reliable for $>90\%$ of galaxies within the range of magnitudes and sizes probed by our early-type sample.

Sky level uncertainties are an important source of systematic error in size measurements when applying profile fitting techniques (e.g., de Jong 1996). We estimate the error in our fitting-derived sizes due to the uncertainty in our local background measurements ($\sigma_{\text{bkg}} \sim 0.2$ ADU) by repeating the fits with the sky level held to constant values of $\pm 1\sigma_{\text{bkg}}$. We find that our size measurements have average uncertainties due to the sky of $\sim 10\%$.

Finally, our galaxy sizes are based on $r_{50}$ in a fixed, observed passband (F850LP), which corresponds roughly to the SDSS $z$-band. Therefore, galaxy sizes at different redshifts are measured at different rest-frame wavelengths; e.g., the central wavelength of the F850LP filter corresponds to rest-frame 7560 Å at $z = 0.25$ and 4846 Å at $z = 0.95$. For a consistent comparison with the local scaling relations from Shen et al. (2003), we correct each $r_{50}$ measurement to rest-frame $r$-band. Early-type galaxies are known to have internal radial color gradients (e.g., Franx et al. 1989; Peletier et al. 1990; Bernardi et al. 2003), with redder colors toward their centers. Such gradients should result in a wavelength-dependent galaxy size. We estimate a correction to shift $z$-band sizes to rest-frame $r$-band based on typical color gradients of $\Delta(B - R)/\Delta \log r = -0.09$ and $\Delta(U - R)/\Delta \log r = -0.22$ from Peletier et al. (1990). We assume an $r^{1/4}$ surface brightness profile and find that this gradient will produce measured sizes in the $U$-band to be about 6.5% bigger than in the $r$-band.
r-band; i.e., $\frac{\Delta r}{\Delta \log \lambda} = -0.25$. Between $z = 1$ and $z = 0$ the same observed passband corresponds to a factor of 2 change in wavelength, or a 7.5% size correction per unit redshift. The correction to rest-frame $r$ band ($z$ band observed at $z = 0.45$) is then given by

$$\frac{\Delta r}{r_{\text{obs}}} = -0.075(z - 0.466). \quad (2)$$

Owing to the mild color gradients this correction is quite small, amounting to only 4.0% (1.5%) decrease (increase) in observed size for $z = 1$ ($z = 0.25$), and as such it does not significantly affect our conclusions. We note that ellipticals with blue cores (i.e., inverted color gradients) have been observed by Menanteau et al. (2001) in the Hubble Deep Field (HDF), yet these galaxies are globally bluer than our red-sequence cut. The assumptions we make regarding color gradients are based on red galaxies; therefore, it is fair to apply this correction to our red-selected sample.

### 2.4.2. Magnitude-Size Distributions

Before proceeding with our analysis of scaling relations using rest-frame quantities, we plot in Figure 5 the magnitude-size distributions in the observed F850LP-band frame for all 928 red-sequence galaxies (split into eight bins of width $\Delta z = 0.1$ spanning redshifts $0.2 < z \leq 1.0$) to illustrate several aspects of our sample. We calculate the apparent magnitude $m_{\text{F850LP}}$ of each galaxy from the total intensity of the best-fit model (see the Appendix). We see that galaxy apparent magnitudes and angular sizes are correlated out to $z = 1$, such that bigger galaxies are

![Figure 2](image-url)
brighter. We note that the effects of \((1 + z)^4\) cosmological dimming appear as a shift of the magnitude-size correlation toward lower surface brightnesses at increasing redshifts. Specifically, between \(z = 0.25\) and \(z = 0.75\) the mean relation has faded by the expected 1.5 mag. Furthermore, nearly all galaxies have \(a_{250} < 1^\prime\), clearly illustrating the need for HST resolution to obtain accurate size measurements for distant galaxies. All red-selected galaxies are well resolved and are well within the >95% detection completeness limits for \(n = 4\) simulated spheroidal galaxies (H05). Therefore, our early-type sample is limited only by the \(R_p = 24\) mag cutoff (corresponding to \(m_{B50} \sim 22\) mag) for reliable photometric redshifts inherent to the COMBO-17 survey. We account for this fully in the following analysis by applying redshift-dependent completeness maps from COMBO-17.

In addition, we show where \(n < 2.5\) (Fig. 5, open squares) red-selected galaxies are found in the magnitude-size plane. Most red \(n < 2.5\) galaxies tend to have lower surface brightnesses.
relative to the spheroid-dominated $n \geq 2.5$ galaxies (filled symbols), and are for the most part highly inclined disk galaxies (see Fig. 4). These results are in qualitative agreement with the different magnitude-size correlations for reddened edge-on disks and early-type galaxies in the local universe (Blanton et al. 2003b).

3. SCALING RELATIONS OF EARLY-TYPE GALAXIES

3.1. Luminosity-Size Relation

We now present the $L_{r}-r_{50}$ relations for early-type galaxies with $0.2 < z \leq 1.0$ and we will compare these to the present-day distribution. In Figure 6 we divide our sample into eight redshift bins of $\Delta z = 0.1$, and for each we plot the absolute $V$-band magnitude against the rest-frame $r$-band size in physical units ($h^{-1}$ kpc). The bulk of the early-type population at each epoch spans roughly a $0.5-5.0$ $h^{-1}$ kpc half-light size distribution, with a handful of smaller ($<0.5$ $h^{-1}$ kpc) and larger ($>5.0$ $h^{-1}$ kpc) galaxies in some redshift slices. Starting at low redshift, the average number of galaxies per redshift slice increases as we sample larger comoving volumes, until $z \sim 0.75$ where the counts start falling off as expected in a magnitude-limited sample. The second lowest redshift bin is quite sparsely populated as a result of large-scale fluctuations.

