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MORPHOLOGICAL EVOLUTION AND THE AGES OF EARLY-TYPE GALAXIES IN CLUSTERS

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ABSTRACT

Morphological and spectroscopic studies of high redshift clusters indicate that a significant fraction of present-day early-type galaxies was transformed from star forming galaxies at $z < 1$. On the other hand, the slow luminosity evolution of early-type galaxies and the low scatter in their color-magnitude relation indicate a high formation redshift of their stars. In this paper we construct models which reconcile these apparently contradictory lines of evidence, and we quantify the effects of morphological evolution on the observed photometric properties of early-type galaxies in distant clusters. We show that in the case of strong morphological evolution the apparent luminosity and color evolution of early-type galaxies are similar to that of a single age stellar population formed at $z = \infty$, irrespective of the true star formation history of the galaxies. Furthermore, the scatter in age, and hence the scatter in color and luminosity, is approximately constant with redshift. These results are consequences of the "progenitor bias": the progenitors of the youngest low redshift early-type galaxies drop out of the sample at high redshift. We construct models which reproduce the observed evolution of the number fraction of early-type galaxies in rich clusters and their color and luminosity evolution simultaneously. Our modelling indicates that ~ 50 % of early-type galaxies were transformed from other galaxy types at $z < 1$, and their progenitor galaxies may have had roughly constant star formation rates prior to morphological transformation. The effect of the progenitor bias on the evolution of the mean M/L ratio and color can be estimated. The progenitor bias is a linear function of the scatter in the color-magnitude relation produced by age variations, and is maximal if the observed scatter is entirely due to age differences. After correcting the observed evolution of the mean M/L_B ratio for the maximum progenitor bias we find that the mean luminosity weighted formation redshift of stars in early-type galaxies $\langle z_* \rangle = 3.0^{+0.9}_{-0.5}$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$, and $\langle z_* \rangle = 2.0^{+0.3}_{-0.2}$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. Our analysis places the star formation epoch of early-type galaxies later than previous studies which ignored the effects of progenitor bias. The results are consistent with the idea that (some) Ly-break galaxies are star forming building blocks of massive early-type galaxies in clusters.

keywords galaxies: evolution, galaxies: elliptical and lenticular, cD, galaxies: structure of, galaxies: clusters

1. INTRODUCTION

Early-type galaxies (elliptical and S0 galaxies) constitute ~ 80 % of the galaxy population in the central regions of nearby rich clusters (Dressler 1980), and studies of nearby and distant clusters have provided strong constraints on their evolution and formation.

The cluster observations have been used to constrain the stellar ages of early-type galaxies. On one hand, there is very good evidence that early-type galaxies form a very homogeneous, slowly evolving population: the scatter in their colors is small, both at low redshift (e.g., Bower, Lucey, & Ellis 1992), and at high redshift (Ellis et al. 1997; Stanford, Eisenhardt, & Dickinson 1998), the scatter in their mass-to-light ratios is equally small (e.g., Lucey et al. 1991, Pahre, Djorgovski, & de Carvalho 1998, Kelson et al. 2000), and the evolution of their mass-to-light ratios is slow (van Dokkum & Franx 1996, Kelson et al. 1997, Bender et al. 1998, van Dokkum et al. 1998a). These results indicate a very high redshift of formation for the stars in early-type galaxies. As an example, van Dokkum et al (1998a) found from the evolution of the Fundamental Plane relation to $z = 0.83$ that the stars in massive early-type galaxies must have formed at $z > 2.8$ for $\Omega_m = 0.3$, $\Omega_\Lambda = 0$, and a Salpeter (1955) IMF. Furthermore the low scatter in colors and M/L ratios implies that the scatter in ages at any redshift is very small (e.g., Ellis et al. 1997, Stanford et al. 1998).

On the other hand, evidence is accumulating that many early-type galaxies in clusters were relatively recently transformed from star forming galaxies. Dressler et al. (1997) report a high fraction of spiral galaxies in clusters at $0.3 < z < 0.5$. These galaxies are nearly absent in nearby rich clusters (Dressler 1980), and hence must have transformed into early-type galaxies between $z = 0.5$ and $z = 0$. Other studies (e.g., Couch et al. 1998, van Dokkum et al. 2000) have confirmed this trend, and extended it to $z = 0.8$. Dressler et al. (1997) found that the increased fraction of spiral galaxies at high redshift was accompanied by a low fraction of S0 galaxies, and concluded that the $z \approx 0.4$ spiral galaxies transformed into S0 galaxies. Other studies have found evidence for merging and interactions in high redshift clusters (Lavery & Henry 1988; Lavery, Pierce, & McClure 1992; Dressler et al. 1994; Couch et al. 1998; van Dokkum et al. 1999). These transformations may provide a way to form young elliptical galaxies in the clusters at late times. The morphological evidence for recent and rapid evolution in the cluster galaxy population is supported by photomet-

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ric and spectroscopic studies, which have found a significant increase of the number fractions of star forming and post star burst galaxies from $z = 0$ to $z = 1$ (e.g., Butcher & Oemler 1978, 1984, Dressler & Gunn 1983, Couch & Sharples 1987, Postman, Lubin, & Oke 1998, Poggianti et al. 1999, van Dokkum et al 2000). Hence the evidence appears secure that many early-type galaxies in clusters were transformed from star forming galaxies at fairly recent times.

The purpose of this paper is to produce models which can bring these apparently different lines of evidence regarding the ages into agreement. Specifically, we analyse the effects of late morphological transformations as found by Dressler et al., and others, on the observed evolution of colors and luminosities with redshift. We show that the effect of "progenitor bias" (Franx & van Dokkum 1996; van Dokkum et al. 2000) can be very significant: if early-type galaxies were transformed from other galaxy types at late times, the youngest progenitors of present-day early-type galaxies drop out of the sample of early-type galaxies at high redshift. Hence the samples of galaxies at low and high redshift are not the same, and in particular, the high redshift samples might be biased towards the oldest progenitors of present-day early-type galaxies. The purpose of this paper is to quantify the effects of progenitor bias, and to estimate the corrections which are required for models which ignore morphological evolution. To that end, we construct relatively simple models for the history of star formation and morphological type of cluster early-type galaxies. We show that the observed slow luminosity evolution and low scatter in the color-magnitude relation and the Fundamental Plane are natural consequences of recent and ongoing assembly of early-type galaxies. We correct the observed evolution for the progenitor bias, and derive the corrected mean age of the stars in early-type galaxies.

Our models are extensions of the earlier work by van Dokkum et al (1998b), Bower et al. (1998), and Shioya & Bekki (1998). These authors considered complex star formation histories of cluster galaxies, but did not investigate the effects of morphological transformations on the observed properties of early-type galaxies at high redshift. The progenitor bias is implicitly included in the very detailed semi-analytical models by, for example, Kauffman & Charlot (1998) and Baugh, Cole, & Frenk (1996). In these complex models it is difficult to isolate and quantify specific effects, such as the progenitor bias. The main contribution of our work is that we use simple analytic models with only three free parameters, which allows us to provide explicit estimates for the effects of morphological evolution on the observed colors and luminosities of early-type galaxies.

2. MODELING

We construct simple models for the evolution of early-type galaxies, which parameterize both their star formation history and morphological evolution. Our models allow the full history to be quantified by three parameters. They are not based on a full physical description of the formation and evolution of galaxies as derived by, e.g., Kauffmann, White, & Guiderdoni (1993) and Baugh et al. (1996).

2.1. *Basic Description*

We assume that early-type galaxies have similar histories of star formation and morphology. The history of each individual galaxy can be described by three parameters: the time when star formation starts, the time when star formation stops, and the variation of star formation between the start and end. The star formation is allowed to increase or decrease with time. It is assumed that the galaxy is classified as an early-type galaxy some time after the cessation of starformation. We assume that the galaxies do not stop their star formation at the same time, but rather have a distribution of cessation times.

This description is fairly generic for many detailed theories of galaxy formation. We do not define the processes driving the morphological transformation and the cessation of star formation. Various processes have been invoked, including gas stripping of spiral galaxies (e.g., Gunn & Gott 1972, Tytler & Vidal 1978, Abadi, Moore, & Bower 1999, Kodama & Smail 2000), tidal interactions (e.g., Fried 1988, Moore et al. 1996), and mergers (e.g., Lavery et al. 1992, van Dokkum et al. 1999). It does not matter in our analysis what process causes the cessation of star formation, and we allow for bursts of star formation to accompany this event.

The transition phase between star forming galaxy and early-type galaxy is assumed to last for a significant time. Immediately after the cessation of star formation galaxies are likely to show tidal features (in case of an interaction or merger), or weak spiral arms. The morphologies of "E+A" or post star burst galaxies seem to be consistent with this scenario. They generally are classified as early-type spirals or tidally distorted systems (Poggianti et al. 1999; Fabricant et al. 2000; van Dokkum et al. 2000). It is not well known how long it takes before these structures fade or disperse; we assume that early-type galaxies are first classified as such ~ 1.5 Gyr after star formation in their progenitors ceased.

