A High Merger Fraction in the Rich Cluster
MS 1054–03 at $z = 0.83$: Direct Evidence for
Hierarchical Formation of Massive Galaxies

ABSTRACT
We present a morphological study of the galaxy population of the luminous x-ray cluster MS 1054–03 at $z = 0.83$. The sample consists of 81 spectroscopically confirmed cluster members in a $3 \times 2 h^{-1}_{50}$ Mpc area imaged in F606W and F814W with WFPC2. We find thirteen ongoing mergers in MS 1054–03, comprising 17% of the $L > L_\ast$ cluster population. Most of these mergers will likely evolve into luminous ($\sim 2L_\ast$) elliptical galaxies, and some may evolve into S0 galaxies. Assuming MS 1054–03 is typical for its redshift it is estimated that $\sim 50\%$ of present-day cluster ellipticals experienced a major merger at $z < 1$. This implies that samples of ellipticals at $z \gtrsim 1$ are special subsets of samples of low redshift ellipticals. The mergers are preferentially found in the outskirts of the cluster, and probably occur in small infalling clumps. Morphologies, spectra, and colors of the mergers show that their progenitors were typically E/S0s or early-type spirals with mean stellar formation redshifts $z_\ast \gtrsim 1.7$. The red colors of the merger remnants are consistent with the low scatter in the color-magnitude relation in rich clusters at lower redshift. The discovery of a high fraction of mergers in this young cluster is direct evidence against formation of ellipticals in a single “monolithic” collapse at high redshift, and in qualitative agreement with predictions of hierarchical models for structure formation.

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6.1 Introduction

We do not know how and when luminous elliptical galaxies were assembled. Traditional models assume that all ellipticals are $10^{10}$ years old, and that they have experienced very little mass evolution after their initial collapse (e.g., Searle, Sargent, & Bagnuolo 1973). In contrast, galaxy formation models in cold dark matter (CDM) cosmologies predict that massive galaxies were assembled in many generations of mergers, and ellipticals experienced their last major mergers at $z < 1$ (Kauffmann 1996; Baugh, Cole, & Frenk 1996).

Ideally, the evolution of the mass function is determined directly from mass measurements of distant galaxies. An alternative approach is to determine the evolution of the merger fraction with redshift. Mergers in present-day rich clusters are rare because the probability of a low velocity encounter is small. Therefore, if cluster ellipticals formed in mergers, the mergers must have occurred before or during the initial collapse of the cluster (Roos & Aarseth 1982; Merritt 1984).

Morphological studies of intermediate redshift clusters have shown that mergers were indeed more common at earlier times (Lavery & Henry 1988 [LH88]; Lavery, Pierce, & McClure 1992 [LPM92]; Dressler et al. 1994 [D94]; Couch et al. 1998 [C98]). These studies indicate merger fractions of $\sim 5\%$ in clusters at $0.2 < z < 0.4$. However, since the mergers are generally blue and of low luminosity they are probably not very massive (e.g., C98). Furthermore, Dressler et al. (1997) suggest that disturbed galaxies in intermediate redshift clusters are generally disrupted disks rather than major mergers. These results indicate that massive cluster ellipticals were assembled at even higher redshift.

Recently it has become possible to extend morphological studies of rich clusters to $z \approx 1$ (e.g., Lubin et al. 1998). In this Letter, we present results from a large area survey of the x-ray selected cluster MS 1054−03 at $z = 0.83$. We determine the merger fraction using an I selected sample of 81 confirmed cluster members covered by a large HST WFPC2 mosaic. We assume $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_0 = 0.3$.

6.2 Observations

The MS 1054−03 field was observed with LRIS (Oke et al. 1995) on the 10m Keck II telescope. Objects were selected on the basis of their $I$ band flux ($20.0 < I < 22.7$). Spectra were taken through six multi-slit masks on 1998 February 28 and March 1. Exposure times were 2400 s for five of the masks and 1200 s for one mask. A cross-correlation program was used to determine redshifts for 186 galaxies in the MS 1054−03 field; 80 turned out to be cluster members. The redshifts were combined with the samples of Donahue et al. (1998) and Tran et al. (1999) giving a total of 89 confirmed cluster members.

We obtained a large HST WFPC2 mosaic of MS 1054−03, consisting of six independent pointings in two filters (F606W and F814W). Integration times were 6,500 s in each passband and at each position. 81 confirmed cluster members are located within the boundaries of the HST mosaic. Accurate magnitudes and colors were determined from the WFPC2 images. Morphological classifications were performed by PvD, MF, and DF, using the F814W images (restframe $\sim B$). The classification methods are described in detail in Fabricant et al. (in prep.) and van Dokkum et al. (in prep.).
6.3 Mergers at $z = 0.83$

The most surprising result of our survey of MS 1054−03 is the high fraction of galaxies classified as “merger/peculiar”. We classified 17% as mergers, compared to 22% ellipticals, 22% S0s, and 39% spirals. Images of the mergers are displayed in Fig. 6.1(a) [Plate 5, page 60], which shows the sixteen most luminous galaxies in MS 1054−03 ordered by total $I$ band luminosity, and Fig. 6.1(b), which shows all fainter mergers. The mergers display a variety of features: double nuclei (e.g., 997), tidal tails (e.g., 1760), and interacting doubles with distorted morphologies (e.g., 1340). The mergers are unresolved in our ground based images. We emphasize that all mergers are spectroscopically confirmed cluster members.