For comparison, in each redshift interval of Figure 6 we show the “ridgeline” of the present-day $L_{r}-r_{50}$ relation for early-type galaxies. The $z \sim 0$ ridgeline is given by the median absolute $V$-band magnitude as a function of galaxy size using a mock catalog of $M_{V} = 5 \log_{10} h$ and $r_{50}$ values that follow the luminosity function of SDSS-selected, red-sequence galaxies from Bell et al. (2004b), and the $L_{r}-r_{50}$ relation for $n \geq 2.5$ galaxies in SDSS from Shen et al. (2003). Using a complete sample of $n \geq 2.5$ galaxies,15 these authors found a $L_{r}-r_{50}$ scaling relation in the local universe that is well fit by a simple power law, and they showed that SDSS early types of a given luminosity follow a lognormal size distribution given by

$$f(r_{50}, \bar{r}_{50}(L), \sigma(L)) = \frac{1}{\sqrt{2\pi}\sigma(L)} \exp\left\{-\frac{\ln^{2}[r_{50}/\bar{r}_{50}(L)]}{2\sigma^{2}(L)}\right\} \frac{dr_{50}}{\bar{r}_{50}},$$

with characteristic median size $\bar{r}_{50}(L)$ and dispersion $\sigma(L)$. The Shen et al. (2003) work is based on half-light radii and total absolute magnitudes from Sérsic (point-spread function [PSF] corrected) fits to the azimuthally averaged surface brightness profiles in the $r$ band (for radial profile fitting, see Blanton et al. 2003b). These present-day ($0.05 < z < 0.15$) sizes are given in observed $r$ band; nevertheless, at a median redshift of $z \sim 0.1$ the sizes are within $1\%$ of $r$-band rest-frame according to our passband correction calculation ($\S$ 2.4). Using $k$-corrections from Blanton et al. (2003a), the SDSS galaxy luminosities have been corrected to the $r$-band rest-frame ($z = 0$), which we translate to rest-frame $V$ band in our adopted ($h$ is a free parameter) cosmology using a mean ($V-r = 0.33$ color for E/S0s (Fukugita et al. 1995). Therefore, as a function of absolute $V$-band magnitude $M_{V} = M_{V} - 5 \log_{10} h$, the local $L_{r}-r_{50}$ relation has median $r$-band size (in units of $h^{-1}$ kpc)

$$\bar{r}_{50}(M_{V}) = 10^{(0.26M_{V} - 4.93)},$$

with dispersion$^{16}$ that increases with decreasing luminosity as

$$\sigma(M_{V}) = 0.27 + \frac{0.18}{1 + 10^{0.8(M_{V} - 19.78)}}.$$

Equation (3) does not directly allow one to plot the ridgeline of the $L_{r}-r_{50}$ relation, because it does not account for the steeply declining luminosity function of early-type galaxies, which at large size will shift the ridgeline toward fainter luminosities. To

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15 We note that the Shen et al. (2003) early-type sample is not color selected; thus there will be some contamination from centrally concentrated galaxies with blue colors. Yet, Shen et al. have stated that the majority of $n \geq 2.5$ SDSS galaxies have red colors of $(g - r) > 0.7$ (see also Blanton et al. 2003b).

16 This expression fits the dispersion of the $L_{r}-r_{50}$ relation for both early and late types to within their respective error bars (see Fig. 6 of Shen et al. 2003).
account for this we construct a large grid of galaxy luminosities and sizes that sample the $L_{V}-r_{50}$ relation of $z \sim 0$ early types with a lognormal dispersion in the size direction given by equations (3)–(5). We then populate this grid so that the $M_{V} - 5 \log_{10} h$ distribution matches the local $B$-band luminosity function given in Bell et al. (2004b), which we transform to rest-frame $V$-band assuming a typical ($B - V = 0.9$ color for E/S0 types) (Fukugita et al. 1995). The grid spans $-24 < M_{V} - 5 \log_{10} h < -16$ in $800 (0.01 \text{ mag})$ cells and $0 < r_{50} < 25 h^{-1} \text{kpc}$ in $500 (0.05 h^{-1} \text{kpc})$ cells, for a fine grid of 400,000 total cells with over 16.9 million $L_{V}$, $r_{50}$ values representative of the $L_{V}-r_{50}$ distribution of early-type galaxies in the present-day universe. We illustrate this mock catalog by plotting its median $M_{V} - 5 \log_{10} h$ (with 16 and 84 percentile limits) as a function of $r$-band size in the left panel of Figure 7. As can be seen in Figure 6, the Shen et al. (2003) ridgeline provides a reasonable fit to the GEMS $L_{V}-r_{50}$ relations out to $z \sim 0.5$. At larger redshifts the relations start to deviate from the local power law, with the largest evolution appearing for the smallest galaxies. In any galaxy evolution scenario we expect that passive luminosity evolution of the stellar populations in galaxies must play a role. We use the mock catalog to study the evolution of the $L_{V}-r_{50}$ relation with redshift in the next section.

### 3.2. Luminosity Evolution at Fixed Galaxy Sizes

We now quantify the evolution seen in Figure 6, which can be interpreted in terms of passive evolution of an ancient stellar population. At a given fixed galaxy size, we measure the luminosity difference relative to the $z \sim 0$ relation as a function of redshift, accounting for selection effects. With the largest sample of size measurements for distant early types to date, we have the first opportunity to examine the evolution of these galaxies as a

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**Fig. 5.—Observed magnitude-size distributions for 928 red-sequence galaxies with robust GIM2D fits spanning redshifts $0.2 < z \leq 1.0$ split into eight $\Delta z = 0.1$ bins. In each panel we plot the half-light semimajor axis length $a_{50}$ and apparent total magnitude $m_{850}$ from Sérsic profile fits to the F850LP-band ACS imaging data. We show the expected uncertainties of the fit quantities with error bars at the upper left of each panel. We denote $n \geq 2.5$ galaxies with filled circles and those with $n < 2.5$ profiles with open squares. The PSF radius ($0.05$) is given by the dashed vertical line. We show the GEMS detection completeness contours from simulations of $n = 4$ spheroids ($H_{0.5}$). From right to left (lower to higher surface brightness), the contours mark the 10, 25, 50, 75, 90, and 95 percent completeness limits; white regions to the left of the contours represent 100% detection completeness. Our simulations are limited to artificial galaxies fainter than $m_{850} = 20$ mag, resulting in the sharp break in the completeness contours at this magnitude. We conclude that our early-type sample selection is not surface brightness–limited. For completeness, we include here the 69 stars misclassified as red-sequence galaxies by COMBO-17 (open stars); we remove these from our further analysis.**
function of their physical size. To this end we divide our sample into three broad size bins as shown in Figure 6, each with sample size in excess of 100, spanning the full range of typical sizes, namely, $0.5 < r_{50} \leq 1.0\ h^{-1}\ kpc$ (bin I); $1.0 < r_{50} \leq 2.0\ h^{-1}\ kpc$ (bin II); and $2.0 < r_{50} \leq 5.0\ h^{-1}\ kpc$ (bin III).

