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The evolution and merging history of cluster ellipticals from $z = 0$ to $z = 0.83$

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The evolution of galaxies is likely to be complex, involving mergers, starbursts, and other dramatic changes in morphology and luminosity. The measurement of the evolution of the mass function of galaxies is therefore essential. This can be accomplished by measuring the evolution of the mass-to-light ratios of galaxies as a function of redshift. The Fundamental Plane relation is uniquely suited to measure the evolution of the mass-to-light ratio of early-type galaxies. We show that the evolution depends sensitively on cosmology and star-formation history. We present results on the evolution of the mass-to-light ratio from the Fundamental Plane out to $z = 0.83$. The early-type galaxies in clusters follow a well-defined relation out the highest redshift. The mass-to-light evolution is very slow, and implies a high mean stellar age in an open universe.

One of the main uncertainties in the interpretation is morphological evolution. If the youngest early types at low redshift appear as other morphological types at high redshift, then the study of early-type galaxies at high redshifts will produce biased results. We discuss the effects of this 'progenitor bias'. We show evidence for significant morphological evolution for all early types (elliptical and S0 galaxies). We find a high fraction of mergers in MS 1054-03, comparable with the fraction of ellipticals. Furthermore, the total fraction of early types in rich clusters decreases from $z = 0$ to $z = 0.83$. These results suggest that the set of early types is not a closed set, but evolving. The effects on the derived evolution of the mass-to-light ratio is relatively small, due to the small scatter.

The next step will be to extend these studies to high redshift clusters, and to the field. This work can provide very strong constraints on the mass evolution of galaxies.

Keywords: galaxies; clusters; galaxy, formation of

1. Introduction

One of the important questions in the field of galaxy formation and evolution is that of the mass evolution of galaxies. Did galaxies form very quickly, at high redshift? Or did galaxies form by the gradual accumulation of smaller building blocks? The earliest models of galaxy formation assumed that galaxies formed very quickly. Later, when it was found that galaxies have large dark halos, the formation time-scale increased manyfold. Subsequent theories of galaxy formation allowed for galaxies to form slowly and at a late moment. In most of these theories galaxies are assembled by the merging of smaller building blocks. Such merging has been observed in the nearby Universe, but the frequency at which it occurs is relatively low (e.g. Toomre 1977).

Hence, one of the major challenges in current-day astronomy is to measure the mass evolution of galaxies, and galaxy clusters; as this will provide an immediate test of these ideas. Unfortunately, the total masses of galaxies are notoriously difficult to measure. Fortunately, we can use other characteristics to establish mass evolution, and these are primarily the circular velocities of gas in spiral galaxies, and the velocity dispersions of stars in early-type galaxies. These kinematic indicators are measured at the scale of the luminous parts of galaxies (very large gas discs in spiral galaxies are generally rare). Hence they cannot provide us directly with information about the total masses. Fortunately, they are most likely related to the halo properties of galaxies, and merging and accumulation of galaxies is expected to lead to evolution of these characteristic velocities.

Another helpful factor is the existence of the Tully–Fisher relation, and the Fundamental Plane. The Tully–Fisher relation is a relation between the luminosity, and rotational velocity, and the Fundamental Plane is a relation between surface brightness, effective scale length, and velocity dispersion. Their relatively small scatter in the nearby Universe implies that we do not have to measure the characteristic velocities for all galaxies, but that we can obtain good insight into galaxy evolution by measuring the evolution of these relations, combined with the evolution of the luminosity function.

In practice, the measurement of the kinematic indicators out to high redshift is hard. In order to obtain reliable rotation curves of spiral galaxies, galaxies need to be resolved, and this is hard (but not impossible) at higher redshift. Early results by Vogt *et al*. (1996) on the Tully–Fisher relation for spiral galaxies have shown that it is possible to achieve this on small subsamples of galaxies. Here we focus on the Fundamental Plane of early-type galaxies. It is easier to work on early-type galaxies, as the galaxies do not need to be resolved to measure their central velocity dispersions (e.g. Franx 1993*a*, *b*). Furthermore, the scatter in the Fundamental Plane is very small.

