Evolution of early-type galaxies in clusters

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Abstract. The slow evolution of the $M/L$ ratios, colors, and line strengths of cluster early-type galaxies to $z \sim 1$ suggests that their stars were formed at very high redshift. At the same time, morphological studies of distant clusters indicate significant evolution in the early-type galaxy population. Striking evidence for strong morphological evolution in clusters is the discovery of a large number of red merger systems in the cluster MS 1054–03 at $z = 0.83$. The presence of these mergers is qualitatively consistent with predictions from hierarchical galaxy formation models, and is direct evidence against an early collapse for all early-type galaxies. In most of the mergers there is no evidence for strong star formation. Therefore the mean stellar ages of the merger products will be much older than the “assembly age”, and do not violate the constraints on the star formation epoch of early-type galaxies imposed by the color-magnitude relation and the Fundamental Plane.

1 Introduction

The field of galaxy evolution in rich clusters has witnessed great progress in recent years, in large part because of the powerful combination of Hubble Space Telescope imaging and spectroscopy with large ground-based telescopes. Examples of successful programs are the MORPHS collaboration [14], who obtained deep HST images of $\sim 10$ clusters at $0.3 < z < 0.5$, and the CNOC group [21], who obtained extensive wide field spectroscopy and imaging of X-ray selected clusters at $0.2 < z < 0.5$.

Our strategy is complementary to these efforts. We are obtaining wide field, deep HST WFPC2 images of several clusters at $0.3 < z < 0.9$, in combination with extensive spectroscopic follow-up using the Keck telescope. The combination of the various programs will produce a balanced data set on distant galaxy clusters.

2 Evidence for old stellar populations

Studies of the evolution of early-type galaxies in clusters are in remarkable agreement. Studies of colors [6,15], $M/L$ ratios [16,9,17,1,10], and line
The strengths [1,11] of early-type galaxies in distant clusters all show that they form a very homogeneous, slowly evolving population all the way from $z = 0$ to $z = 1$. As an example, the scatter in the color-magnitude relation remains very small to $z \sim 1$ [12], placing a strong upper limit on the scatter in ages of early-type galaxy at any given time.

The strongest constraints on the mean star formation epoch have come from the evolution of the Fundamental Plane (FP) relation. The Fundamental Plane [3] is a relation between the effective radius $r_e$, effective surface brightness $\mu_e$, and central velocity dispersion $\sigma$, such that $r_e \mu_e^{0.8} \propto \sigma^{1.25}$. The implication of the existence of the Fundamental Plane is that $M/L$ ratios of galaxies correlate strongly with their structural parameters: $M/L \propto r_e^{0.2} \mu_e^{0.4} \propto M^{0.2}$ [7]. The power of the FP lies in its small scatter and its relation to $M/L$ ratios. The $M/L$ ratios of galaxies evolve because the luminosity of their stellar populations decreases as they age (“passive evolution”), and the 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 [17]. The evolution is surprisingly low, $\ln M/L_B \propto -z$, indicating stellar formation redshifts of $z > 3$ for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0$ [17].

### 3 Evidence for morphological evolution

Although early-type galaxies appear to form a very stable, slowly evolving population, evidence is accumulating that a large fraction of early-type galaxies in nearby clusters was relatively recently assembled, and/or transformed from spiral galaxies. Hence the (usually implicit) assumption in studies of the CM relation or the FP that the set of high redshift early-type galaxies is similar to the set of low redshift early-type galaxies is probably not justified.
3.1 Evolution of the early-type galaxy fraction

Dressler et al. report a high fraction of spiral galaxies in clusters at $0.3 < z < 0.5$ [5]. These galaxies are nearly absent in nearby rich clusters, and hence must have transformed into early-type galaxies between $z = 0.5$ and $z = 0$. Other studies [2,19] have confirmed this trend, and extended it to $z = 0.8$. The evolution of the early-type galaxy fraction is shown in Fig. 2. The early-type fraction decreases by a factor $\sim 2$ from $z = 0$ to $z = 1$, although the trend has significant scatter.