As we probe to farther distances, the $R_{ap} = 24\ mag$ redshift reliability cutoff corresponds to ever brighter luminosities (see Fig. 6). At this magnitude limit the completeness of our early-type sample goes to zero. At brighter magnitudes the completeness rises rapidly to $>90\%$ in most redshift intervals. The COMBO-17 survey includes a well-defined completeness map constructed from Monte Carlo simulations of the survey and its classification scheme (Wolf et al. 2001, 2003, 2004). Specifically, for red-sequence galaxies we have completeness factors as a function of $R_{ap}$ for each redshift interval. We have demonstrated in § 2.4 that the GEMS images of red-selected galaxies are not surface brightness–limited; therefore, the COMBO-17 map provides the selection function for our early-type sample. For brevity we denote the magnitude and redshift-dependent selection function as $S(M'_V, z)$. In each redshift slice of Figure 6 we show schematically the region of nonzero completeness ($open-ended\ rectangles$), and the additional isolated horizontal line represents the faint limit of the completeness map passively faded to $z = 0$. We show the physical size corresponding to the PSF radius ($0.05\ arcsec$) (vertical dashed line).

![Fig. 6.—Rest-frame luminosity-size relations for 728 early-type galaxies in eight redshift epochs spanning $0.2 < z \leq 1.0$. All galaxies have $n \geq 2.5$ profiles and red-sequence colors. In each panel we plot the physical size, from GIM2D fits to F850LP-band images (corrected to rest-frame $r$-band), against $I$-band absolute magnitude. The error bars shown at the bottom right of each panel give the 35% $r_{50}$ uncertainty, and the 10% (interpolated for $z < 0.7$) or 15% (extrapolated for $z > 0.7$) $M_V - 5 \log h$ uncertainties. The ridgeline for the $z \sim 0.1 - r_{50}$ relation for early types ($n \geq 2.5$) from Shen et al. (2003) is shown in each panel for comparison (diagonal line). The present-day ridgeline is the median $M_V - 5 \log h$ at each $r_{50}$ from our mock catalog (see Fig. 7, left). The vertical lines delineate the fixed-size bins: $0.5 < r_{50} \leq 1.0\ h^{-1}\ kpc$ (bin I); $1.0 < r_{50} < 2.0\ h^{-1}\ kpc$ (bin II); and $2.0 < r_{50} \leq 5.0\ h^{-1}\ kpc$ (bin III). The horizontal line attached to the vertical lines gives the faint limit of each redshift-dependent completeness map, corresponding to the $R_{ap} = 24\ mag$ COMBO-17 redshift reliability limit at each redshift interval. Therefore, the open-ended rectangles outline the nonzero completeness regions of $L_V, r_{50}, z$ space, and the additional isolated horizontal line represents the faint limit of the completeness map passively faded to $z = 0$. We show the physical size corresponding to the PSF radius (0.05) at each redshift (vertical dashed line).]
values that are distributed according to the luminosity function of SDSS-selected, red-sequence galaxies from Bell et al. (2004b). Likewise, the stellar mass values that follow the early-type, $g$-band light physical size. The medians in each panel represent the solid line Carlo sampling of the mock local distribution that has been subjected to the same (but passively faded) selection function as our observations. Therefore, for each GEMS galaxy with $z < 0.7$ (bin I); 227 with $z \leq 0.9$ (bin II); and 222 with $z \leq 1.0$ (bin III). We exclude 57 small (bin I) and seven medium (bin II) size early types (Fig. 8, open circles). We fit a line (using ordinary least-squares linear regression) to the $\Delta M_V$ evolution in each panel of Figure 8, constrained to intercept the origin ($z = 0, \Delta M_V = 0$). We limit this analysis to GEMS galaxies (filled circles) within each size bins out to a maximum redshift where the selection function is $\geq 50\%$ according to the mock $z \sim 0$ catalog for a passively fading scenario. Therefore, as outlined with open rectangles in Figure 6, we do linear fits to galaxy samples from the three size bins as follows: 102 with $z \leq 0.7$ (bin I); 227 with $z \leq 0.9$ (bin II); and 222 with $z \leq 1.0$ (bin III). We find significant luminosity evolution for early-type galaxies of all sizes, from $\sim 1.0$ mag for small ($0.5 < r_{50} \leq 1.0$ h$^{-1}$ kpc) systems between $z = 0.7$ and now, to $\sim 0.7$ mag for the largest galaxies between $z = 1.0$ and the present time. We note that the apparently large change in $L_{V}$-$r_{50}$ slope with redshift found in Figure 6 is due mostly to our selection function cutting lower luminosity galaxies at higher redshift. Nevertheless, once we correct for selection effects, the differing amounts of luminosity evolution in each size bin of Figure 8 does represent a significant change in $L_{V}$-$r_{50}$ slope with redshift not observed in previous studies.

In Table 1 we tabulate the slopes of the constrained linear fits to the luminosity evolution for each size bin. We repeat this analysis using passive fading of $S(M'_V, z)$ that is slightly stronger ($z_{\text{form}} = 2$, [Fe/H] = -0.1) and slightly weaker ($z_{\text{form}} = 5$, [Fe/H] = -0.3). In both cases the metallicities are changed in concert with the formation redshifts to reproduce the observed color evolution of the red sequence; see, e.g., Bell et al. (2004b) for more details.
evolution is statistically equivalent (<1 σ differences) between the analyses using three different passive fading parameters. In addition, we calculate ΔM_F values under the null hypothesis of no passive evolution. As Barger et al. (1998) pointed out, not including passive evolution of the luminosity cutoff (here defined by our completeness map) will underestimate the evolution. Nonetheless, even under the null condition we still find significant luminosity evolution in early-type galaxies of a given size. Furthermore, we find that the amount of evolution continues to vary between different fixed-size galaxy populations.

Last, we compare the constrained fit to the luminosity evolution with a fit that is not constrained to go through the z = 0, no evolution origin. For this test we use the same ΔM_F data based on the mock catalog selection with z_form = 3 passive fading assumed, and the same method including bootstrap estimation of dispersion. We plot the unconstrained fits with light-gray bands in each panel of Figure 8, and we provide the best-fit linear parameters (slope and z = 0 intercept) in Table 2. We point out that the intrinsic scatter in the ΔM_F, z correlation, and the fairly restricted redshift range over which we fit, both combine to produce a less well-constrained fit for the smallest galaxies compared with the two larger size bins. In all cases, significant fading of the early-type galaxy population at a given size is clearly detected, and for all but one case18 the difference in fading rates from small to large galaxies is preserved independent of assumptions regarding passive evolution and fitting method.

### Notes

18 We find one exception to the monotonic trend in slopes between the three size bins in the first row of Table 2; i.e., under the (likely unrealistic) assumption of no fading. Here the unconstrained fit to the luminosity evolution in size bin h has a negative (although statistically zero) offset at z = 0 resulting in a flatter slope than the constrained fit to the same data (given in Table 1), and an equivalent, rather than steeper, slope compared to size bin III.