2. Passive evolution, or evolution of the M/L ratio from the Fundamental Plane

We have started a programme to measure the evolution of the Fundamental Plane relation with redshift. Early results can be found in Franx (1993*a*, *b*, 1995). The Fundamental Plane is a relation between effective radius r_e, effective surface brightness I_e, and central velocity dispersion σ of the form

$$r_\mathrm{e} \propto \sigma^{1.24} I_\mathrm{e}^{-0.82}$$

(see, for example, Djorgovski & Davis (1987), Dressler *et al*. (1987), Jørgensen *et al*. (1996), and references therein). Its scatter is low, at 17% in r_e. The implication of the Fundamental Plane is that the M/L ratios of galaxies are well behaved (e.g.

Faber *et al*. 1987). Under the assumption that galaxies are a homologous family, the implied M/L scaling is

$$M/L \propto r_{\mathrm{e}}^{0.22}\sigma^{0.49} \propto M^{0.24}.$$

Such scaling is sufficient for the existence of the Fundamental Plane, and vice versa. The cause of the variation in M/L with mass is not well understood, but it is thought to be mainly due to variations in metallicity (see also Renzini & Ciotti 1993).

The low scatter of the Fundamenal Plane makes it very suitable for the study of evolution of the M/L ratio at higher redshift. The evolution of the M/L ratio at a given redshift can be derived from 5–10 galaxies, and the evolutionary signal is much stronger than the intrinsic scatter. Below we explore models for the evolution of M/L as a function of redshift.

(*a*) *Models for the evolution of the M/L ratio*

The luminosity of a coeval stellar population is expected to evolve with time. Tinsley (1980) showed that the luminosity evolves like

$$L \propto 1/(t - t_{\mathrm{form}})^{\kappa},$$

where $\kappa = 1.3 - 0.3x$, and x is the slope of the initial mass function (IMF). The Miller–Scalo IMF implies $x = 0.25$, and $\kappa \approx 1.2$. Recent studies indicate that the value of κ depends on passband and metallicity (Buzzoni 1989; Worthey 1994). These authors find $0.6 < \kappa < 0.95$ for the V band.

The observer measures redshift, and not time. In redshift space, the evolution depends on the formation redshift of the stellar population z_{form}, and cosmology. For very low values of q_0, the evolution can be approximated by

$$\ln M/L(z) = \ln M/L(0) - \kappa(1 + q_0 + 1/z_{\mathrm{form}})z$$

(Franx 1995). Hence the logarithm of the M/L ratio is expected to decrease linearly with redshift, and the coefficient depends on κ (IMF), q_0, and z_{form}. The rate at which the M/L ratio evolves is a function of several unknown variables, and a direct interpretation of the observed decrease of the M/L ratio may not be very straightforward.

Figure 1*a* shows the expected evolution of the M/L ratio if all galaxies have formed at the same redshift. As can be seen, the evolution depends strongly on the formation redshift. It is unlikely that galaxies formed in such a simple way. For figure 1*b* we explored models in which galaxies form at a range of redshifts. As a result, scatter is introduced in the M/L ratio, which increases with look-back time. This is due to the fact that the relative age difference increases with look-back time.

(*b*) *Complex evolution*

Even the last model is probably an over-simplification of the formation of early types. There is no good reason to assume that all stars in an early-type galaxy formed in a very short burst. A single galaxy may have had a complex formation history, with star formation extending over a long time. The evolution of the M/L ratio will be more complex if such age differences are taken into account. It is likely that the morphologies of galaxies change as well, for example from spiral, to merger, to post-starburst galaxy, to early type. This has important consequences, since the set

