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Formation and Evolution of Galaxies in Clusters

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Abstract.

Elliptical and S0 galaxies dominate the galaxy population in nearby rich clusters such as Coma. Studies of the evolution of the colors, mass-to-light ratios, and line indices of early-type galaxies indicate that they have been a highly homogeneous, slowly evolving population over the last $\sim 65\,\%$ of the age of the Universe. On the other hand, recent evidence suggests that many early-type galaxies in clusters have been transformed from spiral galaxies since $z \sim 1$. Arguably the most spectacular evidence for such transformations is the incidence of red merger systems in several high redshift clusters. Due to this morphological evolution the sample of early-type galaxies at high redshift is only a subsample of the sample of early-type galaxies at low redshift. This "progenitor bias" results in an overestimate of the mean formation redshift if simple models without morphological transformations are used. Models which incorporate morphological evolution explicitly can bring the homogeneity, slow evolution, and morphological transformations into agreement. The modeling shows that the corrected mean formation redshift of the stars in early-type galaxies may be as low as $z \approx 2$ in a Λ dominated Universe.

1. Introduction

The galaxy population in rich clusters is dominated by early-type galaxies (S0 and elliptical galaxies). The study of these objects gives insight in the formation of the most massive disk- and spheroidal galaxies in the Universe, and in the processes governing star formation at early times. Furthermore, cluster galaxies provide critical tests of the hierarchical paradigm for galaxy formation. In currently popular semi-analytical galaxy formation models in a CDM Universe the descendants of the Ly-break population are massive galaxies in groups and clusters (Baugh et al. 1998). These models also predict that significant differences should exist between early-type galaxies in clusters and those in the general field (Kauffmann 1996).

It has been known for a long time that early-type galaxies in clusters form a very homogeneous population: at a given luminosity, they show a very small scatter in their colors, M/L ratios, and line indices (e.g., Bower et al. 1992). The simplest interpretation of this high degree of homogeneity is a small spread in age, although it has been argued that a larger age spread could be "masked" by correlated metallicity variations (e.g., Trager et al. 2000)[1]. Determining the *mean* age of nearby early-type galaxies has proven to be a formidable challenge. The main reason is the well known age-metallicity degeneracy in fitting early-type galaxy spectra (e.g., Worthey 1994). Furthermore, the observed abundance ratios of early-type galaxies cannot be reproduced with simple stellar population synthesis models, which makes absolute determinations of age and metallicity even more uncertain. It is therefore not surprising that most of our understanding of the formation and evolution of cluster early-type galaxies has come from studies of clusters at large lookback times.

Since the seminal work by Butcher & Oemler (1978) on the colors of galaxies in two distant clusters this field has witnessed great progress: measurements of redshifts, morphologies, colors, M/L ratios, and line indices of cluster galaxies currently span $\sim 65\,\%$ of the age of the Universe. Examples of successful ongoing programs are the MORPHS collaboration (Smail et al. 1997), who obtained deep HST images of the cores of ~ 10 clusters at $0.3 < z < 0.5$, the CNOC group (Yee et al. 1996), who obtained extensive wide field spectroscopy and imaging of X-ray selected clusters at $0.2 < z < 0.5$, the work by Lubin, Postman, & Oke on optically selected clusters at $z \sim 0.8$, and our wide field HST imaging and extensive spectroscopy of X-ray clusters[2].

As in many other fields, Hubble Space Telescope imaging and spectroscopy with large ground-based telescopes have been instrumental in this advance. An additional factor has been the success of surveys of increasing sophistication to find ever more distant clusters. The progress in this area that was demonstrated at the meeting is encouraging, and should lead to a better understanding of the interplay between the selection of clusters and the derived evolution of the galaxies within them (see, e.g., the review by Marc Postman).

2. Evolution of early-type galaxies

Studies of the evolution of early-type galaxies in clusters are in remarkable agreement. Studies of their colors (e.g., Ellis et al. 1997, Stanford et al. 1998), M/L ratios (van Dokkum & Franx 1996, Bender et al. 1998, van Dokkum et al. 1998, Kelson et al. 2000), and line indices (Bender et al. 1998, Kelson et al. 2001) show that they remain a very homogeneous population and evolve only slowly all the way from $z = 0$ to $z \sim 1$.