In the current Section we do not specify whether the models apply to elliptical galaxies, S0 galaxies, or both. Observationally, the early-type galaxy fraction is more robust than the relative numbers of elliptical galaxies and S0 galaxies (e.g., Fabricant, Franx, & van Dokkum 2000, van Dokkum et al. 2000). If different histories apply to the two classes of galaxies, two separate models will be needed for each sub-class. We explore such models in Section 5.

The generic effects of late morphological transitions are illustrated in Fig. 1. In panel (a), the evolution of the mass-to-light ratio is shown for a population of galaxies with a small range in age, without any late morphological transitions. As can be seen, galaxies with young stellar populations evolve more rapidly than galaxies with old stellar populations, and hence the spread in M/L ratios increases with redshift (panel b). The mean evolution is faster than that of a single age population formed at $z = \infty$, which is indicated by the dashed line in (b). This type of modelling has been used extensively to constrain the ages of early-type galaxies in clusters: if there are no morphological transitions, the evolution of the mean color or luminosity constrains the mean age of early-type galaxies, and the scatter constrains the spread in ages (e.g., Bower, Lucey, & Ellis 1992, Ellis et al. 1997, van Dokkum et al. 1998(a,b), Bower et al. 1998, Stanford et al. 1998, Ferreras & Silk 2000).

In panel (c), a model is shown in which galaxies are transformed into early-type galaxies at a constant rate. The broken lines indicate galaxies before they are recognized as early-type galaxies. It can easily be seen that the sample of early-type galaxies at high redshift is a small subsample of all galaxies which are classified as early-type galaxies at $z = 0$. The two samples are therefore not directly comparable, and erroneous

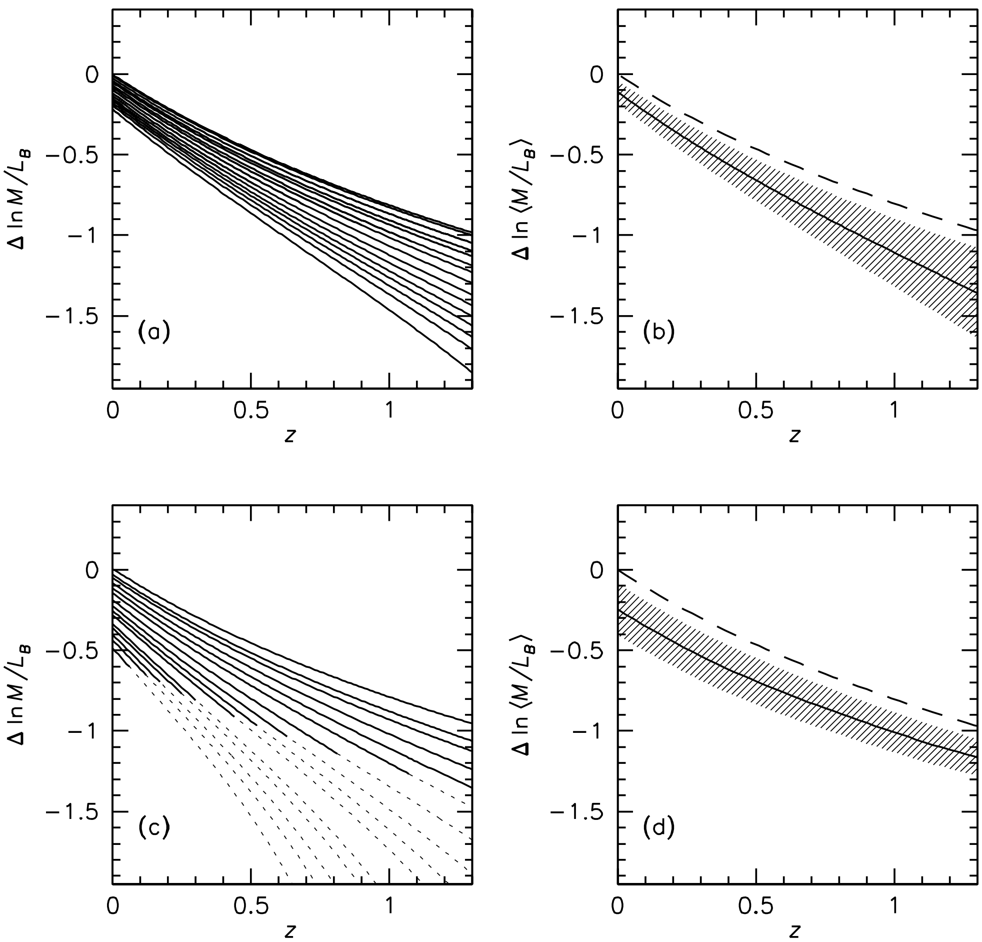

Fig. 1.— Illustration of the evolution of early-type galaxies in traditional models (a,b) and in models with morphological evolution (c,d). Lines in (a) and (c) show the evolution of individual galaxies, with a range of ages. The dashed sections of the curves in (c) indicate that the galaxies are not yet recognized as early-type galaxies. Panels (b) and (d) show the evolution of the mean M/L ratio in these two models. The scatter is indicated by the width of the hatched regions. The dashed line shows the evolution of a single age stellar population formed at $z = \infty$. In models with morphological evolution the mean M/L ratio evolves slowly and the scatter is roughly constant, because more and more young galaxies drop out of the sample at high redshift.

results are derived if morphological evolution is ignored. As a result, the evolution in the mean M/L ratio of the early-type galaxies is very slow (panel d). The slope of the $M/L - z$ relation is comparable to the slope for a single stellar population which formed at $z = \infty$ (indicated by the dashed line), even though the mean formation redshift of the stars in all early-type galaxies at $z = 0$ is low at $\langle z_* \rangle \approx 2$. Even more remarkable is the fact that the scatter in M/L ratios is virtually constant. These effects are caused by the fact that the youngest galaxies continuously drop out of the sample going to higher redshifts. In the subsections below we specify a broader range of models, and explore the consequences.

2.2. *Model Parameters and Methodology*

The full models are quantified by three parameters: $t_{\rm start}$, the time when star formation starts, $\tau_{\rm stop}$, the time scale which characterizes the distribution of times when star formation stops, and f_*, which describes the star formation rate between the start and end of star formation. The last two parameters are defined in the following way.

The parameter $\tau_{\rm stop}$ determines the probability distribution of $t_{\rm stop}$, the time when star formation stops for an individual galaxy:

$$P(t_{\rm stop}) \propto \exp\left(-\frac{t}{\tau_{\rm stop}}\right). \qquad (1)$$

We show later that this expression can provide a satisfactory fit to the data. If $\tau_{\rm stop} \ll t_0$, with t_0 the present age of the Universe, star formation in the progenitors terminated at very high redshift. At the other extreme, $\tau_{\rm stop} = \infty$ corresponds to a constant transformation rate. For each individual galaxy, the morphological transformation to early-type galaxy occurs at $t_{\rm stop} + 0.1t_0$, i.e., ~ 1.5 Gyr after truncation of star formation.

The parameter f_* characterizes the variation of the star formation rate. The star formation history of the galaxies can include bursts, and increasing or decreasing continuous formation rates as a function of time. After star formation ceases, the luminosity and color evolution of such a complex population is well approximated by a single age population of stars with the same luminosity weighted mean age (e.g., van Dokkum et al. 1998b).

Hence for each galaxy we approximate the evolution of the complex population by that of a single age population formed at $t = t_*$, with

$$t_* = f_* t_{\rm stop} + (1 - f_*) t_{\rm start}. \qquad (2)$$

For $f_* \approx 1$, the stellar population is dominated by a burst at the end of the star formation history, and for $f_* \approx 0$ the population is dominated by a burst at the start of the star formation history. If the star formation rate is approximately constant from $t = t_{\rm start}$ to $t = t_{\rm stop}$, then $f_* \approx 0.5$.

We tested the accuracy of our approach by calculating the luminosity and color evolution of galaxies with complex star formation histories (e.g., an exponentially declining star formation rate followed by a star burst), and comparing the results to predictions from single burst models with the same values of f_*. After transformation to early-type galaxy (i.e., > 1.5 Gyr after star formation has ceased) our approximation of luminosity and color evolution is accurate to a few percent. Three possible star formation histories of early-type galaxies are shown in Fig. 2. The model with $f_* = 0.7$ has a star burst at the end of its star formation history, and may be appropriate for spiral galaxies falling into clusters, or mergers. Although these histories are quite complex, $\gtrsim 1.5$ Gyr after star formation has ceased their evolution is similar to that of single age stellar populations formed at $t_* = f_* t_{\rm stop} + (1-f_*) t_{\rm start}$.