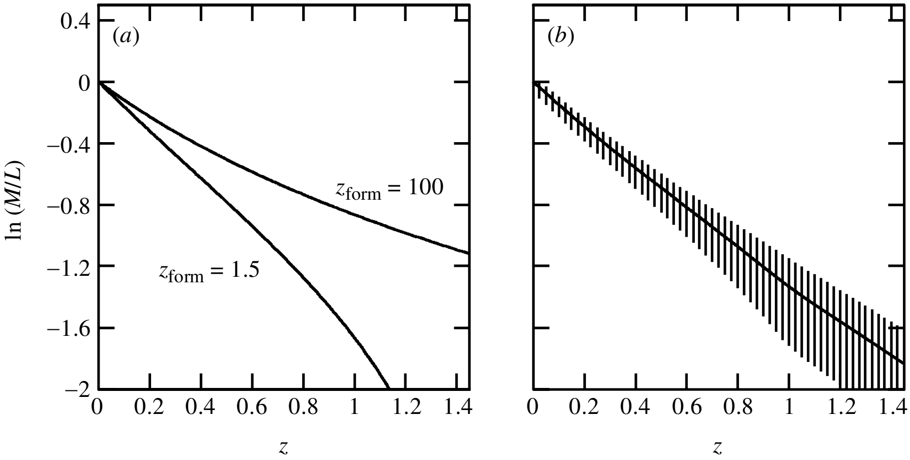

Figure 1. The evolution of galaxies with a simple star-formation history. (*a*) The luminosity evolution for galaxies with coeval populations. Galaxies which formed recently evolve faster. (*b*) The evolution of the mean M/L ratio for a sample of early types which formed at a random time between $z = 1$ and $z = 3$. The shaded area indicates the scatter in the M/L ratio. The scatter in the relation increases with redshift, as the relative age difference increases with look-back time.

of early types at higher redshifts will be a special subset of the set of early types at $z = 0$. If we select early types at higher and higher redshift, we may be selecting a subsample that is more and more biased towards the oldest early types. In short, we may be selecting the oldest galaxies, and find that they are old. The effects of this evolution complicates the interpretation of the results significantly.

3. The Fundamental Plane to $z = 0.83$

With modern telescopes and efficient instrumentation, it is possible to measure the Fundamental Plane out to a redshift of 1. After our first work on Abell 665 (Franx 1993*a*, *b*; Jorgensen *et al*. 1999) and CL0024+16 (van Dokkum & Franx 1996) with the Multiple Mirror Telescope, we started to use the Keck telescopes to measure the Fundamental Plane in three clusters: MS 1358+62 at $z = 0.33$, MS 2053-05 at $z = 0.58$, and MS 1054-03 at $z = 0.83$ (see van Dokkum *et al*. (1998), Kelson *et al*. (2000), and references therein). Figure 2 shows the resulting Fundamental Planes from $z = 0$ to $z = 0.83$. The figure demonstrates how well the relation is defined at each redshift interval.

The scatter in the relation remains low. We find a typical scatter between 15 and 20%, quite comparable with the scatter in nearby rich clusters. The results obtained by other groups at $z < 0.6$ agree well with these results (e.g. Bender *et al*. 1998).

4. Evolution of the $M/L_{\rm B}$ ratio to $z = 0.83$

We can derive the evolution of the $M/L_{\rm B}$ ratio from the offsets of the Fundamental Plane relation as a function of redshift. A necessary assumption is that early-type galaxies in clusters do not have significant morphological evolution between $z = 0$ and $z = 0.83$. We return to this later.

