Formation and Evolution of E and S0 Galaxies from HST and Keck Studies of $z \sim 0.3$–1 Clusters.

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October 15, 1999

**Abstract.** We have witnessed a dramatic increase over the last five years in results on distant galaxies, in large part because of the high resolution imaging capability of HST, and the multiobject spectroscopic capability of the Keck telescopes. Our program to obtain wide-field, multi-color WFPC2 mosaics with HST of intermediate redshift clusters, and spectroscopic membership and high S/N spectroscopy with LRIS on Keck, has provided new insights into the nature of elliptical and S0 galaxies in the cluster environment over a wide range of densities. In particular, most ellipticals, and a significant fraction of the S0 population, have large luminosity-weighted ages, suggesting that their stellar populations were formed at redshifts beyond $z \sim 2$, though the existence of substantial numbers of major mergers in MS 1054-03 at $z = 0.83$ suggests that final assembly of such galaxies may not have occurred until much later for a significant fraction of early-type galaxies.

**Keywords:** Distant Cluster Galaxies; Galaxy Formation; Galaxy Evolution

## 1. Introduction

HST WFPC2 imaging and Keck LRIS spectroscopy have helped to revolutionize our understanding of high redshift galaxies. In particular, they have played a central role in the study of the evolution of early-type galaxies in intermediate redshift clusters.

Over the last four years we have been carrying out HST WFPC2 imaging and Keck multi-slit spectroscopy of three massive, X-ray selected clusters ranging in redshift from CL 1358+62 at $z = 0.33$, to

(See fig1.jpg)

*Figure 1.* The HST WFPC2 36-orbit, six-pointing two-color mosaic of the $z = 0.83$ X-ray cluster MS1054-03. This image covers $5' \times 7'$, i.e., out to $\sim 2h_{70}^{-1}$ Mpc radius.
Figure 2. a) The fundamental plane of 30 E/S0 galaxies in Cl 1358+62 at $z = 0.33$, showing the very tight relation (comparable to that in Coma). The intrinsic scatter is only 14\% in $r_e$. The (small) offset to Coma is evolutionary brightening, since the $(1 + z)^4$ surface brightness dimming has been removed. The full sample of 53 galaxies, including the early-type spirals and E+A galaxies, is shown in (b). The offsets for these galaxies are as expected for a younger luminosity-weighted age for their stellar populations (see Kelson et al. 2000).

MS 2053-04 at $z = 0.58$, and to MS 1054-03 at $z = 0.83$. A key factor that distinguishes this work from other programs with HST is that we have used multiple pointings to cover a wide area around the cluster. The advantage of this approach for many issues relating to cluster and early-type galaxy evolution became clear as the project developed. The results from this program have resulted in two dissertations (Daniel Kelson: UCSC 1998, and Pieter van Dokkum: Groningen 1999).

We have used multiple pointings on HST to image regions with WFPC2 that are typically 5–7$'$ × 5–7$'$ in size. This corresponds to a field size of roughly $1.5h^{-1}_{65} - 2h^{-1}_{65}$ Mpc, centered on the clusters. An example of the mosaic HST images for one of our cluster fields is shown in Figure 1. The fields were imaged with two filters, F606W and F814W. Spectroscopy was carried out using the Keck LRIS multi-object spectrograph, with a field comparable to that of the HST mosaics.

The scientific goals of this program have included constraining the evolution of early-type galaxies, identifying the galaxy characteristics across the cluster as a function of environment and density, analysis of the cluster’s spatial and velocity structure, and determining the mass distribution through weak lensing. The primary tools that we have used for characterizing the evolution of the early-type galaxy population have been the fundamental plane, the color-magnitude relations, and more recently, absorption line strengths.
Intermediate Redshift Cluster Galaxies

Figure 3. Evolution of $M/L_{B'}$ with redshift from the fundamental plane measurements in Coma at $z = 0.02$, CL 1358+62 at $z = 0.33$, CL 0024+16 at $z = 0.39$, MS2053-04 at $z = 0.58$, and MS 1054-03 at $z = 0.83$, for an (a) open $\Omega_m = 0.3$, a (b) flat, matter-dominated $\Omega_m = 1$, and (c) a lambda cosmology $\Omega_m = 0.7, \Omega_m = 0.3$. Single-burst model predictions are shown for a Salpeter IMF ($x = 1.35$) and a range of metallicities, as indicated by the spread in $\Delta \log M/L_{B'}$ for a given $z_{\text{form}}$. The sensitivity to the IMF is shown in (b) as a dotted line ($z_{\text{form}} = \infty$ and a steep IMF with $x = 2.35$), as is the effect of reducing $z_{\text{form}}$ from $z_{\text{form}} = \infty$. The data favor high formation redshifts and a low $q_0$, but this result is sensitive to the IMF.

