Luminosity Evolution of Early-Type Galaxies to $z = 0.83$: Constraints on Formation Epoch and $\Omega_f$

ABSTRACT

We present deep spectroscopy with the Keck telescope of eight galaxies in the luminous X-ray cluster MS 1054−03 at $z = 0.83$. The data are combined with imaging observations from the Hubble Space Telescope (HST). The spectroscopic data are used to measure the internal kinematics of the galaxies, and the HST data to measure their structural parameters. Six galaxies have early-type spectra, and two have “E+A” spectra. The galaxies with early-type spectra define a tight Fundamental Plane (FP) relation. The evolution of the mass-to-light ratio is derived from the FP. The $M/L$ ratio evolves as $\Delta \log M/L_B \propto -0.40z$ ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0$). The observed evolution of the $M/L$ ratio provides a combined constraint on the formation redshift of the stars, the IMF, and cosmological parameters. For a Salpeter IMF ($x = 2.35$) we find that $z_{\text{form}} > 2.8$ and $\Omega_m < 0.86$ with 95% confidence. The constraint on the formation redshift is weaker if $\Omega_{\Lambda} > 0$: $z_{\text{form}} > 1.7$ if $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. At present the limiting factor in constraining $z_{\text{form}}$ and $\Omega$ from the observed luminosity evolution of early-type galaxies is the poor understanding of the IMF. We find that if $\Omega_m = 1$ the IMF must be significantly steeper than the Salpeter IMF ($x > 2.6$).
4.1 Introduction

Measurements of the masses and mass-to-light ($M/L$) ratios of early-type galaxies in distant clusters provide important constraints on galaxy evolution. The luminosity evolution of early-type galaxies can be determined by comparing the luminosities of galaxies of similar masses at different redshifts. Also, mass measurements can be used to constrain the merger rate.

The evolution of the $M/L$ ratio can be measured from the evolution of the fundamental plane of early-type galaxies. The fundamental plane (FP) is a tight correlation between the structural parameters and the velocity dispersion of the form $r_e \propto I_e^{0.83,0.20}$ in the $B$ band (Djorgovski & Davis 1987; Dressler et al. 1987; Jørgensen, Franx & Kjærgaard 1996 [JFK]). Assuming homology, the existence of the FP implies that $M/L \propto M^{0.25,0.04}$, with low scatter (Faber et al. 1987). Therefore, the evolution of the intercept of the FP is proportional to the evolution of the mean $M/L$ ratio (see Franx 1993a).

Studies of the FP out to $z \approx 0.6$ have shown that the $M/L$ ratio of massive cluster galaxies evolves slowly (van Dokkum & Franx 1996 [vDF]; Kelson et al. 1997 [KvDFIF]; Bender et al. 1998; Pahre 1998). The implication is that the stars in massive cluster galaxies were probably formed at much higher redshifts. These results are consistent with other studies of the evolution of the luminosities, colors, and absorption line strengths of bright cluster galaxies (e.g., Aragon-Salamanca et al. 1993, Bender, Ziegler, & Bruzual 1996, Schade, Barrientos, & Lopez-Cruz 1997, Ellis et al. 1997, Stanford, Eisenhardt, & Dickinson 1998).

The constraints on the formation epoch of massive galaxies can be made stronger by extending the studies of the evolution of the $M/L$ ratio to higher redshifts. In this Letter, we report on spectroscopic and photometric observations of eight bright galaxies in the luminous X-ray cluster MS 1054−03 at $z = 0.83$. The fundamental plane is derived, and the evolution of the $M/L$ ratio is established out to $z = 0.83$, when the universe was 50% of its present age ($q_0 = 0.15$).

4.2 Spectroscopy

Galaxies in MS 1054–03 were selected on the basis of their $I$ band flux ($I < 22.1$), and their location in the $B − R$ versus $R − I$ plane. The allowed range in color was broad, thus minimizing any bias against passively-evolving blue cluster galaxies. There was no selection on morphology. The ground based imaging data used for the selection were kindly provided by G. Luppino, and are described in Luppino & Kaiser (1997).

The cluster was observed on February 11, 1997 with LRIS (Oke et al. 1995) on the 10 m W. M. Keck telescope. The multi-aperture slitlets were 1"0 wide, and the seeing was 0"0.9–1"0. The instrumental resolution $\sigma_{\text{inst}} \approx 50$ km s$^{-1}$. The total exposure time was 14400 s. A bright blue star was included in the masks for the purpose of correcting for the H$_2$O absorption at 7600 Å from our atmosphere. The reduction procedures were very similar to those described by vDF and KvDFIF. Eight of the observed galaxies are covered by a deep HST image of the cluster core. In this Letter, we will limit the discussion to these galaxies.

The spectra of the galaxies are shown in Fig. 4.1. Two of the eight galaxies (1430 and 1583) have strong Balmer absorption lines (EW > 4 Å in the rest frame), indicating the presence of a young stellar component. Subsequent low resolution spectroscopy covering a larger wavelength range showed that both galaxies have O II 3727 EW < 5 Å, and hence are classified “E+A” galaxies (Dressler & Gunn 1983).