2.1. Evolution of the Fundamental Plane

The strongest constraints on the mean star formation epoch have come from the evolution of the Fundamental Plane (FP) relation. The Fundamental Plane (Djorgovski & Davis 1987) is a relation between the effective radius r_e, effective surface brightness μ_e, and central velocity dispersion σ, such that $r_e \mu_e^{0.8} \propto \sigma^{1.25}$ in the B band. The implication of the existence of the FP is that M/L ratios of galaxies correlate strongly with their structural parameters: $M/L \propto r_e^{0.2}\sigma^{0.4} \propto$

[1]Note that this interpretation requires that we observe early-type galaxies at a special time, when age and metallicity variations exactly cancel.

[2]Possibly dubbed AWACS, for A Wide Angle Cluster Survey.

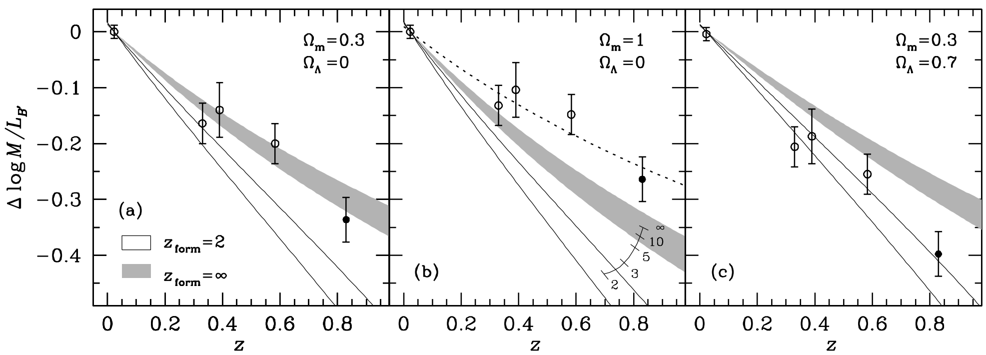

Figure 1. Evolution of the mean M/L_B ratio of early-type galaxies, as determined from the FP relation. The observed evolution is slow, indicating an early formation of the stars.

$M^{0.2}$ (Faber et al. 1987). The power of the FP lies in this relation to M/L ratios, and its usefulness for galaxy evolution studies stems from its small scatter and the fact that it applies to both elliptical and S0 galaxies.

The M/L ratios of galaxies are expected to evolve because the luminosity of their stellar populations decreases as they age ("passive evolution"). The *rate* of evolution depends on the time that has elapsed since the population was formed: the light of young stellar populations is dominated by massive stars which have a short life time on the main sequence, whereas the light of old stellar populations is dominated by long lived, low mass stars. In the rest frame B band, the expected evolution is $M/L \propto (t - t_{\rm form})^{0.91}$ for a Salpeter IMF; the coefficient depends on the passband and the IMF, but is only weakly dependent on the metallicity. As a result, the rate of evolution of the intercept of the FP gives a strong constraint on the mean stellar age of early-type galaxies.

The measured evolution of M/L_B to $z = 0.83$ is shown in Fig. 1, from van Dokkum et al. (1998). The evolution is surprisingly low, $\ln M/L_B \propto -z$, indicating stellar formation redshifts of $z > 2.8$ for $\Omega_m = 0.3$, $\Omega_\Lambda = 0$, and a Salpeter IMF. Studies of the evolution of colors (e.g., Stanford et al. 1998) and line indices (Bender et al. 1998; Kelson et al. 2001) have yielded very similar results. In general, color evolution (effectively the difference between the luminosity evolution in each of two passbands) can not be measured to the same precision as evolution in M/L ratios.

It is difficult, but not impossible, to extend the FP measurements to even higher redshift. The practical limit probably lies around $z \sim 1.3$: 12.5 hr Keck spectra of "Extremely Red Objects" in the cluster RXJ 0848+4453 at $z = 1.27$ are just sufficient to measure velocity dispersions (van Dokkum & Stanford, in prep).

2.2. Evolution of the scatter in the color-magnitude relation

The color-magnitude (CM) relation provides important additional constraints on the star formation epoch of early-type galaxies. Because spectroscopy is not required it is relatively straightforward to obtain large samples, enabling studies of the evolution of the scatter and slope of the relation as well as its zeropoint.