2. Fundamental Plane

The fundamental plane is a tight relation in early-type galaxies between velocity dispersion, effective radius and mean surface brightness that is described by $r_e \propto \langle I_e \rangle^{-0.83} \sigma^{1.20}$. With reasonable assumptions about homology, this implies that $M/L \propto M^{0.25}$. The very small scatter, $\pm 23\%$ in Coma in $M/L_V$, makes it an ideal tool for establishing the evolution of $M/L$ with redshift. Since age is related to $M/L$ for early-type galaxy populations, constraints can be put on their (luminosity-weighted) ages and age distributions. This requires high S/N data, and attention to minimizing systematic errors. For $z \sim 0.3$–1 clusters, HST images are needed to derive $r_e$ and $I_e$, while 8-10 m telescopes are needed for $\sigma$ (6-8 hour integrations were used at Keck at $z = 0.83$).

For CL 1358+62, high S/N spectra were obtained of 53 galaxies in the HST mosaic, resulting in the derivation of the fundamental plane shown in Figure 2 (Kelson et al. 2000). These data made it possible to derive a fundamental plane at $z = 0.33$ that is comparable to Coma. The scatter in $M/L$ in the E/S0 population in CL 1358+62 is just 16%. The offset from Coma constrains the luminosity-weighted ages to $z > 1$, and the consistency of the scatter in the fundamental plane and the color-magnitude relation constrains the luminosity-weighted age dispersion to be $\leq 15\%$.

Based on our preliminary fundamental plane measurements at higher redshift (Kelson et al. 1997, and van Dokkum et al. 1998a), we have used
the offsets in $\Delta M/L$ from Coma to set even stronger constraints, on the luminosity-weighted ages, and on the cosmology, as shown in Figure 3 (van Dokkum et al. 1998a). An Einstein-de Sitter ($\Omega_m = 1$) is only consistent with the data if the IMF is substantially steeper than Salpeter. These data give $\Delta \log M/L_B \propto -0.4z$. Tighter constraints would be placed by observing even slightly higher redshift clusters, though the spectroscopy becomes very time-consuming, even with Keck!

3. Color-Magnitude Relations

The color-magnitude (CM) relations provide a complementary approach to the fundamental plane for characterizing the evolution of early-type galaxies. They provide an independent means of constraining $\Delta t/t$. The use of such relations brings a benefit in that larger samples can be readily obtained (redshifts are easier than velocity dispersions), but the use of these relations for constraining the star formation history of old stellar populations does require very accurate photometry. This can be done with HST data, which also enables the required morphological determinations to be made. The value of such data can be seen in Figure 4 (See fig4.jpg) where color images from HST show the range of morphological and structural information that can be obtained in CL1358+62 at $z = 0.33$.

An extensive CM analysis of the large sample of members with spectroscopic redshifts in CL 1358+62 was carried out by van Dokkum et al. (1998b). The key to this analysis was the very accurate photometry that could be carried out on the WFPC2 images. For galaxies with $V_z < 21$, the photometric uncertainty was demonstrated to be 0.009 mag, rising to only 0.017 mag for fainter objects. With 194 members over a radius of 4.6 arcmin, or 1.2 $h_{65}^{-1}$ Mpc, the colors of galaxies could be investigated as a function of radius. As shown in Figure 5, the elliptical galaxy population shows very small scatter at both small and large radii, and no significant change in scatter with radius (a biweight estimator was used to minimize the effects of outliers). The S0 galaxies likewise show little scatter at small radii, and are essentially identical to the ellipticals, but at larger radii the S0 population is bluer and shows substantially larger scatter: a factor 2 higher than that of the S0s in the center (or the ellipticals at all radii). The difference in the mean color (to bluer colors) in the S0 populations is significant at the 95% confidence level. For the ellipticals at all radii, and the S0s in the central regions, the scatter implies a luminosity-weighted age distribution with $\Delta t/t \sim 0.18$, while the luminosity-weighted age distribution for the S0s
Figure 5. Comparison of the color-magnitude relations for ellipticals and S0s in CL 1358+62 at $z = 0.33$, as a function of radius in the cluster. The scatter in the CM relation of the inner region S0s is the same as the ellipticals (which show no dependence with radius). Outside $r = 118''$, the scatter in the S0 colors is larger than that of the ellipticals and inner S0s by a factor 2, and they are bluer in the mean. The radius 118'' was chosen so as to split the sample into two equal groups.