### Table 1

| \( \Delta M_V \) | \( \Delta \log_{10}(M_V h^2/M_\odot) \) |
|----------------|---------------------------------|
| (1)            | (2)                             |
| Slope          |                                     |
| ΔM_V           | -1.23 ± 0.12                     |
|                | -1.68 ± 0.11                     |
|                | -1.60 ± 0.12                     |
| Δ log_{10}(M_V h^2/M_\odot) | +0.25 ± 0.05                  |
|                | +0.26 ± 0.06                     |
|                | +0.23 ± 0.05                     |

Notes.—We parameterize the amount of luminosity (mag units) or stellar mass (dex units) evolution with the least-squares slope from a best-fit linear relation to the given ordinate (col. [1]) as a function of redshift, constrained to no evolution at z = 0. For each galaxy size bin (I, II, and III), we give the best-fit slopes (cols. [2]–[4]), including their 1σ dispersions from bootstrap resampling. The number of galaxy measurements used in each fit are \( N_I = 102, N_{II} = 227, \) and \( N_{III} = 222 \). In col. (5) we list the different evolution analyses given by various fadings of the selection function (for luminosity evolution), and by various forms of the adopted stellar mass function (for stellar mass evolution).
The two methods of fitting luminosity evolution have different merits. The constrained fitting is anchored directly to $z = 0$, which allows the use of our full knowledge of the local universe. Furthermore, the constrained fits are quite robust as illustrated by the very narrow dispersion we find with bootstrap resampling. On the other hand, the unconstrained fits show clearly the differences between GEMS and SDSS photometric and size measurement calibrations, and for slight deficiencies in our treatment of selection effects; the $z = 0$ offset is $\lesssim 0.45$ mag in all size bins. Finally, we note that for each size bin the unconstrained fit cannot be statistically distinguished from the constrained fit; i.e., the slopes of the tightly constrained fits are always within $1-2\sigma$ of the unconstrained fit slopes (see Tables 1 and 2).

### 3.3. Stellar Mass–Size Relation

We turn our attention now to exploring the stellar mass evolution of GEMS early-type galaxies as a function of fixed size. In Figure 9 we present the $M_s$–$r_{50}$ relations for 728 early types in eight $\Delta z = 0.1$ redshift bins spanning $0.2 < z \leq 1.0$. As with $L_V$–$r_{50}$, the $M_s$–$r_{50}$ relations are quite apparent to at least $z \sim 0.8$.

In each panel of Figure 9 we display the $M_s$–$r_{50}$ relation ridgeline for $z \sim 0$ early-type galaxies from SDSS. Shen et al. (2003) showed that these galaxies also follow a lognormal size distribution of the same general form as equation (3) with a stellar mass dependence. These authors derived stellar masses from SDSS Petrosian luminosities using a model-dependent $M_s/L$ ratio from Kauffmann et al. (2003). For our adopted ($h$ is free parameter) cosmology, the local $M_s$–$r_{50}$ relation has characteristic median size

$$
\log_{10}(\bar{r}_{50}/h^{-1}\text{kpc}) = 0.56 \log_{10}(M_s/h^2/M_\odot) - 5.52,
$$

(6)

with lognormal dispersion

$$
\sigma(M_s/h^2) = 0.29 + \frac{0.53 \times 10^{10} M_\odot}{M_s/h^2},
$$

(7)

given in observed $r$-band size (S. Shen 2004, private communication). Recall that we show in § 3.1 that these sizes are within 1% of those in the rest-frame $r$-band.

Following the method in § 3.1, we create a mock catalog of $M_s$ and $r_{50}$ values that represent the $M_s$–$r_{50}$ distribution of early-type galaxies at $z \sim 0$ from Shen et al. (2003). Briefly, we construct a 400,000 cell grid of galaxy stellar masses and sizes that follow the lognormal distribution given by equations (6) and (7). The grid spans $8.8 < \log_{10}(M_s/h^2/M_\odot) < 12.8$ in 800 (0.005 dex) cells, and $0 < r_{50} < 25 h^{-1}$ kpc in 500 (0.05 $h^{-1}$ kpc) cells. We populate this grid to match the $g$-band–derived stellar mass function for local early-type galaxies from Bell et al. (2003). This mock catalog contains over 17.4 million $M_s$–$r_{50}$ values. We use this mock catalog to study the stellar mass evolution of early types as a function of redshift in the next section. In the right panel of Figure 7, we plot the median value of $\log_{10}(M_s/h^2/M_\odot)$, with its 16 and 84 percentile limits, against $r$-band size. This median provides the Shen et al. (2003) $M_s$–$r_{50}$ ridgeline that we compare to the observed relations at each redshift interval in Figure 9. Here we see that sizes and stellar masses of the GEMS early-type galaxies follow a correlation that is generally consistent with the local $M_s$–$r_{50}$ relation out to $z \sim 0.8$, where the COMBO-17 redshift reliability limit begins to cut into the observed relation. Under the assumption of simple passive luminosity evolution, we expect that galaxies of a given size will maintain a constant stellar mass. We investigate this expectation in the next section.

### 3.4. Stellar Mass Evolution at Fixed Galaxy Sizes

To directly compare any evolution in the luminosity and stellar mass of early types we must analyze the GEMS $M_s$–$r_{50}$ relation in an analogous manner to the $L_V$–$r_{50}$ relation. As with our luminosity evolution analysis of distant galaxies, we calculate how much the $M_s$–$r_{50}$ relation shifts with respect to the local Shen et al. (2003) relation, while accounting simultaneously for the selection effects of our observations. Just as the COMBO-17 redshift reliability limit at $R_{ap} = 24$ imposes an effective absolute magnitude cut at each epoch, the minimum stellar mass that a galaxy has in our sample increases with redshift as expected in a magnitude-limited sample (horizontal lines in each panel of Fig. 9). Therefore, for each redshift bin we determine the simple linear relation between $M_s$ and $R_{ap}$ for each galaxy to convert the COMBO-17 completeness map into a redshift-dependent selection function given as a function of logarithmic stellar mass; i.e., $S(\log_{10} M'_s, z)$, where $M'_s = (M_s/h^2/M_\odot)$. We apply $S(\log_{10} M'_s, z)$ to the $z \sim 0$ mock catalog as before, with one important difference—there is no need to correct the selection function for the effects of passive evolution because a passively evolving galaxy population is not expected to evolve in stellar mass.
We divide the sample into the same three fixed-size bins and for each GEMS early-type galaxy we calculate the stellar mass difference $\Delta \log_{10} M_0 = \log_{10} M_0(z) - \langle \log_{10} M_0(z) \rangle$, which is the difference (in log space) between the stellar mass of the galaxy observed at redshift $z$ and the average stellar mass of 100 galaxies of equivalent size drawn at random from the $z_0$ mock catalog (Fig. 7, right). We show the $M_0-r_{50}$ relation for $z \sim 0$ early types ($n \geq 2.5$) from Shen et al. (2003) in each redshift slice for comparison (diagonal line). Following the format of Fig. 6, we delineate the three fixed-size bins (I, II, and III) with vertical lines, and we depict the low-mass cutoff (horizontal lines) corresponding to the limit for reliable COMBO-17 redshifts ($R_{ap} = 24$ mag). Thus, the open-ended rectangles outline the noncompleteness regions of $M_0$, $r_{50}$, $z$-space. The physical size corresponding to the PSF radius ($0.05$ arcsec) at each redshift is shown by the vertical dashed line.