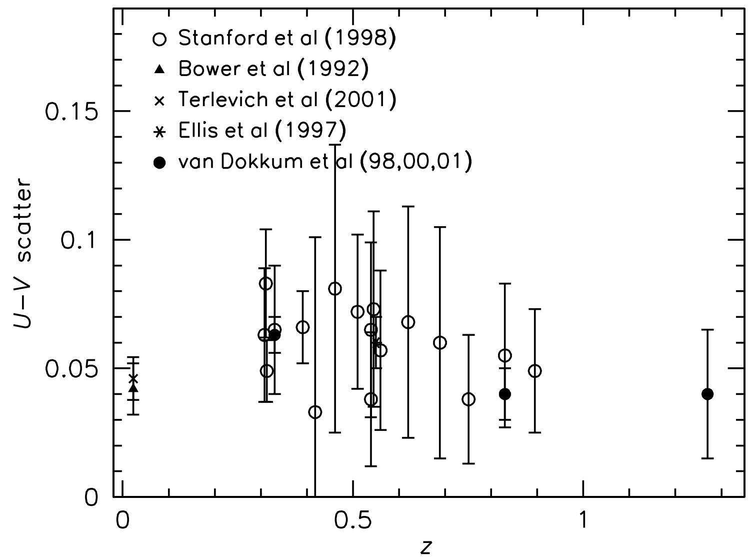

Figure 2. Evolution of the scatter in the color-magnitude relation with redshift, from literature data (see text). The scatter shows little evolution, implying that the scatter in age is small at all times.

The scatter is of particular interest, because it measures the spread in stellar age among early-type galaxies. The rest frame $U-V$ color evolution of a stellar population can be described by $L_V/L_U \propto (t-t_{\rm form})^{\kappa_U-\kappa_V}$, with $\kappa_U \approx 1.08$ and $\kappa_V \approx 0.81$. It can be shown that the scatter in the CM relation at any time t is proportional to the scatter in luminosity weighted age divided by the mean age (e.g., van Dokkum et al. 2000).

The observed evolution of the scatter in the CM relation is shown in Fig. 2. Ground based data are from Bower et al. (1992) and Terlevich et al. (2001) for Coma and from Stanford et al. (1998) for high redshift clusters. HST measurements have smaller errorbars, and are from Ellis et al. (1997) and van Dokkum et al. (1998, 2000, 2001). The scatter remains very small all the way from $z=0$ to $z=1.3$. This result is quite surprising, because the mean age of galaxies should be *at least* a factor 2 smaller at $z=1$. Therefore, if the scatter in the CM relation at $z=0$ is caused by age variations, one might expect the scatter to increase by at least a factor 2 from $z=0$ to $z=1$. Following a similar line of reasoning it has been argued that the scatter in the CM relation of nearby clusters is mainly due to metallicity variations, and that the formation of early-type galaxies is even more synchronized than implied by the tight scaling relations observed at low redshift (e.g., Stanford et al. 1998). Indeed, when taken at face value, the scatter observed at $z=1.27$ implies a spread in age of only $\sim 5\,\%$ at the present epoch!

In summary, studies of the observed evolution of early-type galaxies indicate that they have been a highly homogeneous, slowly evolving population over at least the latter $\sim 65\,\%$ of the age of the Universe. To satisfy the tightest observational constraints it appears that early-type galaxies would have to have formed at very high redshift ($z>3$) in a very short time ($\leq 500\,$Myr).

3. Assembly time of cluster galaxies

3.1. The Butcher-Oemler effect

It has been known for a long time that something must be amiss with the simple picture of early formation presented above. The earliest evidence for significant recent evolution in cluster environments was the discovery of the Butcher-Oemler effect: the increase with redshift of the fraction of blue galaxies in clusters (Butcher & Oemler 1978, 1984). Figure 3 is a compilation showing the evolution of the blue fraction with redshift, with data from Butcher & Oemler (1984), Smail et al. (1998), Fabricant et al. (1991), van Dokkum et al. (2000), and Ellingson et al. (2001).