at $r > 118''$ is $\Delta t/t \sim 0.35$, with (some) outer S0s experiencing star formation almost to the epoch of observation at $z = 0.33$.

This powerful technique is also being applied to our other clusters.

4. Major Mergers in MS 1054–03

The value of the large field coverage of our HST imaging was demonstrated again with our mosaic on MS 1054-03 at $z = 0.83$ (Figure 1), when the morphological types of the 89 members that resulted from the Keck LRIS spectroscopic magnitude-limited sample ($I < 22.2$) were analyzed. The morphological types were split 22% E, 22% S0, 39% spiral and 17% merger/peculiar. To find such a high fraction of luminous merger/peculiar galaxies in such a rich cluster at such a late time was a surprise. The morphological types of the most luminous galaxies in MS 1054-03, plus the lower luminosity merger/peculiar objects, are shown in Figure 6 (See fig6.jpg).

These results are discussed in more detail in van Dokkum et al. (1999). The color magnitude diagram shown in Figure 7b demonstrates one of the remarkable aspects of the mergers in this cluster – they are quite red, with no detected [OII] 3727 Å emission, suggesting minimal
Figure 7. (a) Spatial distribution of the confirmed cluster members in MS 1054-03, with contours of the red galaxy distribution, and the mergers indicated as symbols. (b) Color-magnitude relation of the spectroscopically-confirmed members of MS1054–3. Excluding the three very blue mergers, the bulk of the mergers are only $\sim 0.07$ mag bluer than the CM relation defined by the E/SO early-type galaxies (solid line).

ongoing star formation. The mergers are also found in the outer parts of the cluster, suggesting that they are in infalling clumps (Figure 7a). Most of these mergers are likely to evolve into luminous ($\sim 2 L^*$) early-type galaxies, presumably ellipticals, but also possibly S0s. If confirmed to be generally the case in other rich $z \sim 0.5–1$ clusters, this result suggests that the merging rate in the cluster environment is changing rapidly with redshift (possibly as fast as $(1+z)^6$). This important result is consistent with the predictions of hierarchical clustering models (see, e.g., Kauffmann 1996).

5. Line Strengths

We have recently extended our program to encompass line strength measurements. The high S/N data that were obtained for deriving velocity dispersions for the fundamental planes in the three clusters are also ideal for deriving line strengths. The first results from this program are given in Kelson et al. (1999). An important demonstration of the potential of the use of line strengths for substantial samples of intermediate-redshift, early-type galaxies can be seen in Figure 8. The tight correlation between the metal-sensitive index $C_24668$ Å and the restframe $B – V$ color in CL 1358+62 at $z = 0.33$ has a slope that is consistent with that purely for metallicity variation at constant age, with no need for age variation. Line strengths will prove to be a significant component of our “toolbox” for studying distant galaxies.
6. Summary

The fundamental plane and color-magnitude relations (and the forthcoming line strength studies) provide complementary approaches to establishing the evolutionary history of early-type galaxies. Already our results show that the luminosity-weighted ages of E/S0 galaxies in intermediate redshift ($z \sim 0.3-1$) massive X-ray clusters are old, i.e., $z_f > 2$, with small $\Delta t/t \sim 0.15-0.18$. Furthermore, our recent results on the major mergers in MS 1054-03 indicate that a substantial fraction of the E/S0 population could have undergone a final “assembly” phase at $z < 1$.

Acknowledgements

The lead author is very grateful to David Block for organizing such an excellent conference, and to Margi Crookes for her dedication to making everything work well, and to all those who helped them. I would particularly like to thank the Anglo-American Chairman’s Fund and SASOL for their generous financial support. Support from STScI grants GO07372.01-96A, GO06745.01-95A, and GO05989.01-94A is gratefully acknowledged.
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