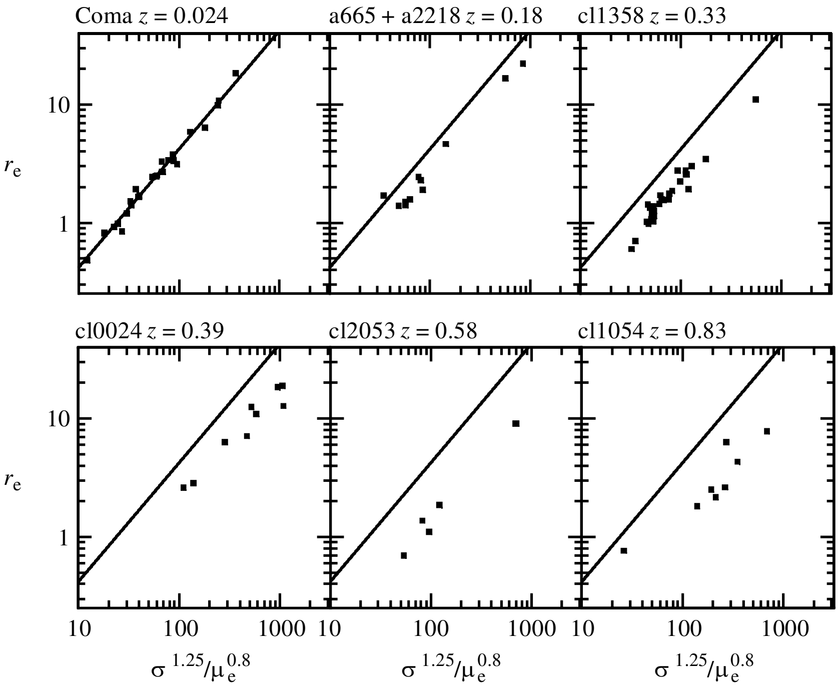

Figure 2. The evolution of the Fundamental Plane from $z = 0$ to $z = 0.83$. The panels show the Fundamental Planes for the programme clusters. The drawn line is the relation for Coma. The cluster galaxies follow a relation very similar to the relation for the Coma galaxies. The main difference is the offset, which is mostly due to surface brightness dimming.

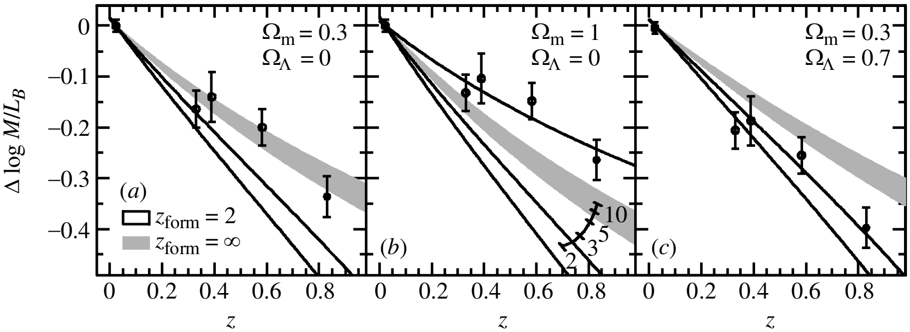

Figure 3. The evolution of the mean M/L_B ratio, after correction for surface brightness dimming. The M/L_B ratio decreases slowly with redshift. The drawn lines indicate stellar population models with formation redshifts of 2. The shaded area indicates models with a formation redshift of ∞. The three panels show the data and models for three different cosmologies. The models can provide good fits for open universes, (*a*) and (*c*), but no good fit for a closed universe, (*b*). In the latter case, the IMF needs to be steepened significantly (indicated by a dashed line).

The result is shown in figure 3. The clusters galaxies show a gradual change in M/L_B ratio, which can be approximated with a simple curve. The results imply that the star-formation history of early-type galaxies in clusters is very similar, consistent with the tightness of the Fundamental Plane and colour-magnitude relation at low redshift.

The evolution of the M/L_{B} ratio is very slow. It can be well fitted with a model in which galaxies form at high redshift ($z_{\mathrm{form}} = 2.8$), if $\Omega = 0.3$. It is very difficult to obtain a good fit for high Ω models (van Dokkum *et al*. 1998). In this case, the IMF needs to be significantly steeper than Salpeter.

The shape of the Fundamental Plane at high redshift is surprisingly similar to the Fundamental Plane at zero redshift. We analysed a sample of 31 early-type galaxies in MS 1358+62 (Kelson *et al*. 2000). This full sample is shown in the panel of figure 2. The slope of the relation for the early-type galaxies is consistent with the slope at zero redshift. Accurate morphologies are essential for this work, as the inclusion of early type spirals changes the relation drastically. It is therefore necessary to obtain imaging with the Hubble Space Telescope (HST) for this kind of work. We are currently working on large cluster samples out to $z = 0.83$.

5. Morphological evolution of cluster galaxies

The results of the previous sections have indicated that the evolution of early-type galaxies in clusters is very slow, and their mean stellar ages very high. We have noted, however, that morphological evolution can produce a bias in our results. If early-type galaxies have a spread in ages, then the youngest galaxies will not look like early types at higher redshifts, and will be excluded from the sample.

We can constrain this effect by studying the morphological evolution of early-type galaxies in clusters. If morphological evolution is significant out to $z = 0.83$, then we might expect to find different morphological distributions at higher redshifts. Such effects have been described before (e.g. Dressler *et al*. 1997), and we present below our new results on the highest redshift cluster studied.