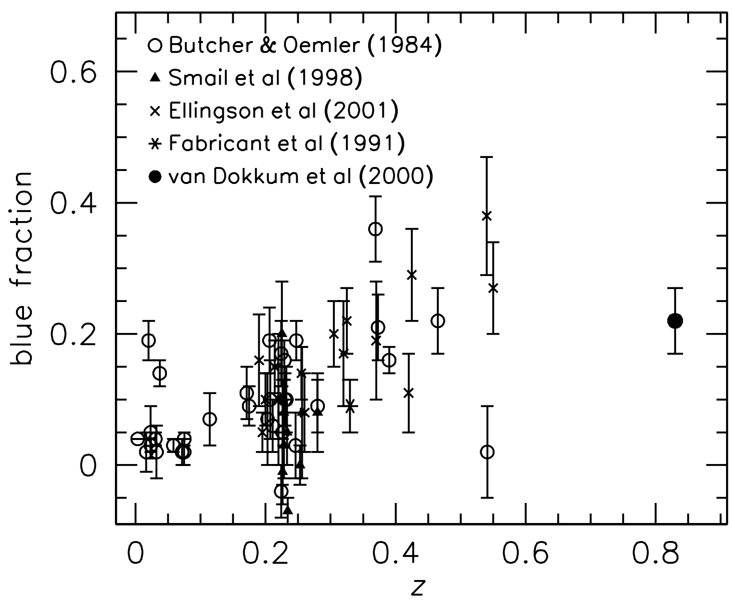

Figure 3. Evolution of the blue galaxy fraction in clusters. The trend has significant scatter.

There is clearly a trend in Fig. 3, albeit with a large scatter. Much of the work on cluster galaxies in subsequent decades – too much to do justice in this short review – was aimed at understanding the nature of these blue galaxies. It has become clear that most of the blue galaxies are not early-type galaxies but low mass spirals and irregulars (e.g., Smail et al. 1997). Some show ongoing star formation; others are currently not forming stars but have enhanced Balmer absorption lines indicating a recent star burst (e.g., Dressler & Gunn 1983). Among the more persistent ideas is that the Butcher-Oemler effect is driven by infall of blue, late-type galaxies from the field, which subsequently lose their fuel for star formation in interactions with other galaxies and/or the hot X-ray gas (e.g., Abraham et al. 1996, Ellingson et al. 2001). In this picture, the redshift dependence of the blue fraction may be the result of a decreasing infall rate with time, and/or reflect the well established overall decrease of the star formation rate in the field population (e.g., Kauffmann 1995).

It is usually assumed that a sizable fraction of the blue population are progenitors of (low mass) red early-type galaxies in nearby clusters (e.g., Kodama & Bower 2001), in apparent conflict with the early formation of early-type galaxies inferred from studies of their color and luminosity evolution.

3.2. Evolution of the early-type galaxy fraction

Dressler et al. (1997) report a high fraction of spiral galaxies in clusters at $0.3 < z < 0.5$. These galaxies are much rarer in nearby rich clusters, 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. 2001) have confirmed this trend, and extended it to $z = 1.3$. The evolution of the early-type galaxy fraction is shown in Fig. 4. The early-type fraction decreases by a factor ~ 2 from $z = 0$ to $z \sim 1$, although the trend has significant scatter.

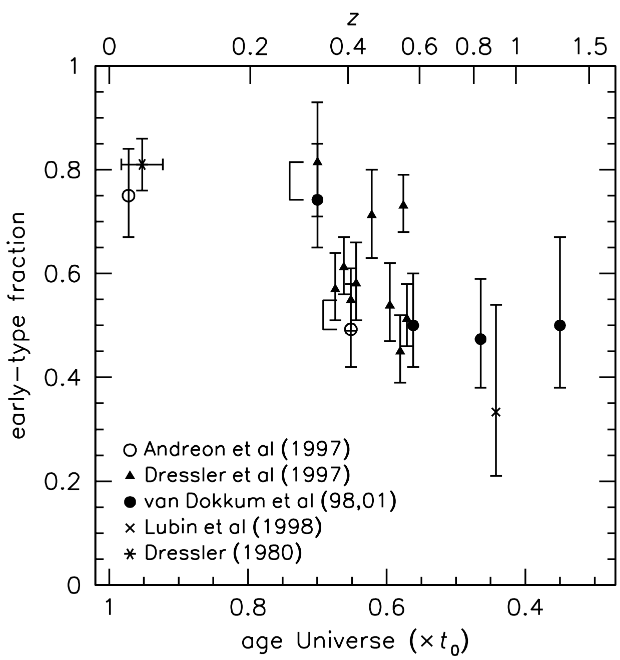

Figure 4. Evolution of the early-type galaxy fraction compiled from various studies, and taken from van Dokkum et al. (2001).