We divide the sample into the same three fixed-size bins and for each GEMS early-type galaxy we calculate the stellar mass difference $\Delta \log_{10} M_0 = \log_{10} M_0(z) - \langle \log_{10} M_0(z) \rangle$, which is the difference (in log space) between the stellar mass of the galaxy observed at redshift $z$ and the average stellar mass of 100 galaxies of equivalent size drawn at random from the $z \sim 0$ mock $M_0-r_{50}$ distribution, which is weighted by $S(\log_{10} M_0(z), z)$. Therefore, for each GEMS galaxy of a fixed size we find the present-day stellar mass from the mock catalog using the same selection as our observations. The mock catalog is based on a $g$-band mass function; below we discuss the effects that two other mass function estimates have on the local sample selection we use for this calculation.

To quantify any redshift evolution of the stellar mass of early-type galaxies, we fit lines to the $\Delta \log_{10} M_0$ values as a function of redshift following the same procedure as in §3.2. As before, we limit the analysis to the same subset of GEMS galaxies per fixed-size bin (see open rectangles marked I, II, and III in Fig. 9). In the three panels of Figure 10 we plot the linear fits to the stellar mass evolution constrained to have no evolution at $z = 0$. The red bands represent the best-fit and the 68 percentile distribution of fits (1σ dispersion) from 200 bootstrap resamples. We present the fit results in Table 1. We find a modest change in stellar mass for early-type galaxies in each size bin. For the two smaller size bins ($\leq 2 h^{-1}$ kpc) the stellar mass appears to have been somewhat larger in the past. Conversely, the largest early-type galaxies ($> 2 h^{-1}$ kpc) may have had slightly less stellar mass at earlier look-back times. We repeat the above analysis using local mock $M_0-r_{50}$ distributions that follow two additional stellar mass functions based on $K$-band ($r$-band concentration-selected) and $g$-band ($g-r$ color-selected; i.e., $g_{col}$) from Bell et al. (2003). As shown in Table 1, we find that the stellar mass evolution results are independent of the mass function we use to construct the present-day mock catalog.
Last, we repeat the linear regression analysis for the redshift evolution of \( \Delta \log_{10} M'_r \) (g-band–based), but in this case we allow the fit to be unconstrained. We present these results in the panels of Figure 10 using light-gray bands (see also Table 2). As with the constrained fits, the two smaller size bins show modest \( M_* / L \) evolution (here at the \( \sim 3 \sigma \) level). In contrast with the constrained fit for > 2 h\(^{-1}\) kpc galaxies, which has negative slope, the unconstrained slope is statistically flat; i.e., consistent with no stellar mass evolution as expected if large early-type galaxies contain passively-evolving stellar populations as suggested by the luminosity evolution (§ 3.2). However, we note again that for each size bin the unconstrained slopes are statistically indistinguishable (here at the 2 – 3 \( \sigma \) level) from the constrained fit slopes. Furthermore, the unconstrained fits for all size bins intercept the \( z = 0 \) axis with an offset of roughly -0.2 dex in \( M_* \). This 2 – 3 \( \sigma \) effect suggests that our mass scale is somewhat lighter than that of the SDSS, yet the offset is well within the systematic uncertainties of our stellar mass estimates (see § 2.2).

4. DISCUSSION

4.1. Comparison with Previous Work

Overall the evolution that we see for the \( L_V - r_{50} \) relation of different galaxy subsets is in good agreement with earlier, more restricted studies based on much smaller data sets. The large field of the GEMS survey (~15 h\(^{-1}\) Mpc on a side) permits us to come closer to a cosmologically representative “field” sample of early-type galaxies. In addition, the large sample size allows us for the first time to demonstrate that the strength of luminosity evolution, at a given size, depends inversely on early-type galaxy size (see constrained fits in Fig. 8): \( \Delta M_V / \Delta z \sim -1.6 \pm 0.1 \) for small galaxies (\( r_{50} \leq 1 \) h\(^{-1}\) kpc), \( \Delta M_V / \Delta z \sim -1.3 \pm 0.1 \) for medium-sized galaxies (1 < \( r_{50} \) \leq 2 h\(^{-1}\) kpc), and \( \Delta M_V / \Delta z \sim -0.7 \pm 0.1 \) for large galaxies (2 < \( r_{50} \) \leq 5 h\(^{-1}\) kpc).

Past work has been limited mostly to cluster environments (Barrientos et al. 1996; Pahre et al. 1996; Schade et al. 1997; Barger et al. 1998; Ziegler et al. 1999), where the increased densities provided reasonable sample sizes (\( N < 200 \)) within the small imaging field of WFPC2. These studies all found an increase in luminosity with look-back time (at a given size) of about 1 mag in rest-frame \( B \)-band per unit redshift. Allowing for the \( B \) versus \( V \)-band differences and comparing the evolution at comparable sizes (~3 h\(^{-1}\) kpc), we find in comparison no evidence for environmental differences in evolution.

Schade et al. (1999) and Trujillo & Aguerri (2004) have selected small early-type galaxy samples (\( N < 50 \)) with WFPC2 observations that are sampled from “field” environments at \( z < 1 \) in a way that should be statistically representative of the cosmic average, and found similar luminosity evolution for galaxies of a fixed size in the field as compared to clusters. For example, Trujillo & Aguerri found that small early-type galaxies in the HDFs were 1.35 ± 0.1 mag brighter in rest-frame \( V \)-band at \( z \sim 0.7 \) when compared to the present-day relation from Shen et al. (2003).