(*a*) *Observations of MS 1054-03*

We have taken deep, multicolour images of MS 1054-03 at six pointings with WFPC2 on the HST. The Keck telescope was used to take 200 spectra, aimed to be complete to an I magnitude of 22.7. The typical integration time per galaxy was 40 min. We were able to measure redshifts of 186 galaxies, and of those, 80 were cluster members. Together with data from literature, we found 89 cluster members, of which 81 lie in the area of the HST images.

(*b*) *Merger fraction*

We classified the spectroscopically confirmed cluster members, analogous to our classification of galaxies in MS 1358+62 (Fabricant *et al*. 2000). We classified galaxies along the revised Hubble sequence. We allowed for a separate category of mergers. We combined the three classifications from three of us, and verified that the results were robust from classifier to classifier. The results are presented in van Dokkum *et al*. (1999, 2000).

The main outcome of this exercise is the high fraction of mergers in MS 1054-03. Many of these mergers are very luminous. One of the most striking ways to display the effect is to show a panel with the 16 brightest galaxies (figure 4). Five out of

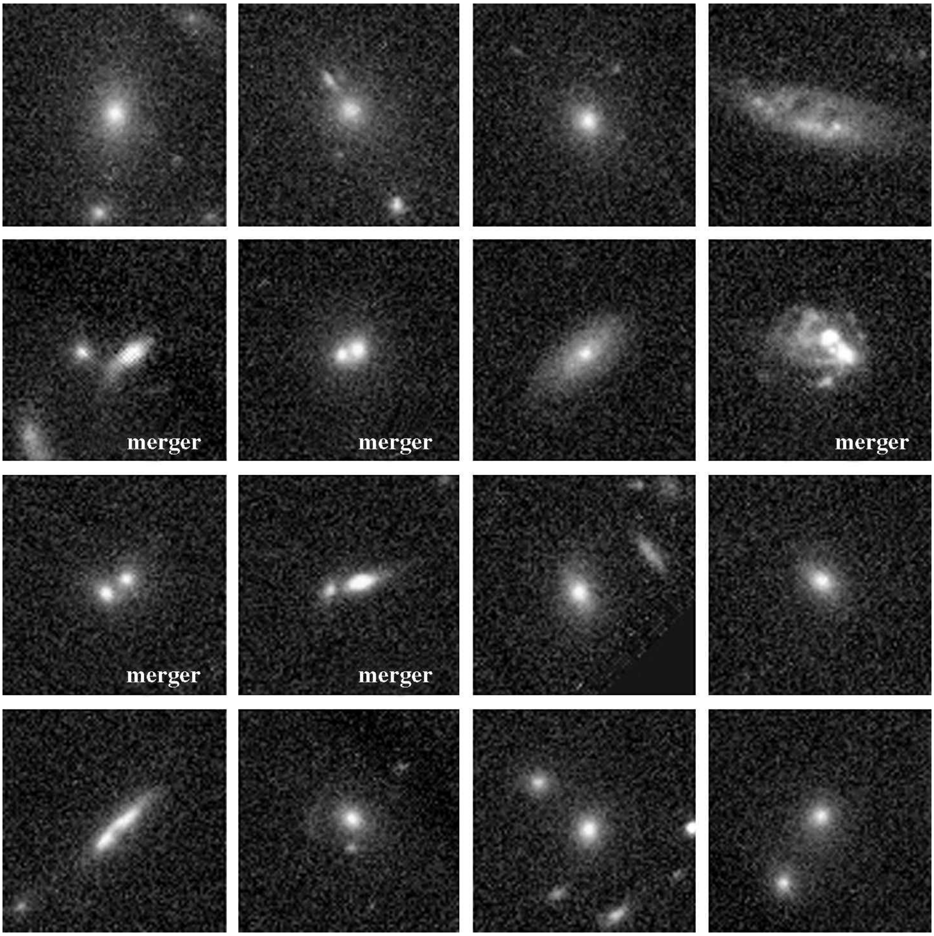

Figure 4. Brightest 16 galaxies in MS 1054-03 at $z = 0.83$. These galaxies are spectroscopically confirmed cluster members, and selected on the basis of their rest-frame B luminosity. Five out of 16 are classified as mergers. The fraction of mergers remains similar if galaxies are corrected for the luminosity brightening. Each image has a physical scale of $30h^{-1}$ kpc on a side.

these 16 were classified as mergers. A colour version of figures 4 and 5 can be found at http://www.strw.leidenuniv.nl/~franx/clusters.