Dressler et al. found that the increased fraction of spiral galaxies at high redshift is accompanied by a low fraction of S0 galaxies, and concluded that the $z \approx 0.4$ spiral galaxies transform into S0 galaxies. They postulate that the formation of elliptical galaxies predated the virialization of the clusters in which they now live. However, there is some controversy over the relative numbers of elliptical and S0 galaxies in distant clusters[3]. Dressler et al. claim that S0 galaxies are virtually absent at $z \sim 0.4$, suggesting a factor ~ 4 evolution over

[3]Importantly, there is no such controversy over the *combined* number of Es and S0s, i.e., the early-type galaxy fraction.

the past $\sim 4\,$Gyr. Others have debated this, and find a much milder evolution in the E/S0 ratio (e.g., Andreon et al. 1997).

One of the problems is the difficulty in distinguishing elliptical and S0 galaxies at high redshift (see Fabricant et al. 2000 and references therein). Spatially resolved kinematics may offer an elegant solution. An example is shown in Fig. 5. From the HST image alone it is difficult to determine whether this $z = 0.83$ galaxy is an elliptical or an S0. The kinematics reveal a rapidly rotating cold disk in addition to a hot bulge, and show that this object is a massive S0.

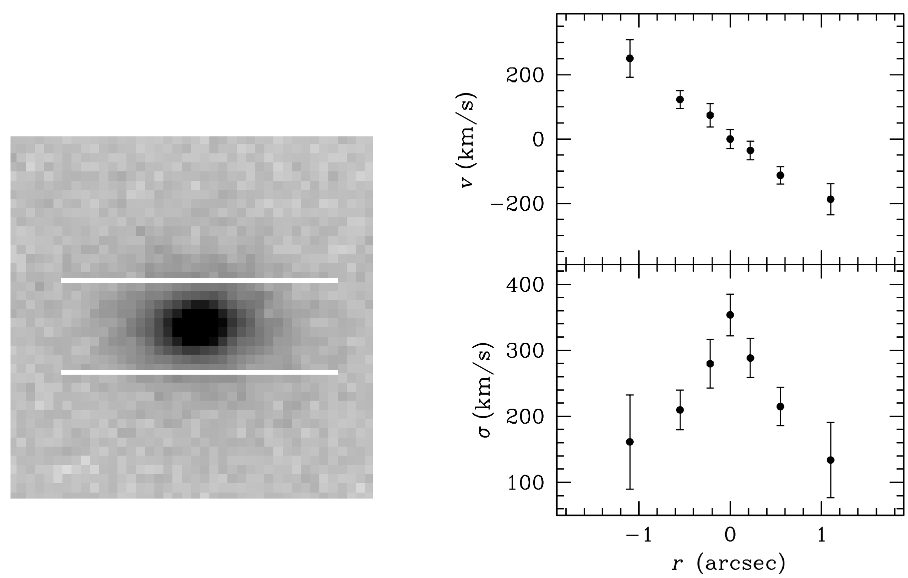

Figure 5. Based on the HST image shown at left it is difficult to determine whether this $z = 0.83$ galaxy is an E or an S0. The kinematics reveal a rapidly rotating disk, demonstrating that this is an S0.

3.3. Mergers in $z \sim 1$ clusters

The discovery of a large number of red merger systems in the cluster MS 1054–03 at $z = 0.83$ is arguably the most spectacular evidence for recent formation of massive early-type galaxies (van Dokkum et al. 1999). We obtained deep, multicolor images of this cluster at 6 pointings with WFPC2 on HST. Redshifts of galaxies in this field were obtained with the Keck Telescope; 89 of those are cluster members. The survey is described in van Dokkum et al. (2000).

We found that 17 % of the galaxies in MS 1054–03 are merger systems. Most of the mergers are very luminous ($M_B \sim -22$ in the rest frame, or $\sim 2L_*$ at $z = 0.83$), and a striking way to display our result is to show a panel with the 16 brightest confirmed cluster members (Fig. 6). Five were classified as mergers.