Taking into account the changes in \( M_* / L \) ratio that are implied by the color evolution of early-type galaxies in the last 8 Gyr, we find that the largely passive luminosity evolution of the \( L_V - r_{50} \) relation implies little or no evolution of the \( M_* - r_{50} \) relation since \( z \sim 1 \). Figure 10 shows that the average stellar mass in early-type galaxies of a given size has remained fairly constant over the interval 0 < \( z < 1 \). Concentrating on the constrained fits (see also Table 1), we see that galaxies smaller than 2 h\(^{-1}\) kpc may have been slightly more massive (0.25 and 0.11 dex, respectively, for small and medium sizes) at \( z \sim 1 \) than they are at the present, while larger galaxies may have been somewhat less massive. In general, our findings agree with those of Trujillo et al. (2004b), who found very little stellar mass evolution since \( z \sim 2.5 \) using a sample of 168 galaxies of all morphological types from the HDF-S. Moreover, the constrained fits to the \( M_* - r_{50} \) relation evolution are also qualitatively consistent with studies of the Kormendy relation (e.g., Barger et al. 1998), absorption lines (e.g., Ziegler & Bender 1997; Kelson et al. 2001), color-magnitude relation (e.g., Kodama et al. 1999; Bell et al. 2004b; Holden et al. 2004), and FP (e.g., Kelson et al. 2000; van Dokkum et al. 2001; Treu et al. 2002; van de Ven et al. 2003; Gebhardt et al. 2003; van der Wel et al. 2004), which all found changes in \( M_* / L \) consistent with passive evolution of the stellar populations in early-type galaxies since \( z \sim 1 \).
The unconstrained fits to the data in Figure 10 may indicate marginally significant evolution. In all cases, the observed trends within the redshift ranges probed by the data are 0.5 dex or less, in the sense that distant early-type galaxies may be denser than their low-redshift counterparts. This trend appears strongest for the $0.5 < z < 1.0$ $h^{-1}$ kpc sample, where we find the strongest evolution of the $L_V - r_{50}$ relation (Fig. 8, left). At this stage, it is difficult to reliably assess the significance of this possible evolution owing to systematic uncertainties of the $M_\ast/L$ ratios (which are 0.3 dex). In this context, it is interesting to note first results of a systematic study of the $0.7 < z < 1.1$ early-type galaxy FP by van der Wel et al. (2004); they found that dynamically derived $M/L$ ratios of six intermediate-redshift early-type galaxies showed a slightly stronger color-$M/L$ correlation than expected in a single-burst model. The most straightforward interpretation of this would be an increasing importance of bursts of star formation in low mass (therefore small) early-type galaxies; aging bursts bias color-based $M_\ast/L$ estimates high by up to 0.3 dex (Bell & de Jong 2001). Thus, the apparently strong evolution of the $M_\ast - r_{50}$ relation for small (low mass) galaxies could be enhanced artificially by the effect of bursts of star formation, whose frequency is naturally expected to be higher at earlier times.

4.2. Understanding the Evolution of Early-Type Galaxy Scaling Relations

Taken by themselves, the observed evolution of the $L_V - r_{50}$ and $M_\ast - r_{50}$ scaling relations is insufficient to constrain the characteristic evolutionary fates of individual early-type galaxies. For example, one can imagine morphological transformations and changes in star formation history caused by galaxy mergers, disk growth, and fading of previously star-forming disks that will cause galaxies to drift in and out of the early-type and/or red-sequence galaxy populations (e.g., Baugh et al. 1996; Steinmetz & Navarro 2002). Thus, evolution of the scaling relation of the populations should be interpreted in terms of the evolution of the early-type galaxy populations, rather than in terms of the evolution of the individual galaxies themselves.

Observationally, the results of this paper are consistent with passive evolution of the early-type galaxy population as predicted by the monolithic collapse scenario (Eggen et al. 1962; Larson 1974). This model describes the formation of present-day spherical systems through the collapse of a massive gas cloud followed by a brief burst of SF early in the history of the universe ($z_{\text{form}} > 2$). For this model any changes in the observed properties of early-type galaxies over time are due to simple passive fading of the coeval stellar populations.

Yet, a large number of works (Chen et al. 2003; Bell et al. 2004b; Drory et al. 2004; Cross et al. 2004; Conselice et al. 2005) have found that the total stellar mass density in early-type galaxies, defined either by color or morphology, has built up by roughly a factor of 2 in the last 8 Gyr since $z \sim 1$. Regardless of the mechanisms driving this evolution (e.g., mergers, disk fading, etc.), the lack of drastic evolution in the $M_\ast - r_{50}$ relation indicates that early-type galaxies to first order either move along the $M_\ast - r_{50}$ relation as they evolve, or they appear on it when they join the sample of early-type red sequence galaxies. The lack of strong evolution in the $M_\ast - r_{50}$ relation since $z \sim 1$ is an important constraint that early-type galaxy formation theories will have to satisfy.

It is interesting to note that both disk fading and galaxy mergers may naturally satisfy the observational constraints. It is possible that some disk-dominated galaxies with reasonably massive bulges cease to form stars at intermediate redshift (owing perhaps to gas consumption or removal of its gas supply). As the massive stars in the disk die, the disk fades very quickly, increasing greatly the prominence of the bulge. Under the assumption that the disk stellar mass--size correlation does not evolve with redshift (as justified by Trujillo et al. 2004b; Barden et al. 2005), and noting that the local disk and bulge stellar mass--size correlations are within 0.2 dex of each other over a wide stellar mass range (see Fig. 11 of Shen et al. 2003), it is quite possible that disk fading would produce early-type galaxies that adhere closely to the redshift-independent $M_\ast - r_{50}$ relation.

Another possible formation mode for early-type galaxies is through major galaxy mergers (e.g., Naab & Burkert 2003; Khochfar & Burkert 2003), where the remnant has suffered violent relaxation and is spheroidal and pressure-supported (Toomre & Toomre 1972; Barnes 1992). Detailed studies of close pairs have shown that an important fraction of $\sim L^*$ galaxies may merge between $z \sim 1$ and the present day (Carlberg et al. 1994; Le Fèvre et al. 2000; Patton et al. 2002; Conselice et al. 2003), making this a potentially important formation mode for early-type galaxies. Yet, it is unclear whether a merger between two gas-rich galaxies will lead to a remnant that will satisfy our observed lack of significant evolution in the $M_\ast - r_{50}$ correlation (see, e.g., Barnes 2002, for a systematic study of gas-rich galaxy mergers; unfortunately the relationship between progenitor and remnant size was not explored in this work).