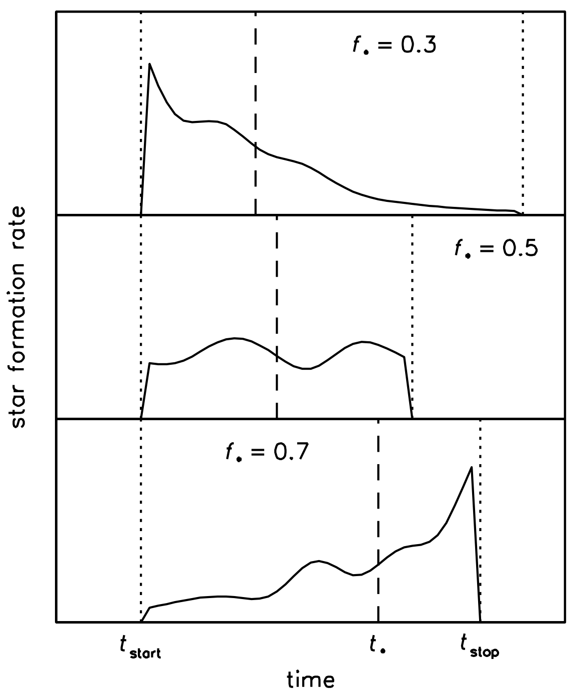

Fig. 2.— Illustration of our parameterization. Galaxies start forming stars at $t_{\rm start}$, and star formation terminates at $t_{\rm stop}$. Galaxies do not stop their star formation at the same time, but have a distribution of cessation times, parameterized by the transformation timescale $\tau_{\rm stop}$. The star formation history between $t_{\rm start}$ and $t_{\rm stop}$ can be quite complex, and may include star bursts. It is parameterized by the parameter f_*, which describes whether star formation is more weighted towards $t_{\rm start}$ or $t_{\rm stop}$.

Our parameterization allows straightforward computation of luminosities and colors of galaxies, because the luminosity evolution of a single age stellar population can be approximated by a power law (e.g., Tinsley 1980, Worthey 1994). Therefore, to good approximation,

$$L \propto \frac{1}{(t-t_*)^{\kappa}}. \qquad (3)$$

The coefficient κ depends on the passband, the IMF, and the metallicity. In this paper we will limit the discussion to rest frame B band luminosities, and rest frame $U-B$ colors. Our results can easily be expressed in other (rest frame) bands. The Worthey (1994) models give $\kappa_B = 0.91$ and $\kappa_U = 1.07$ for solar metallicity and a Salpeter (1955) IMF. The color evolution can be approximated by

$$\frac{L_B}{L_U} \propto (t-t_*)^{\kappa_U - \kappa_B}. \qquad (4)$$

Expressed in magnitudes, color and luminosity evolution are related through

$$\begin{aligned} \Delta(U-B) &= (\kappa_U - \kappa_B)\kappa_B^{-1} \Delta B \qquad (5)\\ &\approx 0.18 \Delta B \qquad (6) \end{aligned}$$

in these models. The evolution of the mean color and scatter in the color will therefore be similar to the scaled evolution of the mean M/L ratio and its scatter.

In the following, we use Monte-Carlo simulations to calculate model predictions for given values of $\tau_{\rm stop}$, f_*, and $t_{\rm start}$. This approach has the advantage that the mean and scatter in colors and luminosities at a given time can be computed using the same methods as for the observations. In the simulations, all galaxies start out as star forming objects at $t = t_{\rm start}$. Each galaxy is assigned a value for $t_{\rm stop}$, the time when star formation ceases. The distribution of $t_{\rm stop}$ is given by Eq. 1, with boundary condition $0 < t_{\rm stop} < 0.9 t_0$, with t_0 the present age of the Universe. At each timestep t, objects which satisfy the condition $t_{\rm stop} + 0.1 t_0 < t$ are selected as early-type galaxies. Using Eq. 3 and 4 these galaxies are assigned a luminosity and a color. The central value and the spread of the color and luminosity distribution at time t are calculated with the biweight statistic (Beers, Flynn, & Gebhardt 1990). This statistic was also used by Stanford et al. (1998) and van Dokkum et al. (1998b, 2000) to calculate the scatter in the high redshift color-magnitude relation. We note that the evolution of the mean M/L ratio and colors of early-type galaxies can also be evaluated analytically. In Appendix A we give approximate expressions which can be used for most applications.

2.3. *Examples of Models with Progenitor Bias*

We calculate the predicted evolution of the M/L ratio and its scatter for several models. To demonstrate the effects of progenitor bias we consider two classes of models, one with mild morphological evolution ($\tau_{\rm stop} = 0.2 t_0$) and one with strong morphological evolution ($\tau_{\rm stop} = 0.5 t_0$). Figure 3 shows the results.

In models with $\tau_{\rm stop} = 0.2 t_0$ morphological evolution is not very important to $z = 1$, and $\approx 80\,\%$ of present-day early-type galaxies were already in place at that redshift. In models with $\tau_{\rm stop} = 0.5 t_0$, on the other hand, only $\approx 50\,\%$ of early-type galaxies were in place at $z = 1$. In all panels of Fig. 3 broken lines show the class of models with mild morphological evolution, and solid lines show models with strong morphological evolution.

2.3.1. *Effect of Varying the Star Formation History*

Panels (a), (b), and (c) show the effect of changing the star formation history, while keeping the time of onset of star formation fixed at $t_{\rm start} = 0$. The results for the evolution of the mean M/L ratio are shown in panel (a). Quite remarkably, nearly all

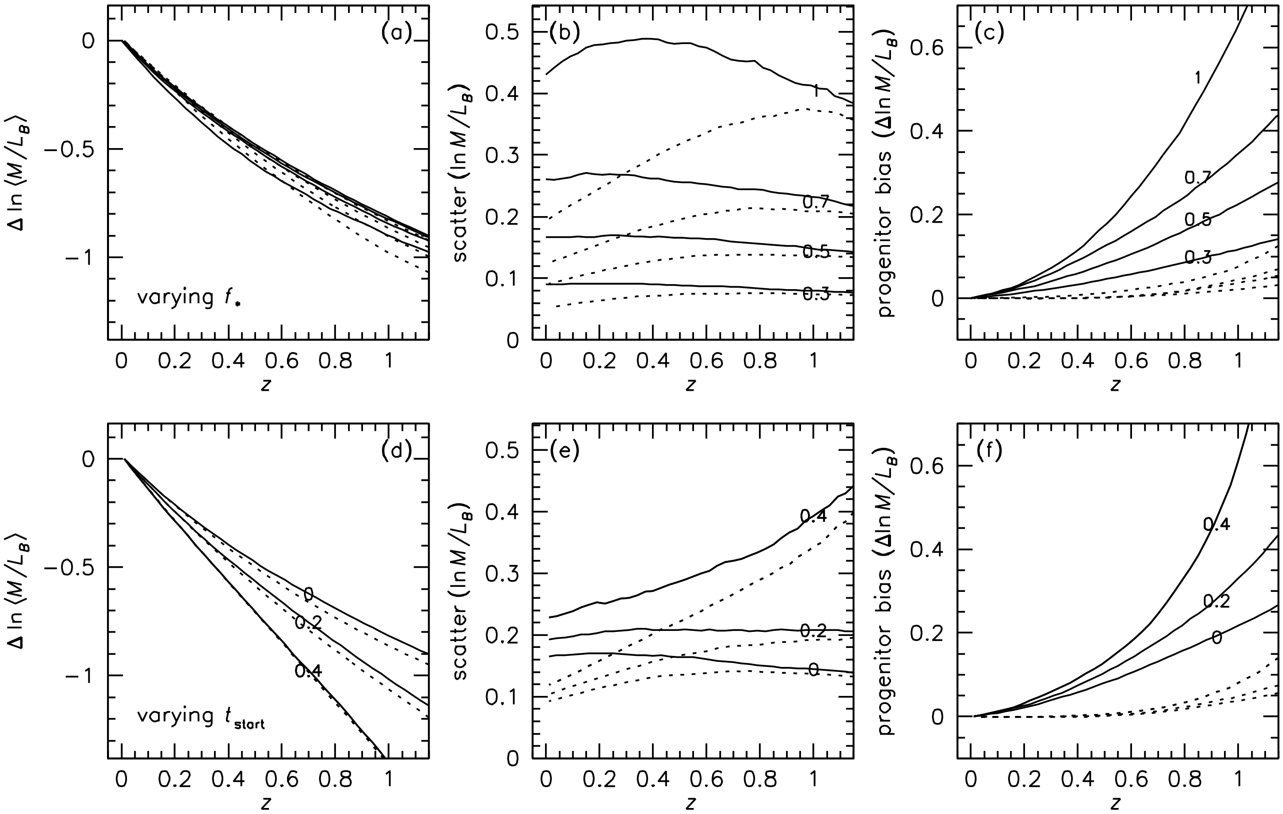

Fig. 3.— Predicted evolution of the mean M/L ratio and its scatter in various models with progenitor bias. In all panels, solid lines show models with strong morphological evolution to $z = 1$ ($\tau_{\rm stop} = 0.5t_0$) and broken lines show models with mild morphological evolution ($\tau_{\rm stop} = 0.2t_0$). Panels (a,b,c) demonstrate the effect of varying the star formation history, parameterized by f_*. The evolution of the mean M/L ratio (panel a) is remarkably similar in all models, whereas the scatter (panel b) and the progenitor bias (panel c) are very sensitive to the star formation history. Panels (d,e,f) show the effect of varying the time of onset of star formation, $t_{\rm start}$. Varying $t_{\rm start}$ has a large effect on the evolution of the mean M/L ratio, as well as on the scatter and the progenitor bias. The models indicate that the observed transformation rate and the observed scatter suffice to predict the progenitor bias.