The mergers are generally red, with a few exceptions. Similarly, the spectra of most of the mergers do not show strong emission lines. These results suggest that the bulk of the stars was formed well before the merger. Hence the stellar age of the merged galaxies will be significantly different from the “assembly

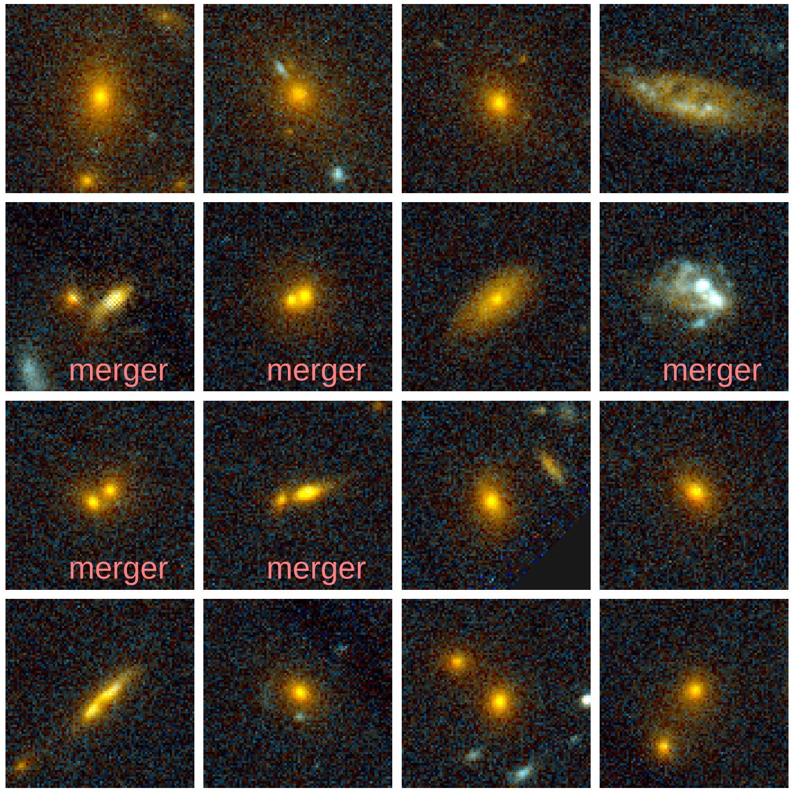

Figure 6. The 16 brightest confirmed members of MS 1054–03 at $z = 0.83$, ordered by I magnitude. Note the large number of mergers. A color version of this figure can be found at http://www.astro.caltech.edu/~pgd/ms1054.

age". The physical reason for the low star formation is unknown: it is possible that the massive precursor galaxies had already lost their cold gas due to internal processes (such as super winds, or winds driven by nuclear activity). Alternatively, the cold gas may have been stripped by the cluster X-ray gas, or exhausted in an earlier phase of merging in dense, infalling groups.

It is not yet known whether the galaxy population of MS 1054–03 is typical for its redshift. One possibility is that such a phase of enhanced merging occurs at different redshifts for different clusters. In MS 1054–03 the mergers probably occur in infalling subclumps, and its high merger fraction could be related to its overall unvirialized state (van Dokkum et al. 1999).

We recently completed a morphological study of an even higher redshift cluster, RXJ 0848+4453 at $z = 1.27$ (van Dokkum et al. 2001). The Brightest Cluster Galaxy has an asymmetric outer envelope, demonstrating that it recently experienced a merger or strong tidal interaction. The second brightest galaxy is yet another red merger system, in this case between three galaxies of comparable brightness. This remarkable system shows that red mergers are not unique to MS 1054–03, and may even be common at $z \sim 1$. Studies of more clusters are required to better quantify the role of these red mergers in the formation of massive galaxies.

4. Effects of morphological evolution: the progenitor bias

The existence of the Butcher-Oemler effect, the evolution of the early-type galaxy fraction, and the presence of mergers in distant clusters imply that simple models for the evolution of early-type galaxies in clusters are insufficient. Therefore, we need to consider more complex models that incorporate morphological transformations. The problem was first addressed in Franx & van Dokkum (1996), and worked out in van Dokkum & Franx (2001).

4.1. Complex models

We assume that early-type galaxies have two phases in their history: first a relatively long phase in which they were forming stars, at a rate which can be constant, or variable with time. Second, they are transformed into galaxies without star formation, through a merger, gas-stripping, or other mechanism. During a period of ≈ 1 Gyr they are classified as post-starburst galaxy, merger galaxy, or other "special type". After that, they are classified as normal early-type galaxies. As a result, the set of early-type galaxies evolves, and the set of galaxies classified as early-types at $z = 0$ is not the same as the set of galaxies classified as early-types at high redshift.