Mergers between gas-poor progenitors are easier to model, and numerous studies have found that merging early-type galaxies will produce remnants that adhere reasonably well to the FP, but slowly drift away from the $M_\ast - r_{50}$ relation of the progenitor population (Navarro 1990; Dantas et al. 2003; Nipoti et al. 2003; González-García & van Albada 2003; Shen et al. 2003). Nipoti et al. (2003) and Navarro (1990) showed that $\log_{10}(M_{\text{remnant}}/M_{\text{original}}) \sim 1.1 \log_{10}(M_{\text{remnant}}/M_{\text{original}})$; that is, one dissipationless 1:1 merger will lead to a size increase of $\sim 0.33$ dex. For a factor of 2 increase in stellar mass, the $M_\ast - r_{50}$ relation (e.g., eq. [6]) shows a $\sim 0.17$ dex increase in size. Thus, galaxies undergoing dissipationless merging will gradually move toward radii that are larger than galaxies not undergoing merging.

As outlined earlier, dissipationless merging is expected to be a much more important process for high-mass galaxies (Khochfar & Burkert 2003). Therefore, we can focus on the evolution of the $M_\ast - r_{50}$ relation for galaxies with $2 < r_{50} < 5$ $h^{-1}$ kpc—here the observations place an upper limit of 0.14 dex (unconstrained fit) on the evolution of the $M_\ast - r_{50}$ relation zero point since $z \sim 1$, and show a scatter of $\sim 0.5$ dex. Therefore, combining the model predictions (that one major merger will move a remnant 0.16 dex from the $M_\ast - r_{50}$ relation defined by the progenitor population) and the observational upper limits on $M_\ast - r_{50}$ relation evolution and scatter, we conclude that the most massive galaxies have suffered at most one major dissipationless merger since $z \sim 1$ on average (from the zero-point evolution), and that only a small fraction of massive early-type galaxies could have suffered several major dissipationless mergers (from the scatter). We note that the constrained fit to the $M_\ast - r_{50}$ relation evolution for the largest early-type galaxies has negative slope, which would result in a lower average merger rate. In either case, these data place a limit of $< 1$ equal-mass merger on average over the last half of cosmic time for large galaxies.

4.3. Strength of Luminosity Evolution Dependence on Galaxy Size

It is worth discussing briefly the size dependence in the evolution of the $L_V - r_{50}$ relation apparent in Figure 8. Focusing on the largest early-type galaxies with $2 < r_{50} \leq 5$ $h^{-1}$ kpc, we find that the intercept of the $L_V - r_{50}$ relation is $\sim 0.7$ mag brighter at $z \sim 1$, compared to the present day. In contrast, smaller galaxies...
evolve more rapidly toward the present; extrapolated to \( z \sim 1 \), we find 1.5–2 mag of evolution in the \( L_{V} - r_{50} \) relation.

This difference in evolution is statistically significant, thus leaving two possible classes of interpretation: (1) smaller galaxies have significantly younger luminosity-weighted stellar ages, leading to significantly more rapid luminosity evolution; and (2) there is scale-dependence in the evolution of the \( M_{*} - r_{50} \) relation related to different formation routes for low- and high-mass early-type galaxies. At some level, both effects should contribute; we conclude here that we cannot at this stage differentiate between these two possibilities.

The interpretation that smaller galaxies have younger stars compared to the larger systems, is consistent with recent deep determinations of galaxy cluster CMRs at \( 0.8 \leq z \leq 1 \) (Kodama et al. 2004; de Lucia et al. 2004), where the faint end of the red sequence is systematically suppressed compared to the local universe.\(^{20}\) This is also consistent with analyses of the stellar populations and dynamically derived \( M/L \) ratios of morphologically selected early-type galaxies in the local universe (Kuntschner 2000; Trager et al. 2000; Thomas et al. 2005), and at \( z \sim 1 \) (van der Wel et al. 2004), where low-mass early-type galaxies have younger stellar populations than high-mass early types. In this interpretation, one expects that the bulk of the slope evolution in the \( L_{V} - r_{50} \) relation is driven by the rapid evolution in \( M_{*}/L \) ratios of low-mass galaxies, compared to their older high-mass counterparts.\(^{21}\)

There is also evidence from studies of local early-type galaxies that low-mass early-types have different properties than high-mass early-type galaxies (Kormendy & Bender 1996; Gebhardt et al. 1996; Faber et al. 1997; Ravindranath et al. 2001). Stereotypical high-mass early-type galaxies have boxy isophotes, steep outer light profiles, constant surface brightness (or “cuspy”) cores, and are supported primarily by random motions of stars in a triaxial potential. In contrast, lower mass early-type galaxies tend toward disky isophotes, steep power-law light profiles without a resolved core, and derive partial support from organized rotation. These differences in properties are naturally interpreted in terms of different formation mechanisms, where higher mass early-type galaxies suffer from late dissipationless major mergers and lower mass early-type galaxies result from lower mass-ratio interactions and/or mergers of galaxies with significant gas contents (Naab & Burkert 2003; Khochfar & Burkert 2003). It is also possible that some low-mass early-type galaxies could form through disk instabilities in small, very high surface density disks (see, e.g., Cole et al. 2000, for one implementation of this process). Interpreted in this way, the evolution of the slope of the \( L_{V} - r_{50} \) relation could be attributed primarily to genuine evolution in the \( M_{*} - r_{50} \) relation, and differences in the rate of \( M_{*}/L \) evolution as a function of stellar mass may play a secondary role.

Viewed in this context, the slight differences in stellar mass evolution (Fig. 10) as a function of size suggests that it is impossible to rule out scenario 2 at this stage. Yet, the earlier discussion made it clear that within the uncertainties inherent to the estimation of \( M_{*}/L \) from optical SEDs, it is impossible to convincingly argue against or in favor of changes in the \( M_{*} - r_{50} \) relation. Therefore, we conclude that disentangling the relative importance of the above two mechanisms in driving the redshift-dependent slope of the \( L_{V} - r_{50} \) relation is impossible at this time. Future works, utilizing larger samples with spectroscopic redshifts and velocity dispersions, will clarify this issue considerably.