model predictions lie very close to the line for old populations which formed at the start of the Universe ($z_{\rm form} = \infty$). We find little dependence on the tranformation time scale $\tau_{\rm stop}$ or on f_*, which characterizes the star formation history. This result illustrates the dramatic effects of the progenitor bias, as the mean stellar age of the galaxies at $z = 0$ can be as low as half the age of the Universe (for $f_* = 1$), and yet the apparent evolution follows the relation for very old populations formed at infinite redshift. The reason for this behaviour is that the formation models are almost scale free. In models with a constant transformation rate, at any time the youngest half of the galaxies have been added to the sample in the last half of the age of the Universe at that time. As a result, the mean stellar age of the galaxies is an almost constant fraction of the age of the Universe, independent of the star formation histories of individual galaxies, and the mean mass-to-light ratios and colors will evolve as if the stars formed at very high redshift. In the Appendix we demonstrate this effect analytically. The absolute colors and mass-to-light ratios at $z = 0$ will be different for these models, but these are notoriously difficult to interpret uniquely (e.g., Worthey 1994, Faber et al. 1999).

Fortunately, the scatter in M/L ratios and colors is much more sensitive to the transformation timescale and star formation histories. We show the scatter in M/L ratios in panel (b). For a given morphological transformation rate the variation in the average scatter is large, because it is a strong function of the star formation history of galaxies. As we will see later, this implies that observations of the scatter put important constraints on the models. For galaxies with later star formation, f_* increases, and the scatter increases almost linearly with f_*. For the limiting case of a constant transformation rate ($\tau_{\rm stop} = \infty$), we find that the scatter is well approximated by $\sigma(\ln M/L_B) \sim 0.3 f_*$ (see Appendix). The scatter is not strongly dependent on redshift because of the scale-free nature of the models. In such scale-free models, the relative age differences between early-type galaxies at any epoch is fairly constant. The scatter is proportional to the age differences between galaxies relative to the mean age (e.g., van Dokkum et al. 1998b). As galaxies are continuously added to the sample, the range in ages increases at the same rate as the mean age; hence the spread in ages relative to the mean age remains constant. In the Appendix this effect is demonstrated analytically. Only in models with mild morphological evolution to $z = 1$ (indicated by the broken lines in Fig. 3) we find an increase of the scatter with redshift. In these models the scatter is very low at $z = 0$, and at $z > 0.5$ reaches values similar to those in models with strong morphological evolution.

The progenitor bias of the models is shown in panel (c). We define the progenitor bias at given redshift as the difference between the M/L ratio of early-type galaxies and the M/L ratio of all progenitors of present-day early-type galaxies. This is the "error" in the observed M/L ratio that is caused by the late addition of early-type galaxies to the sample. As the figure shows, the bias increases with increasing tranformation time scale $\tau_{\rm stop}$, and increasing f_*. Both parameters also cause the scatter to increase. For models with strong morphological evolution the progenitor bias can be approximated by

$$\mathrm{bias}(\ln M/L_B) \approx 1.3 \times \mathrm{scatter}(\ln M/L_B) \times z \tag{7}$$

This approximation is accurate to $\lesssim 10\,\%$ for $\tau_{\rm stop} > 0.5 t_0$. This result suggests that the progenitor bias can be estimated on the basis of the observed transformation rate, and the observed scatter. The star formation history is the individual galaxies, as parametrized by f_*, is not needed to estimate the effect. This is a very useful result, as it is difficult to constrain the value of f_* directly from the observed colors and luminosities.

2.3.2. *Effect of Varying the Time of Onset of Star Formation*

Panels (d), (e), and (f) show the effect of changing the time of onset of star formation $t_{\rm start}$, while keeping the star formation history constant at $f_* = 0.5$ (i.e., approximately constant star formation from $t_{\rm start}$ to $t_{\rm stop}$). The evolution of the mean M/L ratio for the various models is shown in panel (f). The evolution is very sensitive to the time of onset of star formation: there is an almost linear relation between the time when star formation commences and the rate of M/L evolution. The reason for this behaviour is that the mean age of the stellar population in all galaxies is lower for higher values of $t_{\rm start}$. As will be shown in Sect. 3 the observed evolution of the mean M/L ratio places strong constraints on the time when star formation commenced in early-type galaxies.

The scatter and the progenitor bias are shown in panels (e) and (f). They both depend on the value of $t_{\rm start}$, such that the scatter is higher and the progenitor bias stronger for later onset of star formation. As a result of this dual dependence the relation between the progenitor bias and the observed scatter (Eq. 7) is not very sensitive to the value of $t_{\rm start}$, once again indicating that the observed rate of morphological evolution and the observed scatter suffice to estimate the progenitor bias.

3. APPLICATION TO OBSERVATIONS

The models described in the previous Section can be applied to observations of early-type galaxies in clusters at $0 < z < 1$. Parameters to fit are the evolution of *(i)* the early-type galaxy fraction, *(ii)* the mean M/L_B ratio, as determined from the Fundamental Plane, *(iii)* the scatter in M/L_B, and *(iv)* the scatter in the color-magnitude relation. Free parameters are the morphological transformation rate (parameterized by $\tau_{\rm stop}$), and the star formation histories of galaxies prior to the transformations (parameterized by f_* and $t_{\rm start}$).

3.1. *Data*

The evolution of the early-type galaxy fraction in clusters is shown in Fig. 4(a) (taken from van Dokkum et al. 2000). Data points are from Dressler (1980), Andreon, Davoust, & Heim (1997), Dressler et al. (1997), Lubin et al. (1998), Fabricant et al. (2000), and van Dokkum et al. (2000). The early-type fraction decreases by a factor ~ 2 from $z = 0$ to $z = 1$. The scatter around the downward trend is significant, and it will be interesting in the future to explore systematic differences in the evolution depending on cluster type. In this Section we do not distinguish elliptical galaxies and S0 galaxies within the class of early-type galaxies. In Sect. 5 we explore models in which both classes are modeled separately.

The evolution of the early-type galaxy fraction is possibly influenced by the inclusion of low mass galaxies undergoing star bursts. Since the samples are magnitude selected, the presence of such galaxies at high redshift would decrease the fraction of early-type galaxies, and would be unrelated to the evolution of massive galaxies. For the cluster MS 1054–03 at $z = 0.83$ we have a large data set of confirmed members with accurate colors (van Dokkum et al. 2000), and we tested the importance of this effect by determining the early-type galaxy fraction among red galaxies alone. If we limit the analysis to red galaxies with $(U-B)_z > 0.3$ the early-type fraction changes from 45 % to 52 %. This result indicates that the brightening of low mass galaxies has a minor effect on the fraction of early-type galaxies. Other effects may have the opposite effect. As an example, biases introduced by the selection of the clusters themselves probably cause us to *under*estimate the evolution of the early-type galaxy fraction (see, e.g., Kauffmann 1995).

The evolution of the rest frame M/L_B ratio with redshift is shown in Fig. 4(b) and is taken from van Dokkum et al. (1998a). Data are from Jørgensen et al. (1996), van Dokkum & Franx (1996), Kelson et al. (1997), and van Dokkum et al. (1998a). The M/L ratio evolution is derived from the evolution of the zeropoint of the Fundamental Plane relation (see van Dokkum & Franx 1996). The evolution is well determined, because the Fundamental Plane has very small scatter.

The scatter in $\ln(M/L_B)$ is shown in Fig. 4(c). The data point at $z \approx 0$ is from Jørgensen et al. (1996). Data points at higher redshift are from Kelson et al. (2000) ($z = 0.33$), Kelson et al. (1997) ($z = 0.58$), and van Dokkum et al. (1998a) ($z = 0.83$). The highest redshift points have considerable uncertainty, because they are derived from small samples.