A similar mosaic of the cluster MS 1358+62 at $z = 0.33$ is shown in figure 5. The absence of mergers in this lower redshift cluster, and the much more homogeneous colour distribution are notable.

The enhancement of peculiar galaxies in MS 1054-03 could be due to the brightening of low-mass galaxies during a starburst. We verified that the merger fraction remains high if the galaxies are selected by mass, instead of (blue) luminosity.

The optical colours of the mergers are consistent with this result. As shown in figure 6, 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 of the mergers were formed well before the mergers. Hence the stellar age of the merged galaxies is significantly different from the 'assembly age', i.e. the time at which the galaxy 'was put together'.

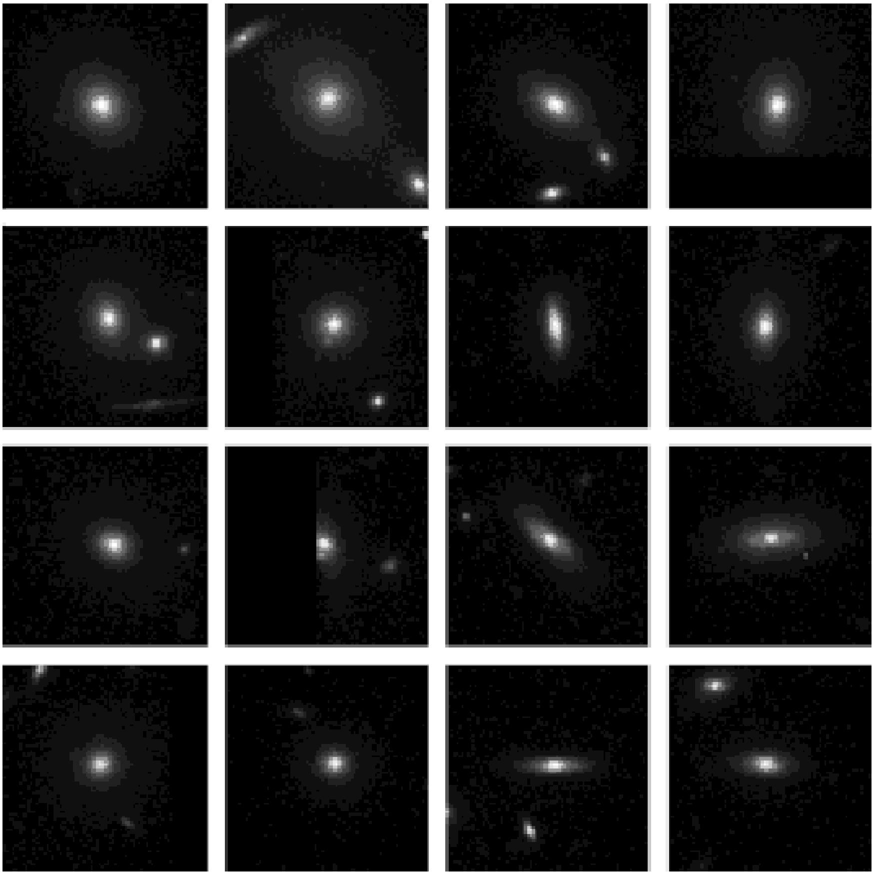

Figure 5. Brightest 16 galaxies in MS 1358+62 at $z = 0.33$, selected in the same way as the galaxies in MS 1054-03. Each image has a physical scale of $30h^{-1}$ kpc on a side.

The results are consistent with the hypothesis that the mergers evolve into ellipticals. Their scatter in the colour-magnitude diagram is significantly larger than the scatter for the ellipticals (0.073 versus 0.045 in rest frame U-B). After ageing of the stellar populations, the scatter of the total population of mergers + ellipticals will have decreased from 0.054 at $z = 0.83$ to 0.015 at $z = 0$. Hence a low scatter at $z = 0$ does not mean that all galaxies in the population are homogeneous and very old: the influence of merging can be small if the star formation involved with the merging is low.