The merger fraction of 17% is significantly higher than in clusters at lower redshift, as discussed in the Introduction. Furthermore, as demonstrated in Fig. 6.1 [Plate 5, page 60] the mergers in MS 1054−03 extend to high luminosities: five of the sixteen brightest galaxies were classified as mergers. Only seven out of sixteen were classified as ellipticals or S0s, two of which (1584 and 710) have a luminous companion within 20 $h_50$ kpc. The median luminosity of the mergers is $M_T^B < -22$ ($\approx 2L_*$ at $z = 0.83$).

The majority of the mergers will probably evolve into elliptical galaxies (e.g., Toomre & Toomre 1972, Barnes 1998), thereby increasing the number fraction of massive ellipticals at later times. However, not all mergers form ellipticals. Simulations indicate that disks can survive mergers between galaxies of very different mass (Barnes 1998), and so some mergers may evolve into S0s (e.g., galaxy 1583). In most cases there is no evidence for the presence of gas to form a new disk: only 15% of the mergers have EW [O II] $\lambda 3727 \AA > 5 \AA$.

Since the merger fraction is comparable to the elliptical fraction and merger timescales are short ($< 1$ Gyr; e.g., Rix & White 1989), the implication is that more than $\approx 50\%$ of present-day cluster ellipticals were assembled in mergers at $z < 1$. A direct consequence is that samples of ellipticals at $z \geq 1$ are special subsets of samples of ellipticals at $z = 0$.

A possible concern is that some of the mergers are misclassified. Several show two galaxies separated by $\approx 1''$ ($10 h_50$ kpc) in a common envelope without obvious tidal features (e.g., galaxies 997 and 1163). One could argue that these objects are not bound, but chance projections along the line of sight. However, the probability of a chance projection within $1''$ is smaller than $10^{-3}$. Furthermore, for the brightest mergers we can constrain the velocity differences between the galaxies from our spectroscopy. No double peaks were seen in the cross-correlation functions, implying $\Delta v < 500$ km s$^{-1}$. Both arguments are strong evidence that the galaxies are bound, and that we are witnessing mergers in progress.

6.4 Mechanism

The merger fraction in MS 1054−03 is surprisingly high, given the high velocity dispersion of the cluster ($\approx 1150$ km s$^{-1}$; Tran et al. 1999). Since the progenitors of the mergers must have had low relative velocities, the mergers are probably taking place in cold subclumps which are falling into the cluster. This is supported by the spatial distribution of the mergers, shown in Fig. 6.2. The mergers occur preferentially in the outskirts of the cluster, consistent with recent infall.

Furthermore, the cluster itself is irregular and elongated, as indicated by the iso-density contours in Fig. 6.2 and the x-ray distribution (Donahue et al. 1998). Our data suggest that the cluster consists of three clumps at the same radial velocity. We conclude that the mergers are possible because the cluster is viewed before final virialization, and hence before stripping of the halos of infalling subclumps.
6.5 Assembly Time versus Star Formation Epoch

In most cases the merging galaxies are bulge-dominated, red, and have no detected \([\text{O} \text{II}] 3727 \, \text{Å} \) emission. Hence, they are mergers between ellipticals, S0s or Sas. The most striking examples of these (nearly) dissipationless mergers are galaxies 997 and 1163. In contrast to mergers in the nearby field (Liu & Kennicutt 1995), the star formation rate is very low, although several galaxies have enhanced Balmer lines indicating a modest star burst. A major puzzle is how and when the progenitors of the mergers lost their gas.

The ages of the mergers relative to the other cluster galaxies can be estimated from their location in the color-magnitude plane. Figure 6.3 shows the color-magnitude relation of confirmed members of MS 1054–03. Mergers are indicated with \( \infty \) symbols. The median color of the mergers is modestly bluer (by \( \approx 0.08 \) magnitudes in \( U-B \)) than the CM relation defined by the early-type galaxies, indicating that their luminosity weighted ages are \( \approx 40\% \) lower (Worthey 1994). Assuming galaxies on the CM relation formed their stars at \( z \geq 3 \) (van Dokkum et al. 1998b), the stars in the mergers have a luminosity weighted mean formation redshift \( z_f \gtrsim 1.7 \). We conclude that the mean stellar ages of present-day cluster ellipticals are much larger than the ages of their last major mergers. We note in passing that only three of the mergers satisfy the Butcher & Oemler (1978) criteria for a blue galaxy. The blue fraction in MS 1054–03 is \( \approx 20\% \); \( \approx 75\% \) of the blue galaxies are spirals.