The scatter in the $U-B$ color-magnitude relation is taken from van Dokkum et al. (2000) and shown in Fig. 4(d). Data are from Stanford et al. (1998), Bower, Lucey, & Ellis (1992), Ellis et al. (1997), van Dokkum et al. (1998b), and van Dokkum et al. (2000). The observations were brought to a common (rest frame) band by using $\sigma(U-B) = 1.4\sigma(B-V)$ and $\sigma(U-B) = 0.6\sigma(U-V)$, as derived from the Worthey (1994) models. The scatter is roughly constant with redshift, at $\sigma(U-B) \approx 0.03$ magnitudes.

3.2. *Constraints on Model Parameters*

3.2.1. *Transformation Time Scale*

The observed evolution of the early-type galaxy fraction directly constrains the transformation time scale $\tau_{\rm stop}$. This is demonstrated in Fig. 3(a), which shows the redshift dependence of the transformed galaxy fraction for different values of the transformation time scale.

We varied the transformation time scale between $\tau_{\rm stop} = 0$ and $\tau_{\rm stop} = \infty$. If $\tau_{\rm stop} = 0$ all morphological transformations occur at very high redshift and if $\tau_{\rm stop} = \infty$ the transformation rate is constant. The observed evolution of the early-type galaxy fraction, shown in Fig. 4(a), gives a best fitting value of $\tau_{\rm stop} \approx 0.5 t_0$. Values between $0.3 t_0$ and $1.7 t_0$ are consistent with the data at the 90 % confidence level.

The clusters in Fig. 4(a) form a very heterogeneous sample, and a potential worry is that the evolution is severely affected by selection biases. As a test of the robustness of the

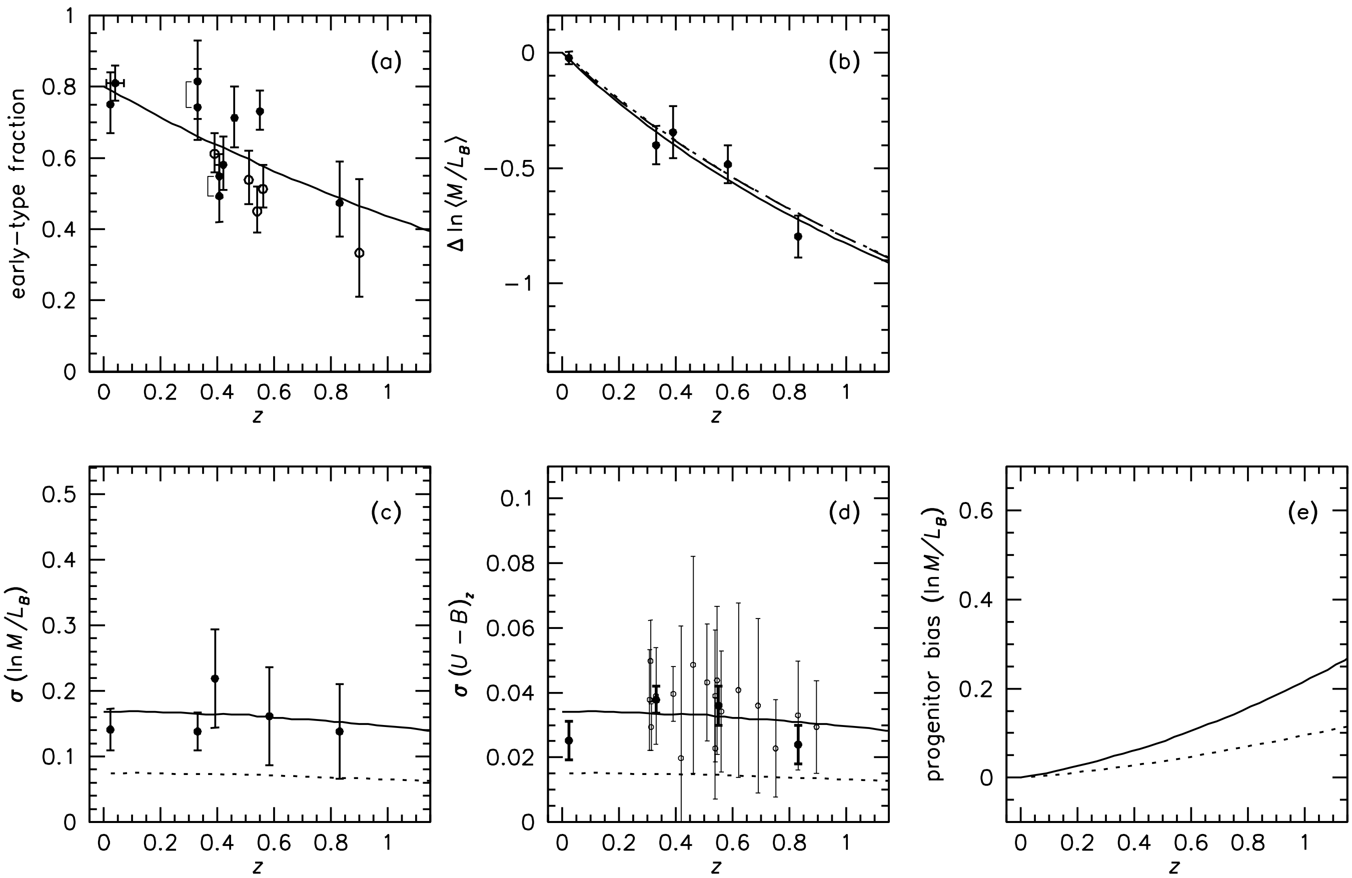

Fig. 4.— Comparison of observations to model predictions. Shown are the evolution of the early-type galaxy fraction (a), the evolution of the mean M/L_B ratio (b), the scatter in $\ln(M/L_B)$, as derived from the scatter in the Fundamental Plane of early-type galaxies (c), and the scatter in the $U-B$ color-magnitude relation (d). Sources of the data are described in the text. The solid lines show the best fitting model, with $\tau_{\rm stop} = 0.5t_0$, $f_* = 0.5$ (i.e., a constant star formation rate), and $t_{\rm start} = 0$. This model provides an excellent fit to the data. The broken lines show a model with $f_* = 0.25$ (i.e., a declining star formation rate). This model allows for additional scatter in the FP and the CM relation as a result of, e.g., metallicity variations or mergers. The progenitor bias is shown in panel (e). It is a strong function of f_*, and hence the scatter. The observed scatter provides an upper limit to the bias of ≈ 0.2 in $\ln(M/L_B)$ at $z = 1$.

transformation rate we fitted all clusters with high X-ray luminosities separately. Solid symbols in Fig. 4(a) are clusters with $L_X > 10^{44.5}\,h_{50}^{-2}$ ergs s^{-1} (see van Dokkum et al. 2000). This sample gives a very similar best fit value of $\tau_{\rm stop} \approx 0.45t_0$. We note, however, that the morphological transformation rate is one of the main uncertainties in our study. We will return to this issue in Sect. 5.

3.2.2. *Star Formation Histories*

We next explore models with the best fit transformation time $\tau_{\rm stop} = 0.5t_0$, and we vary the time of onset of star formation $t_{\rm start}$ and the parameter describing the star formation history f_*.

As demonstrated in the previous Section, the rate of evolution of the mean M/L ratio has an approximately linear dependence on the value of $t_{\rm start}$. The observed evolution, shown in Fig. 4(b), is very slow. The dashed line indicates a simple single burst model with $z_{\rm form} = \infty$. This model provides a good fit to the data, as was previously shown by van Dokkum et al. (1998a). We find a best fitting value of $t_{\rm start} = 0.03t_0$. Values between $t_{\rm start} = 0$ and $t_{\rm start} = 0.2t_0$ are consistent with the data at the 90 % confidence level. The implication is that star formation commenced at high redshift ($z > 2.5$) in early-type galaxies. The line in Fig. 4(b) shows the best fitting model with $t_{\rm start} = 0$.

As was demonstrated in Sect. 2 the star formation history between $t_{\rm start}$ and $t_{\rm stop}$ is constrained by the observed scatter in M/L ratio and color. This strong dependence of the scatter on the star formation history was discussed earlier by van Dokkum et al. (1998b) and Bower et al. (1998) in the context of "traditional" models which do not include morphological evolution. If all scatter in the color-magnitude relation and the Fundamental Plane is produced by age variations, the best fitting model has $f_* = 0.52$ (i.e., an approximately constant star formation rate), with values to $f_* = 0.62$ consistent with the data at the 90 % confidence level. The lines in Fig. 4(c) and (d) show the model with $f_* = 0.5$. For values of f_* lower than 0.5 the scatter is underpredicted, and additional scatter due to, e.g., merging, metallicity variations, or dust is allowed. As an example, the broken lines show a model with $\tau_{\rm stop} = 0.5t_0$, $t_{\rm start} = 0$, and $f_* = 0.25$. The preferred values of $f_* \leq 0.5$ correspond to gradual star formation histories similar to those depicted in the upper two panels of Fig. 2.