The evolution of the M/L ratio of individual galaxies is shown in Fig. 7c. The evolution of the M/L ratio of each galaxy is indicated with a dotted line when it is not yet classified as early-type, and with a continuous curve when it is classified as early-type galaxy. As is obvious from the plot, the continuous addition of young early-type galaxies to the sample has a significant effect on the evolution of the mean M/L ratio: the newly added galaxies pull the mean M/L ratio to lower values. As a result the evolution of the mean M/L ratio of the full sample is very slow – much slower than the evolution of the M/L ratio of "typical" individual galaxies. This effect is called "progenitor bias": as we compare the M/L ratios of early-type galaxies at different redshifts, we compare between different sets of galaxies, and the evolution of their properties can be misinterpreted when morphological evolution is ignored.

The evolution of the mean M/L ratio of the early-types is shown in Fig. 7d. As can be seen, the mean evolution is slow. The slope of the $M/L - z$ relation is comparable to the slope for a single galaxy which formed at very high redshift, even though the mean formation redshift of all early-type galaxies at $z = 0$ is low at $z_{\rm form} = 2$. The long dashed curve in the figure indicates the evolution of the mean M/L ratio of all galaxies classified as early-types at $z = 0$. The evolution is much faster, as expected. The difference between these two curves is caused by the progenitor bias, and it can be quite substantial.

The scatter for the early-types at any redshift is indicated by the shaded region in Fig. 7d. Because the youngest galaxies drop out of the sample at higher redshift, the scatter remains constant, or even decreases slightly at higher redshift. The same holds for the scatter in the CM relation. This counter-intuitive result can be explained by the fact that the models are approximately

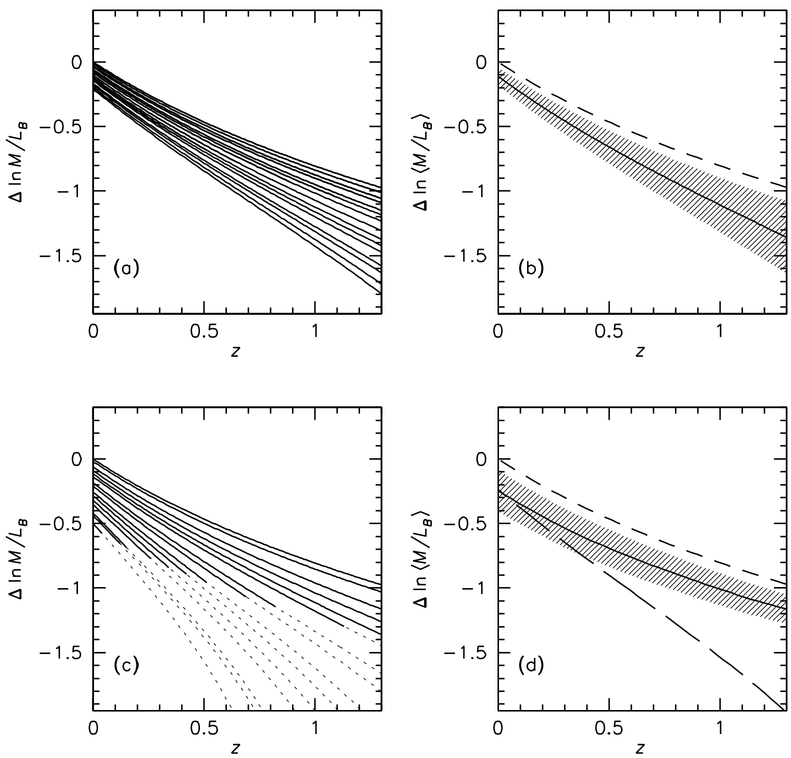

Figure 7. Model predictions for the evolution of the M/L ratio for simple models (a,b), and complex models with morphological transformations (c,d). See text and van Dokkum & Franx (2001).

scale free in time, and the relative age differences between the early-type galaxies are similar at all times.