5. CONCLUSIONS

In order to place constraints on the processes driving early-type galaxy evolution at \( z \leq 1 \), we have analyzed the evolution of the luminosity-size and stellar mass–size relations using a sample of 728 early-type galaxies with \( 0.2 < z \leq 1.0 \) from the GEMS survey in the ECDF-S. The sample was selected to have concentrated light profiles with Sérsic \( n \geq 2.5 \) and rest-frame optical colors within 0.25 mag of the red-sequence ridge at its epoch. At a given half-light radius \( r_{50} \), early-type galaxies were more luminous in the past. Selection effects were carefully accounted for throughout using detailed completeness maps derived for the parent COMBO-17 photometric redshift catalog. We find that the \( L_{V} - r_{50} \) relation has evolved in a manner that is consistent with the passive aging of ancient stellar populations. In addition, we find evidence for an evolving tilt of the \( L_{V} - r_{50} \) relation, in the sense that smaller galaxies fade more rapidly toward the present day than larger galaxies. Using \( M_{*}/L \) ratios derived from the COMBO-17 SEDs, we rule out any substantive evolution in the \( M_{*} - r_{50} \) relation, also consistent with the simple passive evolution scenario.

Clearly, these results would be consistent with passive evolution of the early-type galaxy population (i.e., passive aging of existing stars, no merging), where a younger age for smaller galaxies is indicated by the tilting \( L_{V} - r_{50} \) relation. Yet, this interpretation is too simplistic; a number of surveys have demonstrated that the total stellar mass in the early-type galaxy population (as defined here) has increased by roughly a factor of 2 since \( z \sim 1 \). Bearing in mind this evolution, our results imply that newly added early-type galaxies follow \( L_{V} - r_{50} \) and \( M_{*} - r_{50} \) relations similar to the more established early types. A disk-fading origin for the newly added early-type galaxies appears to be consistent with the data. Through comparison with models, the role of dissipationless merging is limited to \( < 1 \) major merger on average since \( z = 1 \) for the most massive galaxies. The predicted evolution for gas-rich mergers is not yet robustly predicted, so it is impossible to comment on this possible formation route. In this context, the evolving tilt of the \( L_{V} - r_{50} \) correlation could reflect a different origin of low-mass early-type galaxies and/or younger stellar populations; the present data are insufficient to discriminate between these possibilities.

We are extremely grateful to Shiyin Shen for providing \( r \)-band lognormal size distributions as a function of stellar mass, and for helpful discussions regarding his all-important local scaling relations from SDSS. For productive discussions we thank Rose Finn, Kelly Holley-Bockelmann, Neal Katz, Dušan Kereš, Ari Maller, Houjun Mo, and Ignacio Trujillo. Support for the GEMS project was provided by NASA through grant number GO-9500 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. for NASA, under contract NAS5-26555. D. H. M. and S. J. acknowledge support from the National Aeronautics and Space Administration (NASA) under LTSA grant NAG5-13102 (D. H. M.)

\(^{20}\) It is worth noting that one may well expect a change in CMR slope with redshift if low-mass galaxies are on average younger.

\(^{21}\) It is interesting to speculate that owing to biased galaxy formation (in the sense that the central parts of high-mass halos collapse at higher redshift than the central parts of lower mass halos), one may expect a mild dependence of age on mass, under the assumption that one can suppress late cooling in early-type galaxy halos. One may expect to see an age difference between cluster and field early-types in this interpretation; the observational evidence in this regard is controversial, and the most fair statement that can be made is that if there is an age difference as a function of environment, then this dependence is rather weak (e.g., Bernardi et al. 1998; Hogg et al. 2003).
and NA65-13063 (S. J.) issued through the Office of Space Science. E. F. B. and S. F. S. acknowledge financial support provided through the European Community’s Human Potential Program under contracts HPRN-CT-2002-00316, SISCO (E. F. B.), HPRN-CT-2002-00305, and Euro3D RTN (S. F. S.). K. J. is supported by the German DLR under project number 50 OR 0404. C. W. is supported by a PPARC Advanced Fellowship. C. H. acknowledges support from GIF.

APPENDIX

SÉRISCI FITS

For our primary analysis we use GIM2D (Simard et al. 1999, 2002) to fit a single Sérsic model to the two-dimensional radial light profile of each galaxy from the F850LP imaging. The GIM2D software takes the PSF into account by convolving it with the best-fit model profile during fitting, and it uses the SExtractor-produced segmentation mask to deblend galaxies from nearby companions. The profile fits provide information that allow us to select morphologically early-type galaxies from the red sequence (as described in § 2.3.2). In addition, effective size (i.e., half-light radii $r_{50}$; see § 2.4) measurements and other structural parameters are provided by the Sérsic fitting.

Galaxy profile fitting requires a well-defined model of the PSF and precise knowledge of the background sky level. We use a universal, high S/N PSF derived from 548 bright but unsaturated stars from the Mark I suite of GEMS ACS frames in the F850LP passband (for a first impression, see Jahnke et al. 2004; K. Jahnke et al. 2005, in preparation). Through detailed testing we find that this PSF provides sufficient accuracy for the galaxy fitting (H05). Moreover, with our simulations we explore three different methods for determining sky values: (1) using the SExtractor sky value “local” to each galaxy; (2) adopting a fixed constant value per individual ACS frame given by the SExtractor “global” estimate; and (3) letting GIM2D calculate the mean sky. We find that the Sérsic fitting results are most robust when using the first method, bearing in mind that other local sky estimates may perform equally well or better.

The Sérsic model is represented by seven free parameters: total intensity, semimajor axis scale length, ellipticity $e$, position angle, index $n$, and model $x, y$ centering. For each galaxy fit, GIM2D automatically determines the initial values and limits for the parameter space to be explored by using the segmentation mask, which is affected by the choice of detection configuration (see § 2.1). With our simulations (H05) we find that this method provides reliable fits for $>90\%$ of galaxies within the range of magnitudes and sizes probed by our early-type sample.

We check the fits using a variety of tests. First, we check the recovered ellipticity of each fit and find no trends with redshift or total $n_{850}$ magnitude. Likewise, the Sérsic $n$ distributions show no trends with $z$ or $m_{850}$ for galaxies with $n \geq 2.5$. As expected, we see a slight trend such that highly inclined sources have low $n$ values (i.e., disk-dominated), and large $n$ values are more often less inclined. Last, we compare the GIM2D total $m_{850}$ magnitudes with the model-independent determinations from SExtractor (mag_best). We find a median offset of 0.29 mag (independent of brightness) with a dispersion of 0.18 mag, in the sense that GIM2D recovers total $m_{850}$ magnitudes from all fixed-size bins out to $z \sim 1$. We note that the majority of galaxies have E/S0 visual morphologies, and that an inspection of the fit residuals shows that the fitting does a fair job recovering the flux and overall profile shape. The fitting results presented here ($r_{50}$ sizes and Sérsic indices) will be published in their entirety by B. Häußler et al. (2005, in preparation).

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