3.3. *The Progenitor Bias*

Our best fitting model has $\tau_{\rm stop} = 0.5t_0$, $t_0 = 0$, and $f_* \leq 0.5$. The progenitor bias, expressed as the difference between the observed M/L ratio of early-type galaxies and the M/L ratio of all progenitors of early-type galaxies in nearby clusters, is shown in Fig. 4(e). The progenitor bias is maximal if $f_* = 0.5$, in which case the scatter in the CM relation and the FP is entirely produced by age variations. In this extreme model the progenitor bias is approximately $0.2 \times z$ in $\ln M/L_B$, or $0.04 \times z$ in $U-B$ color.

We stress that these values are upper limits, because the scatter can be caused by other effects than age. As shown in the previous Section, the progenitor bias scales linearly with the scatter introduced by age variations. For example, if $f_* = 0.25$ the scatter due to age is only half the observed scatter. In this case the progenitor bias is only $0.1 \times z$ in $\ln M/L_B$ (indicated by the broken line in Fig. 4e).

It is interesting to compare these results to the simple scaling with the observed scatter that was derived in Sect. 2.3.1. Using the observed scatter of ≈ 0.15 in $\ln M/L_B$ Eq. 2.3.1 gives a progenitor bias of $\sim 0.2z$, identical to the value we derived from the full fitting of the models to the observations. This remarkable agreement demonstrates quantitatively that the observed transformation rate and the observed scatter suffice to predict the progenitor bias. In particular, knowledge of the detailed star formation histories of the galaxies ($t_{\rm start}$ and f_* in our models) is not required.

3.4. *Dependence on Cosmology*

We used $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$ to calculate the model predictions and the data points shown in Fig. 4. The models depend on the cosmological model because of the conversion from time to redshift. The observed evolution of the mean M/L ratio also depends on the cosmology, because effective radii of galaxies are measured in arcseconds. As demonstrated in Bender et al. (1998) and van Dokkum et al. (1998a) the dependencies can be quite strong, and the observed evolution of $\ln M/L_B$ provides an upper limit on Ω_m (assuming the slope of the IMF is not significantly steeper than the Salpeter (1955) value). Note that the models and data shown in Fig. 4 are not dependent on the Hubble constant, because the luminosity evolution of stellar populations can be approximated by a power law and all data points are relative to nearby clusters.

Our results are very similar for a Universe with a cosmological constant ($\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$). The predicted evolution of the early-type galaxy fraction remains virtually unaffected, and the best fitting value for the transformation time scale remains $\tau_{\rm stop} \approx 0.5t_0$. The observed evolution of the mean M/L_B ratio is more rapid in this cosmology, and is no longer well fitted by models with extremely high formation redshift of the stellar population (see also van Dokkum et al. 1998a). Models with $t_{\rm start} = 0$ predict too slow evolution, and good fits are obtained for $t_{\rm start} = 0.15t_0$. Because the stellar populations of early-type galaxies are younger for $t_{\rm start} > 0$ the predicted scatter in M/L ratios and colors is higher for a given value of f_*. As a result, the observed scatter is best fitted for $f_* \approx 0.4$ in this cosmology, as compared to $f_* \approx 0.5$ for a Universe without cosmological constant.

4. CORRECTING FOR PROGENITOR BIAS

The evolution of the M/L ratio can be corrected for progenitor bias. Our best fitting model indicates that the observed evolution of the M/L ratio underestimates the true evolution by $\approx 0.2 \times z$ in $\Delta \ln\langle M/L_B\rangle$, and $\approx 0.04 \times z$ in $\Delta\langle U-B\rangle$. van Dokkum et al. (1998b) found $\Delta \ln\langle M/L_B\rangle = (-0.9 \pm 0.1)z$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$, or $\Delta \ln\langle M/L_B\rangle = (-1.1 \pm 0.1)z$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The evolution after applying the maximum correction for progenitor bias is $\Delta \ln\langle M/L_B\rangle \approx -1.1z$, or $\Delta \ln\langle M/L_B\rangle \approx -1.3z$ for positive cosmological constant. We conclude that the progenitor bias has a small ($\lesssim 20\,\%$), but non-negligible effect on the observed evolution of the mean M/L ratio from $z = 0$ to $z = 1$. The corrections are upper limits, because it is assumed that the scatter in luminosities and colors is entirely due to age variations among the galaxies.

The observed evolution of the mean color and M/L ratio of early-type galaxies indicates a very high redshift of formation for their stars (e.g., van Dokkum & Franx 1996, Schade, Barrientos, & Lopez-Cruz 1997, Stanford et al. 1998, van Dokkum et al. 1998a, Kodama et al. 1998). Because the true evolution of early-type galaxies is underestimated as a result of the progenitor bias, the ages of their stars are *over*estimated.

We constrain the formation epoch of the stars in early-type galaxies from the corrected evolution of the mean M/L ratio. First we assume that the scatter in the color-magnitude relation and the Fundamental Plane is entirely caused by age variations. Using $\Delta \ln\langle L_B\rangle = 1.1z$ in Eq. 3 we find that the mean luminosity weighted formation time of the stars in early-type galaxies $\langle t_*\rangle = 0.16t_0$, or $\langle z_*\rangle = 3.0^{+0.9}_{-0.5}$ when expressed in redshift. For $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ $\Delta \ln\langle L_B\rangle = 1.3z$, and we find $\langle z_*\rangle = 2.0^{+0.3}_{-0.2}$. As a check on our procedure, we also computed the mean formation epoch directly from the Monte-Carlo simulation which gave the best fit to the observations. The age derived from the simulation is identical to the age derived from the corrected evolution of the M/L ratio.

If the scatter in the color-magnitude relation and the Fundamental Plane is not entirely caused by age variations, the mean age of the stars is higher. Both the mean age and the scatter have an approximately linear dependence on f_* (Eq. 2 and A9). Therefore, for a given morphological transformation rate the mean age of the stars is to good approximation a linear function of the scatter at $z = 0$. From the Monte-Carlo simulations with $\tau_{\rm stop} = 0.5t_0$ we find

$$\langle t_*\rangle/t_0 \sim 2 \times \sigma_{\ln M/L(B)} \qquad (8)$$

$$\sim 10 \times \sigma_{U-B} \qquad (9)$$

for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. If the contribution of age variations to the scatter is negligible the correction for progenitor bias is negligible as well, and we find $\langle z_*\rangle \approx 6.5$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$, and $\langle z_*\rangle \approx 2.6$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ (cf. van Dokkum et al. 1998a). Unfortunately it is observationally difficult to disentangle the contributions of age and metallicity to the observed scatter (e.g., Trager et al. 2000).

5. SEPARATING ELLIPTICAL AND S0 GALAXIES

In the previous Sections we have treated early-type galaxies as one class. However, Dressler et al. (1997) separated the evolution of elliptical and S0 galaxies, and found that the ratio of the fractions of S0 and elliptical galaxies evolves rapidly from $z = 0$ to $z \approx 0.55$.

Figure 5 shows the evolution of the number fractions of S0 galaxies and elliptical galaxies separately, for the Dressler et al. (1997) clusters (solid symbols). The dotted lines are linear fits to the data. As can be seen, the S0 fraction increases by a factor of ~ 5 towards lower redshift, whereas the elliptical fraction drops by $\sim 30\,\%$ from redshift $z = 0.55$ to $z = 0$. Dressler et al. (1997) interpret the rapid evolution of the S0 fraction as evidence for transformation of spiral galaxies to S0 galaxies since

$z = 0.55$. As pointed out by Fabricant et al. (2000) the decrease in the elliptical galaxy fraction over time requires substantial accretion onto clusters since $z = 0.55$.

We model this evolution in the following way: we assume that the fraction of ellipticals is constant with time, and that S0 galaxies are formed from the spiral galaxies that are present in the clusters at $z = 0.55$. We ignore the fact that infalling spiral galaxies are also transformed into S0 galaxies. The evolution of the S0 galaxies is approximated reasonably well by a model with a constant transformation rate (Fig. 5). The overprediction of the fraction of S0 galaxies at high redshift implies that we underestimate the differences between the elliptical and S0 galaxies.