4.2. Application to data

Figure 8 shows two models which fit the evolution of the M/L ratio measured from the Fundamental Plane, and the evolution of the scatter in the color-magnitude relation. The morphological transformations are described by a simple function which provides a good fit (panel a). Two models are explored for the star formation rate during the phase when the galaxies are spirals: the solid line indicates a model with constant star formation rate, and the dotted line shows a model with declining star formation rate. They both fit the evolution of the M/L ratio well (panel b). The model with the declining star formation ratio underpredicts the scatter in the color magnitude relation and M/L ratios. Hence for this model the scatter is not produced entirely by age differences, but also by scatter in the metallicity-magnitude relation, or other effects.

The progenitor bias for the two models is different, as might be expected from the difference in the predicted scatter due to age variations. When the evolution of the M/L ratio is fitted with a simple model without morphological transformations, we obtain a mean formation redshift $z_{\rm form} = 6.5$. The complex

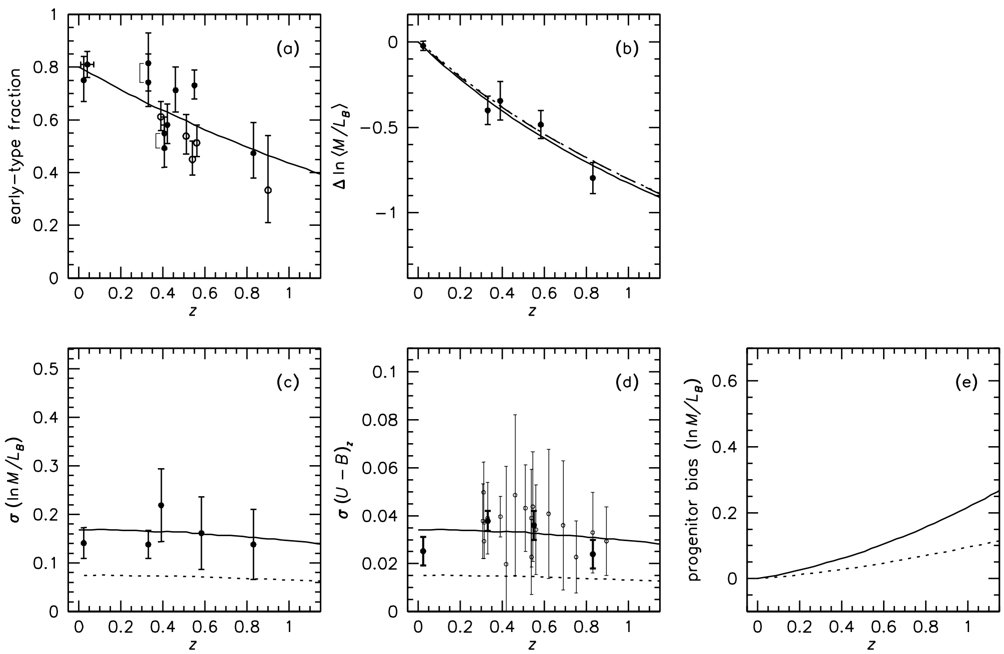

Figure 8. Complex models fitted to observations. Models which include morphological transformations can fit the evolution of the early-type galaxy fraction (a), the mean M/L ratio (b), and the scatter in the FP (c) and the CM relation (d) simultaneously. The error that is made when using simple models (i.e., without morphological transformations) is shown in (e). See van Dokkum & Franx (2001) for details.

model with constant star formation produces an estimate of $z_{\rm form} = 3$. The model with a declining star formation rate produces $z_{\rm form} = 4$. These values apply for a cosmology with $\Omega_m = 0.3$. They change to 2.6, 2.0, and 2.2, respectively, for a flat universe with $\Omega_m = 0.3$. Hence the effects of the progenitor bias are modest, but should not be ignored.

5. Conclusions

Models which include morphological transformations can reconcile two apparently contradictory lines of evidence: the low scatter in the color magnitude relation and the slow evolution of the M/L ratio on one hand, and the morphological evolution observed in rich clusters on the other. A basic framework for galaxy evolution in clusters, which includes infall and morphological transformations, seems to be developing and future observations will be aimed at refining and testing these ideas. The available data at $z \sim 1$ are still sparse, and the clusters that have been studied so far may not be typical progenitors of "run of the mill" nearby clusters. It is expected that ACS on HST will make it much easier to study clusters at this epoch; the future of this field can therefore be considered bright!

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