We test whether the colors of the mergers are consistent with measurements of the scatter in the CM relation at \( z < 1 \). The intrinsic scatter in the CM relation of the existing Es and E/S0s at \( z = 0.83 \) is low at \( 0.027 \pm 0.013 \) in restframe \( U-B \), consistent with the results of Stanford, Eisenhardt, & Dickinson (1998). The scatter in the combined sample of ellipticals and mergers (i.e., the sample of future ellipticals) is much higher, at \( 0.054 \pm 0.011 \). This scatter will decrease at later times, because the fractional age differences between the galaxies will be smaller (e.g., van Dokkum et al. 1998a). We have evolved the CM relation forward in time using the simple models presented in van Dokkum et al. (1998a), and find that the \( U-B \) scatter in the CM relation of ellipticals and mergers will be \( \approx 0.035 \) at \( z = 0.5 \), and only \( \approx 0.015 \) at \( z = 0 \). These numbers are consistent with the observed scatter in the CM relation at low and intermediate redshift (Bower, Lucey, & Ellis 1992; Ellis et al. 1997; Stanford et al. 1998; van Dokkum et al. 1998a).
6.6 Discussion

The large number of mergers in MS 1054–03 implies strong evolution in the merger fraction from \( z = 0 \) to \( z = 0.83 \). This is illustrated in Fig. 6.4, which shows the evolution of the merger fraction in rich clusters with redshift. Solid symbols are CL 1358+62 at \( z = 0.33 \) and MS 1054–03 at \( z = 0.83 \). We determined the merger fraction in CL 1358+62 from a sample of 194 spectroscopically confirmed cluster members imaged with WFPC2 (van Dokkum et al. 1998a). The merger fraction in this cluster can be compared directly to that in MS 1054–03, since the sample selection, field size (in Mpc) and classification method are identical. Merger fractions for other rich clusters were estimated from the literature; in order of increasing redshift from Dressler (1980), LH88, C98, LPM92, and D94. These merger fractions are based on ground based imaging of blue galaxies (LH88, LPM92) or visual classifications of HST images (D94, C98). The evolution of the merger rate can be parameterized by \( f \propto (1 + z)^m \). We find \( m = 6.0^{+1.1}_{-0.7} \). The best fit is indicated with the solid line.

It is interesting to compare the evolution of the merger fraction in clusters to that in the field. The broken line in Fig. 6.4 is a fit to the fraction of field galaxies in close pairs, from Patton et al. (1997). A direct comparison with the cluster data is difficult because the latter are based on visual classifications, which include both close pairs and merger remnants. We note, however, that these fractions are comparable in the outer parts of MS 1054–03. Although the normalization is uncertain, the rate of evolution can be compared directly. Both the cluster environment and the field show strong evolution. The evolution in clusters might even be stronger than in the field. This result is mainly driven by the very low merger fraction in low redshift clusters. The rapid evolution in the cluster environment could be due to an enhanced accretion rate onto clusters at high redshift, and/or enhanced merging during the collapse of massive clusters.

The increase with redshift of the merger rate of massive galaxies is in qualitative agreement with predictions from hierarchical galaxy formation models (e.g., Kauffmann 1996, Baugh et al. 1996), although it is a challenge to explain both the recent assembly of massive early-types and the early formation of their stars. The presence of the mergers in MS 1054–03 is direct evidence against formation of massive ellipticals in a “monolithic” collapse at very
Figure 6.4: Evolution of the merger fraction in clusters. The solid symbols are the clusters CL1358+62 at $z = 0.33$ and MS1054–03 at $z = 0.83$ from our study. Literature studies of rich clusters are indicated by open symbols. The solid line is a fit to the cluster data. The broken line is a fit to the fraction of field galaxies in close pairs from Patton et al. (1997). The merger fraction evolves rapidly in clusters and in the field, possibly even stronger in clusters.

Assuming merging does not alter the shape of the mass function, the mergers cause an increase in $M_*$ of $\approx 15\%$. This can be contrasted to the strong evolution in the number density of massive field galaxies inferred by Kauffmann & Charlot (1998) from the lack of luminous $K$-band selected galaxies at $z > 1$. Although this result is still uncertain, the implication may be that massive galaxies in the field were assembled more recently than those in clusters.

This study demonstrates that large field studies with HST, in combination with deep spectroscopy from the ground, can show directly how galaxy formation proceeded. The large field was essential, since the mergers are preferentially located in the outskirts of the cluster. More wide field observations of high redshift clusters would be valuable to test whether MS1054–03 is typical for its redshift. Studies of early-type galaxies in groups and the field at high redshift are necessary to establish whether their evolution has an environmental dependence.

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References

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