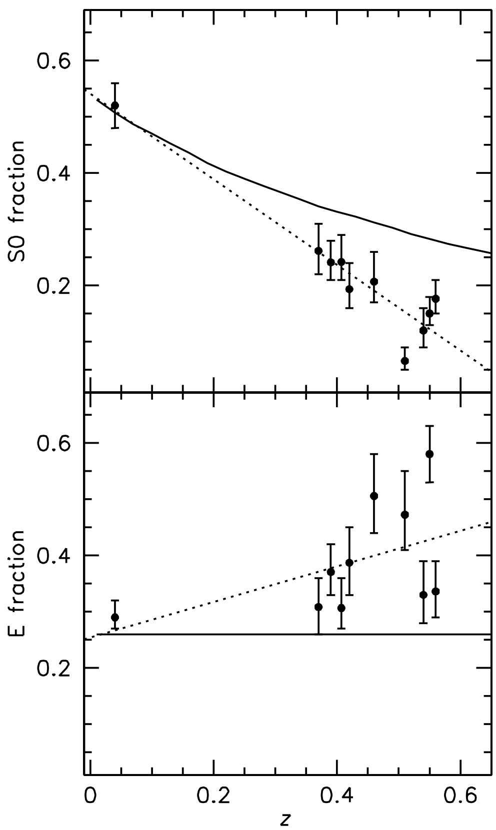

Fig. 5.— Evolution of the number fraction of elliptical galaxies and S0 galaxies separately, from Dressler et al. (1997) (solid symbols). The S0 fraction decreases with redshift, whereas the elliptical fraction increases. The dotted lines are linear fits to the data. The solid lines show the evolution in our hybrid model.

In our first models, we assume that the star formation rate for the spiral galaxies is constant in time ($f_* = 0.5$), and that star formation starts at $t_{\rm start} = 0$ for all galaxies. Figure 6 shows the evolution of the mean M/L ratio in this model, for elliptical galaxies (dotted line), S0 galaxies (dashed line), and elliptical and S0 galaxies combined (solid line). The model reproduces the observed evolution of the M/L ratio of the combined sample of elliptical galaxies and S0 galaxies. However, elliptical galaxies in this model have systematically higher M/L ratios and redder colors than S0 galaxies at all redshifts. The difference is ≈ 0.24 in $\ln M/L_B$, or ≈ 0.05 in $U-B$ color. This difference corresponds to a difference of ≈ 20 % in luminosity weighted age (e.g., Worthey et al. 1994). This large difference arises because all elliptical galaxies formed their stars at extremely high redshift in this model, whereas the S0 galaxies are continuously transformed from star forming galaxies.

This result is in conflict with studies of luminous early-type cluster galaxies at low and intermediate redshift, which indicate very little difference in luminosity weighted age between luminous elliptical and S0 galaxies in the cores of rich clusters (e.g., Jørgensen, Franx, & Kjærgaard 1996, Ellis et al. 1997, van Dokkum et al. 1998a, Jones, Smail, & Couch 2000, Kelson et al. 2000). Other studies have reported S0 galaxies with younger stellar populations, but these tend to have low luminosities (e.g., Caldwell et al. 1993, van Dokkum et al. 1998b, Kuntschner & Davies 1998).

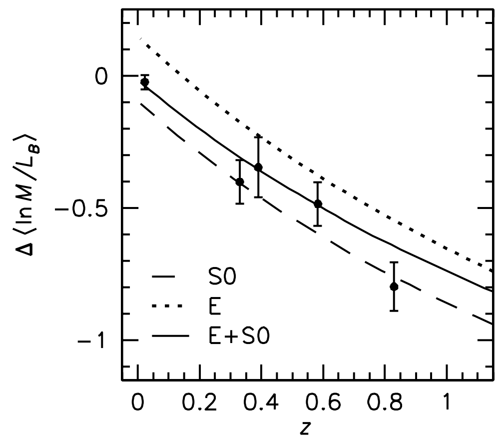

Fig. 6.— Predicted evolution of the mean M/L_B ratio for a model with different evolutionary histories for elliptical galaxies and S0 galaxies. It is assumed that all elliptical galaxies formed at extremely high redshift, whereas S0 galaxies are continuously transformed from star forming galaxies. This model predicts a difference of $\Delta \ln(M/L_B) \approx 0.24$ between luminous elliptical galaxies and S0 galaxies at all redshifts.

There are several ways in which this conflict can be solved. First, we can adapt the starformation histories. The model assumes that star formation in elliptical and S0 galaxies commenced at $z = \infty$, and that their star formation rate was approximately constant from $t_{\rm start}$ to $t_{\rm stop}$. If star formation in elliptical galaxies commenced at a later time the systematic difference between elliptical and S0 galaxies is reduced. If $t_{\rm start} = 0.2 t_0$ for elliptical galaxies (i.e., star formation commenced at $z \approx 2.5$) the systematic difference in M/L ratio between elliptical and S0 galaxies at $z = 0$ is very small. However, it increases to ≈ 0.3 in $\ln(M/L_B)$ at $z = 0.8$. This corresponds to a systematic difference in $U-B$ color of 0.06, which is inconsistent with the low scatter in the CM relation of early type galaxies at $z = 0.83$ (van Dokkum et al. 2000).

An alternative explanation for the small observed difference between luminous elliptical and S0 galaxies is that most of their stars were formed at very high redshift. In our models, this corresponds to low values of f_*, the parameter describing the star formation history. The systematic difference in M/L ratio scales linearly with f_*, and for values of $f_* \lesssim 0.2$ the systematic age difference between elliptical and S0 galaxies is $\lesssim 5$ % at all redshifts. This explanation can be tested with the help of direct measurements of the star formation rates of the spiral galaxies in intermediate redshift clusters.

A third possibility is that the effects of metallicity cancel the effects of age (e.g., Worthey, Trager, & Faber 1996, Shioya &

Bekki 1998, Trager et al. 2000). The spiral galaxies would be enriched in metals compared to the elliptical galaxies of the same luminosity, and hence their colors would be redder, and their M/L ratios higher than that of elliptical galaxies with the same age. This solution requires exact fine tuning between age and metallicity to keep the scatter small. It can be tested by direct observations of absorption line strengths of elliptical and S0 galaxies in nearby and distant clusters. The first studies do not appear to indicate significant differences between massive elliptical and S0 galaxies (e.g., Kuntschner & Davies 1998, Jones et al. 2000, Kelson et al. 2001).

Finally, the separation of ellipticals and S0's is very difficult, and it is not clear whether a clear distinction can be made between elliptical galaxies and S0 galaxies with L_* luminosities (e.g., Jørgensen & Franx 1994, Rix & White 1990). The latter study demonstrated that many elliptical galaxies contain significant disks, and would be classified as S0 galaxies when seen edge-on. Jorgensen and Franx argued that the Coma elliptical and S0 galaxies can be approximated well by a population of galaxies which has a homogeneous distribution in the ratio of bulge light to total light. In this case, no clearcut distinction would exist between S0 galaxies and elliptical galaxies, and the evolutionary histories would not be so different between the galaxies. This might also explain the fact that the classifications between different authors agree well when the total fraction of elliptical and S0 galaxies is considered, but not when the classes are separated (e.g., Andreon 1998, Fabricant et al. 2000). Quantitative classifications would be able to resolve this issue, especially if detailed attention is given to the classification uncertainties due to projection effects.

6. SUMMARY AND CONCLUSIONS

In this paper we have quantified the effects of morphological evolution on the observed properties of early-type galaxies in clusters at $0 < z < 1$. A manifestation of morphological evolution is the "progenitor bias": at high redshift, the progenitors of the youngest present-day early-type galaxies drop out of the sample. In general, the observed evolution of the mean luminosity and color of early-type galaxies is slower than the true evolution of all progenitors of early-type galaxies, and the scatter in luminosity and color is smaller. If morphological evolution is strong the observed mean evolution is similar to that of a single age stellar population formed at $z = \infty$, and the scatter is approximately constant with redshift. These results can be derived analytically (cf. Appendix A).

In traditional models it is difficult to explain the low number fractions of early-type galaxies in distant clusters and the homogeneity and slow evolution of their stellar populations simultaneously. We have shown that the observed constant scatter in the CM relation and the FP and the slow evolution of the mean M/L ratio are natural consequences of morphological evolution. Observations of early-type galaxies in clusters at $0 < z < 1$ are well fitted by our models, and we can constrain the morphological transformation rate and the star formation histories of galaxies prior to transformation from the fits. The observed evolution of the early-type galaxy fraction constrains the transformation rate, the evolution of the mean M/L ratio constrains the time of onset of star formation, and the scatter in the color-magnitude relation and the Fundamental Plane constrain the star formation histories of galaxies prior to transformation. The best fits are obtained if approximately 50 % of present-day early-type galaxies were transformed from other morphological types at $z < 1$, star formation commenced at early times ($z > 2.5$), and star formation was approximately constant prior to transformation. Such gradual star formation histories are consistent with the low numbers of star burst galaxies seen in intermediate redshift clusters (e.g., Abraham et al. 1996, Balogh et al. 1998, Ellingson et al. 2000), although some star bursts could be concealed by dust (Poggianti et al. 1999).