Dressler et al. [5] 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. Other studies [12,4,2,18] have found evidence for merging and interactions in high redshift clusters [2,12,13]. These transformations may provide a way to form young elliptical galaxies in the clusters at late times.

3.2 Mergers in MS 1054–03 at $z = 0.83$

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. We have obtained deep, multi-color images of MS 1054–03 at 6 pointings with WFPC2 on HST. The Keck telescope was used to measure redshifts of 186 galaxies, and 80 of those are cluster members. Together with data from the literature, we found 89 cluster members, 81 of which are in the HST mosaic. We classified the galaxies along the revised Hubble sequence, allowing for a separate category of mergers. We combined classifications of three of us, and verified that the results were robust from classifier to classifier. The results have been presented in [18,19].
The most surprising result of our survey of MS 1054–03 is the high fraction of mergers. Most of the mergers are very luminous ($M_B \sim -22$ in the rest frame, or $\sim 2L_\odot$ 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. 3). Five out of these 16 were classified as mergers.

![Fig. 3. The sixteen brightest confirmed members of MS1054–03 at $z = 0.83$, ordered by $I_{F814W}$ magnitude. Note the large number of mergers. A color version of this figure can be found at http://www.astro.caltech.edu/~pgd/ms1054.](image)

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 merger. Hence the stellar age of the merged galaxies will be significantly different from the “assembly age”, i.e., the time that has elapsed since the galaxy “was put together”.

The colors of the mergers are consistent with the hypothesis that they will evolve into early-type galaxies. After aging of the stellar populations, the
scatter of the total population of mergers + early-type galaxies will be very similar to the measured scatter in the CM relation at $z < 0.6$. 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.

3.3 Close pairs

Visual classifications are subjective in their nature. An objective way to establish whether interactions and mergers were more prevalent in high redshift clusters is to investigate the distribution of galaxy – galaxy separations. Figure 4 shows the average galaxy density around red galaxies in our HST mosaic of MS 1054–03, excluding the central $200\,h^{-1}\,\text{kpc}$. The number of galaxies in each bin is weighted by the area; therefore, a flat distribution would show that the galaxies in the outer parts of the cluster are distributed uniformly.

There is clearly an excess of pairs at small separations ($< 10\,h^{-1}\,\text{kpc}$). This result confirms the large number of interacting galaxies in this cluster, and is completely independent from the morphological classifications. Only $\sim 50\%$ of the close pairs were classified as mergers. The other half may constitute a reservoir of “future” mergers. It will be interesting to measure the velocity differences of paired galaxies, to confirm their physical association.

Fig. 4. The overdensity of pairs in the outskirts of MS 1054–03. There is a clear excess of pairs at small separations $< 10h^{-1}\,\text{kpc}$. This is independent confirmation of the enhanced interaction rate in MS 1054–03.
4 Discussion

The presence of the mergers is direct evidence against an early collapse of all massive early-type galaxies at very high redshift, and is in qualitative agreement with hierarchical galaxy formation models. The main uncertainty is the assumption that the galaxy population in MS 1054–03 is typical for its redshift. It is important to test whether other clusters at similar redshift also show enhanced interaction rates in their outskirts. It may be 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 unvirialized state [18].

It may seem difficult to reconcile the homogeneity and slow evolution of early-type galaxies with the strong evolution inferred from morphological studies. However, the observations of MS 1054–03 clearly show that the sample of early-type galaxies at high redshift is only a subset of the sample of low redshift early-type galaxies. Studies of the evolution of early-type galaxies systematically discard the youngest progenitors of present-day early-types, and this leads to a biased estimate of their age. We have dubbed this effect the “progenitor bias” [18], and we model its effects on the observed evolution of early-type galaxies in detail in [20].

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