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 cluster environment may play an important role: the cold gas may have been stripped by the cluster X-ray gas. Observations of more clusters may shed further light on this effect.

(c) *Pair fraction*

Whereas the classifications of galaxies remains a subjective procedure, counting close pairs of galaxies is a very objective way to establish whether interactions and

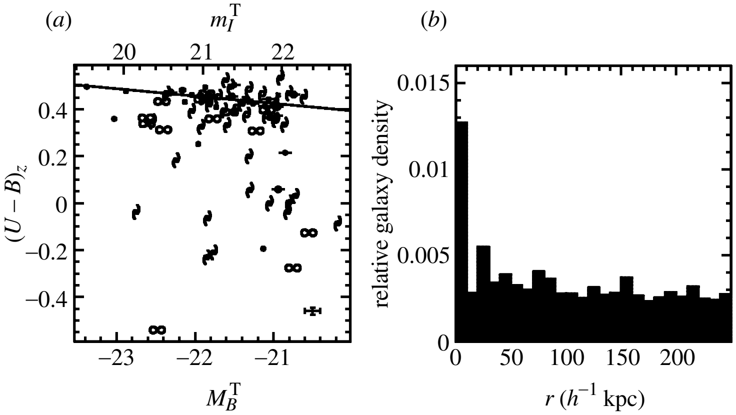

Figure 6. (a) The colour magnitude diagram for confirmed cluster members of MS 1054-03. The mergers are indicated by ∞ symbols. They are generally red, although slightly bluer than ellipticals and S0s. After ageing to $z = 0$, the scatter in the sample of ellipticals + mergers will be identical to that of ellipticals in nearby clusters. (b) The overdensity of pairs in the outskirts of MS 1054-03. There is a clear excess of pairs at small separations of less than $10h^{-1}$ kpc. This is independent confirmation of the enhanced interaction rate in MS 1054-03.

mergers are enhanced. Furthermore, the distribution of pairs may shed light on the future merging rate in the cluster. We have counted the number of pairs in the outskirts of the cluster, to avoid the high density core. The pair fraction is shown in figure 6b. As we can see, there is an excess of pairs at small separations (less than $10h^{-1}$ kpc). Half of these are classified as mergers, the other half not. These may constitute a reservoir of 'future' mergers. It will be interesting to measure the velocity differences of the galaxies in pairs.

(d) *Evolution of the fraction of early types*

The results on MS 1054-03 have demonstrated that the fraction of mergers is high in at least one cluster. It remains to be seen how typical this result is for other clusters. At a minimum, the high merger fraction in MS 1054-03 shows that late merging can occur, and is likely to produce early-type galaxies which will form a homogeneous set at low redshift. At a maximum, most or all early types in clusters went through a phase of late merging. The merging phase may even be later (i.e. at lower redshift) for galaxies in less massive clusters, and the field. A full description of these effects will have to wait until large samples of field galaxies and low-mass cluster galaxies have been studied. In the meantime, we can study the morphological fractions in rich clusters to test whether they are consistent with a gradual evolution.

We take a slightly different approach from that of Dressler *et al.* (1997). Whereas those authors focused on the ratio of ellipticals to S0s in higher redshift clusters, we study the fraction of early types (i.e. ellipticals plus S0s). This is motivated by the fact that we apply the Fundamental Plane to all early types, and by the practical difficulty in separating ellipticals and S0s, especially at high redshift.

We show our preliminary results in figure 7. Notice the gradual decline in early type fraction with redshift. Clearly, many clusters will need to be studied to measure this effect reliably. Nevertheless, the figure indicates that the assumption that early types do not evolve morphologically is not justified by these data.