The observed color and luminosity evolution of early-type galaxies can be corrected for the effects of progenitor bias. We have shown that for a given morphological transformation rate the progenitor bias is proportional to the scatter in M/L ratio or color. The correction is maximal if the scatter in the CM relation and the FP at $z = 0$ is entirely due to age variations between galaxies. This maximum correction to the evolution of rest frame $\Delta \ln\langle M/L_B\rangle$ is approximately $-0.2 \times z$, and the correction to the evolution of rest frame $\Delta\langle U-B\rangle$ is approximately $-0.04 \times z$. These corrections can easily be computed for other rest frame bands using stellar population synthesis models. As an example, the Worthey (1994) and Bruzual & Charlot (2000) models give $\Delta(U-V) \approx 1.7\Delta(U-B)$ for solar metallicity and Salpeter (1955) IMF. Therefore, the correction to $\Delta\langle U-V\rangle$ is $\sim -0.07 \times z$. The corrections are upper limits, because variations in dust content and metallicity probably contribute to the scatter. On the other hand, as pointed out by, e.g., Trager et al. (2000) variations in metallicity and age may conspire to produce a low scatter. If this is confirmed the corrections may be larger than the values given here.

Because the mean luminosity and color evolution are underestimated, the mean age of the stars in early-type galaxies that is derived from them is overestimated in traditional models. We find that the mean luminosity weighted formation redshift of early-type galaxies can be as low as $\langle z_*\rangle = 3.0^{+0.9}_{-0.5}$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$, or $\langle z_*\rangle = 2.0^{+0.3}_{-0.2}$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, if the scatter in the CM relation and the FP is entirely caused by age variations. This result is important, because previous studies which ignored the effects of progenitor bias found much earlier formation epochs of the stars in early-type galaxies (e.g., Ellis et al. 1997, Stanford et al. 1998, van Dokkum et al. 1998a). The redshift range 2 – 3 is of interest because it is observationally accessible. In particular, our results are consistent with the idea that (some) Ly-break galaxies are the star forming building blocks of present-day early-type galaxies in clusters (Baugh et al. 1998).

In our main analysis we treated the evolution of early-type galaxies as one class, but we also explored a model which separates the two classes. In our model, only the S0 galaxies evolve morphologically from spiral galaxies, as advocated by Dressler et al. (1997). The model predicts that colors and M/L ratios of luminous S0 galaxies in nearby clusters are systematically offset from those of elliptical galaxies, in the sense that elliptical galaxies are redder and have higher M/L ratios. This result is in conflict with studies of bright early-type galaxies in the cores of rich clusters, which generally find very little difference between elliptical and S0 galaxies (e.g., Bower et al. 1992, Ellis et al. 1997). There are several ways to resolve this conflict: star formation may have started later in the elliptical galaxies, or most of the star formation in elliptical and S0 galaxies must have occurred at very early times, long before morphological transformation to early-type galaxy. Alternatively, there might be a conspiracy between age and metallicity (e.g., Trager et al. 2000) such that S0 galaxies have systematically higher metallicities than elliptical galaxies of the same luminosity. This can be tested by absorption line measurements; current measurements do not indicate such an effect for cluster galaxies. Finally, the separation between elliptical and S0 galaxies may not be very sharp. Rix & White (1990) showed that many S0 galaxies will be classified as elliptical galaxies when not viewed edge-on. Jørgensen and Franx (1994) showed that the elliptical and S0 galaxies in Coma can be modeled by a population of galaxies with a homogeneous distribution of bulge-to-total light ratio. Hence, the galaxies which are classified as elliptical galaxies may also have evolved since $z = 1$.

It is interesting to compare our results to predictions of semi-analytical galaxy formation models in CDM cosmologies (White & Frenk 1991; Cole 1991). Because the morphologies of galaxies change quite rapidly in these models (e.g., Baugh, Cole, & Frenk 1996, Kauffmann 1996) progenitor bias is an important ingredient. In particular, the models provide reasonable fits to the observed scatter in the CM relation (Kauffmann & Charlot 1998; Cole et al. 2000) and the evolution of the mean M/L ratio of massive galaxies (Diaferio et al. 2000), even though galaxies in these simulations have quite complex (star) formation histories. However, in these complex models it is difficult to isolate and study specific effects such as the progenitor bias. The main contribution of our work is that we use very simple models with only three free parameters. We show that the effects of progenitor bias can be constrained directly from the observations, and it is straightforward to reproduce our results.

The main uncertainty in the present paper is the rate of morphological evolution. More high resolution, large field studies of distant clusters are needed to constrain the evolution of the early-type galaxy fraction better. Detailed simulations are needed to determine the effects of infall on the observed properties and morphological mix of cluster galaxies (e.g., Ellingson et al. 2000). Furthermore, studies of the evolution of the mass function of rich clusters to $z = 1$ are necessary to determine whether high redshift clusters are representative progenitors of present-day rich clusters. As pointed out by, e.g., Kauffmann (1995) significant evolution in the mass function of rich clusters may result in a "progenitor bias" at the cluster level.

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APPENDIX

ANALYTIC EXPRESSIONS

Evolution of the Mean Luminosity and Color

Combining Eq. 1 – 3 gives the following approximate expression for the observed evolution of the mean M/L_B ratio of early-type galaxies:

$$M/L_B(t) \propto \frac{\tau_{\rm stop}\left[1-\exp\left(-\frac{t-0.1t_0}{\tau_{\rm stop}}\right)\right]}{\int_0^{t-0.1t_0}\exp\left(-\frac{t'}{\tau_{\rm stop}}\right)\left[t-(f_* t'+t_{\rm start})\right]^{-\kappa_B}dt'}. \tag{A1}$$

Similarly, the color evolution can be approximated by

$$\frac{L_B}{L_U}(t) \propto \frac{\tau_{\rm stop}\left[1-\exp\left(-\frac{t-0.1t_0}{\tau_{\rm stop}}\right)\right]}{\int_0^{t-0.1t_0}\exp\left(-\frac{t'}{\tau_{\rm stop}}\right)\left[t-(f_* t'+t_{\rm start})\right]^{\kappa_B-\kappa_U}dt'}. \tag{A2}$$

For given f_* the integrals can be evaluated analytically.

If $\tau_{\rm stop} = \infty$ and $t_{\rm start} = 0$ (i.e., in the case of a constant transformation rate) evaluation of the integral in Eq. A1 gives

$$M/L_B(t) \propto \frac{f_*(1-\kappa_B)(t-0.1t_0)}{t^{1-\kappa_B}-\left[t-f_*(t-0.1t_0)\right]^{1-\kappa_B}}. \tag{A3}$$

For $t \gg 0.1 f_* t_0$ this reduces to

$$M/L_B(t) \propto \frac{f_*(1-\kappa_B)}{1+(1-f_*)^{1-\kappa_B}}t^{\kappa_B}. \tag{A4}$$

This approximation is accurate to better than $\sim 3\,\%$ for $f_* \lesssim 0.5$ and $z \lesssim 1$. As a consequence,

$$\Delta\ln(M/L_B)(t) \approx \kappa_B \ln(t). \tag{A5}$$

Similarly, the color evolution reduces to

$$\Delta(U-B) \approx (\kappa_U-\kappa_B)\,2.5\log(t). \tag{A6}$$

These expressions are identical to the evolution of a single age stellar population that was formed at $z = \infty$.

Evolution of the Scatter

For $t_{\rm start} = 0$ the scatter in $\ln M/L$ at time t can be approximated by

$$\begin{aligned}\sigma(\ln M/L)(t) &\approx \kappa\,\sigma\left(\ln(t - f_* t_{\rm stop})\right) \\ &\approx \kappa \frac{\sigma(t - f_* t_{\rm stop})}{\langle t - f_* t_{\rm stop}\rangle} \\ &= \kappa \frac{f_* \sigma(t_{\rm stop})}{t - f_* \langle t_{\rm stop}\rangle}. \end{aligned} \tag{A7}$$

For a constant morphological transformation rate the distribution of $t_{\rm stop}$ is a simple top hat, bounded by $t_1 = 0$ and $t_2 = t - 0.1 t_0$. The 1σ spread of a top hat distribution is $0.29(t_2 - t_1)$, and the mean is $(t_2 - t_1)/2$. As a result,

$$\sigma(\ln M/L) = \kappa \frac{0.29 f_* t - 0.029 t_0}{(1 - 0.5 f_*)t - 0.05 t_0}. \tag{A8}$$

For $t/t_0 \gg 0.1 f_*$ (i.e., at low redshift) and small f_*, this reduces to

$$\sigma(\ln M/L_B) \approx \kappa_B \frac{0.29 f_*}{1 - 0.5 f_*} \tag{A9}$$

$$\sim 0.3 f_* \tag{A10}$$

in the rest frame B band. Similarly, the scatter in the color can be approximated by

$$\sigma(U - B) \approx 2.5(\log e)(\kappa_U - \kappa_B) \frac{0.29 f_*}{1 - 0.5 f_*} \tag{A11}$$

$$\sim 0.05 f_*. \tag{A12}$$

The scatter is to good approximation independent of redshift, and a strong function of f_*, the parameter describing the star formation history of individual galaxies.

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