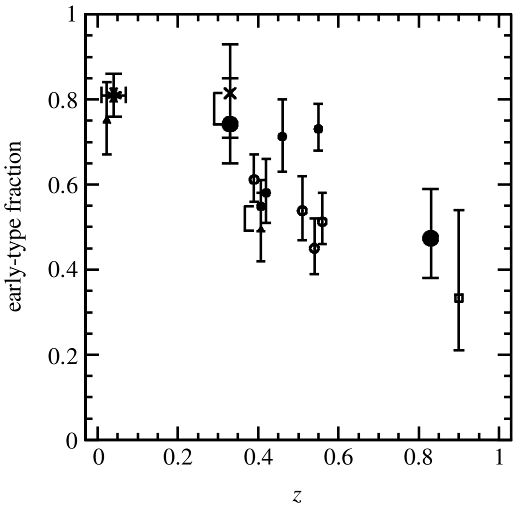

Figure 7. The fraction of early-type galaxies as a function of redshift (van Dokkum *et al*. 1999, and references therein). The filled symbols show X-ray bright clusters. The large symbols show clusters for which we have full membership information and morphological types. Two clusters have been classified by two groups, and the results are linked. All datasets, including the extensive data by Dressler *et al*. (1997), are consistent with a gradual evolution.

A full discussion of the implications will be given elsewhere (van Dokkum & Franx 2000). We can estimate roughly how this might effect our Fundamental Plane measurement. The results imply that only 60% of early types were in place at $z = 0.83$. In the simplest models, these 60% would be the oldest 60% of early types at zero redshift. The zero point of the Fundamental Plane for this oldest 60% would be shifted by a value comparable with the scatter in the Fundamental Plane, which is 15% in the mass-to-light ratio. The gradient would be underestimated by about $0.3 \times z$.

This simple discussion shows that it is essential to use relations with small internal scatter. The effects of biases are directly proportional to the scatter. This makes the Fundamental Plane uniquely suited for evolutionary studies.

6. Discussion

We have shown that it is possible to determine the Fundamental Plane at intermediate redshifts, all the way up to $z = 0.83$. The relation is well defined at these redshifts, with a relatively low scatter less than 20%. The mean evolution of the M/L_B ratio is low, at about $\Delta \log M/L_B = 0.4z$ for $\Omega = 0.3$. This evolution is consistent with an early star formation epoch for our galaxies, and is difficult to reconcile with a closed universe and normal IMF. We note, however, that the current measurement may be biased, mostly due to the fact that we only use non-star-forming red galaxies. We may therefore exclude the star-forming progenitors of current-day early-type galaxies.

We have therefore started to study the morphological fractions in our programme clusters. As a first result, we have found a high fraction of mergers in our highest redshift cluster, MS 1054-03 at $z = 0.83$. The mergers are generally red. The fraction of mergers is comparable with the number of ellipticals. The results are qualitatively consistent with the hypothesis of hierarchical galaxy formation. The relatively old stellar age of the mergers compared with the young 'assembly age' is consistent with predictions from semi-analytical models (e.g. Kauffmann 1996).

The results are inconsistent with the hypothesis that all ellipticals are formed and assembled at very high redshift. Nevertheless, many questions remain open. (i) Is the result for MS 1054-03 typical for high redshift clusters? Is the merger fraction higher or lower in the field? It is interesting to note that studies of the field give high merger fractions and/or pair fractions at intermediate redshift (e.g. Patton *et al*. 1997; Le Fevre *et al*. 1999). It remains to be seen whether these field mergers are as massive as the mergers found in MS 1054-03. (ii) What is the typical redshift at which the mass of early-type galaxies was half of the current mass? (iii) When did the major episode of star formation occur?

More complete studies, of both clusters and the field, are necessary to answer these questions. We have roughly estimated the effect of morphological evolution on the evolution of the Fundamental Plane. We show that it is proportional to the scatter, which, fortunately, is low. The Fundamental Plane is therefore uniquely suited for evolutionary studies.

Studies are in progress to extend this work to higher redshift, and to the field (e.g. Treu *et al*. 1999; van Dokkum *et al*. 2000). These can be expected to yield results relatively soon. The new generation optical telescopes will allow a rapid extension of this type of work to larger samples, higher redshifts, and lower galaxy masses.

The future observations will be used to determine the evolution of the distribution of circular velocities for galaxies $F(v_{\mathrm{c}}, z)$, and the evolution of stellar masses locked up in early-type galaxies $F(M_*, z)$. This requires accurate observations of the evolution of the luminosity function and the 'mass relations' in the field. The final outcome of such a programme can be expected to provide strong constraints on the models of galaxy formation and evolution.

It is a pleasure to thank the organizers for a stimulating conference.

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