We determined the central velocity dispersions of the galaxies from a fit to a convolved template star in real space, following the procedures outlined in vDF and KvDFIF. The spectral regions that are dominated by bright sky lines were given low weight in the fit. The
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Figure 4.1: HST images and Keck spectra of the galaxies in MS 1054−03 with measured dispersions. The most prominent spectral feature in most galaxies is the 4300 Å G band observed at $\approx 7870$ Å. Galaxies 1430 and 1583 have strong Balmer absorption lines, and are “E+A” galaxies. Galaxy 1484 is the brightest cluster galaxy.

Balmer lines in the E+A galaxies were masked. The resulting dispersions, corrected to an aperture of $3''/4$ at the distance of Coma (cf. vDF), are listed in Table 1. We experimented with the choice of template star, the continuum filtering, and the fitting method (e.g., fitting in Fourier space rather than real space) to assess the systematic uncertainties, and estimate them to be $\sim 5\%$.

There are several galaxies with dispersions in the range $250 - 300$ km s$^{-1}$, showing that massive galaxies exist at $z = 0.83$. The dispersions of the two E+A galaxies are $153 \pm 12$ km s$^{-1}$ and $212 \pm 25$ km s$^{-1}$. These values are significantly higher than the typical dispersions of E+A galaxies at lower redshift ($\sim 100$ km s$^{-1}$; Franx 1993b, KvDFIF).

4.3 Photometry

Hubble Space Telescope (HST) WFPC2 imaging data of the central parts of MS 1054−03 were taken by Donahue et al. (1998) on March 13, 1996 through the $F814W$ filter. The total exposure time was 15 600 s. Following the usual reduction process the images were deconvolved with the clean algorithm (Høgbom 1974), using Tiny Tim (Krist 1995) PSFs appropriate for the positions of the galaxies on the WFPC2 chips. The six galaxies with early-type spectra appear to be unperturbed E and S0 galaxies (Fig. 4.1). The two E+A galaxies have more peculiar morphologies. Galaxy 1430 has a disk with faint spiral structure, and is lopsided. Galaxy 1583 also has a disk, and a very luminous, compact bulge. It may be interacting with the small companion galaxy to the South.

We determined effective radii and effective surface brightnesses of the galaxies using the 2D fitting method outlined in vDF. The values of $r_e$ (in arcseconds) and $\mu_e,F814W$ are listed in Table 1. As noted by many authors (e.g., JFK), the errors in $r_e$ and $I_e$ are correlated, and the correlation is almost parallel to the Fundamental Plane. Therefore, the product $r_eI_e^{0.83}$, which enters the FP, can be determined to high accuracy.
4.4 The Fundamental Plane and Evolution of the $M/L$ Ratio

The edge-on projection of the fundamental plane in MS 1054–03 is shown in Fig. 4.2. The surface brightnesses ($I_e \equiv 10^{-0.4 \mu_e}$) have been corrected for the $(1+z)^4$ cosmological dimming. The effective radii were converted using $q_0 = 0.15$ and $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. The open symbols are the two E+A galaxies. The small dots are galaxies in Coma at $z = 0.023$, taken from JFK. The line is the fit from JFK. The six galaxies with early-type spectra define a clear FP, with low scatter ($\sim 0.045$ in log $r_e$). The slope is similar to that of the Coma cluster. A larger sample is needed to determine the scatter and the slope reliably. The offset of the FP of MS 1054–03 with respect to the FP of Coma is due to the evolution of the $M/L$ ratio between $z = 0.83$ and the present.

The E+A galaxies are over-luminous with respect to the prediction from the FP defined by the other galaxies in MS 1054–03, consistent with the presence of a young population. The E+As have lower masses than the other galaxies in the sample. In the following analysis, we will only consider the galaxies with early-type spectra. Therefore, our conclusions may only apply to a subset of the galaxy population. We will return to this point in Sect. 4.5.

We determined the evolution of the $M/L$ ratio from the FP. In Fig. 4.3, the evolution of the $M/L$ ratio from $z = 0.02$ to $z = 0.83$ is plotted. Included in the Figure are data for Coma at $z = 0.02$ from JFK, for CL 0024+16 at $z = 0.39$ from vDF, and for CL 1358+62 at $z = 0.33$ and MS 2053+03 at $z = 0.58$ from KvDFIF. All data were transformed to a common rest frame band, equivalent to the $F814W$ band in the observed frame at $z = 0.83$. This band is very close to the $B$ band redshifted to $z = 0.83$, and is denoted $B_e$. For MS 1054–03 at $z = 0.83$, $B_e \equiv F814W + 2.5 \log (1+z)$. The transformations for the other clusters were derived in a similar way as is described in vDF. For all clusters, the observed bands are close to the redshifted $B$ band, and the color terms in the transformations are small. Since the observed colors of the galaxies are used in the transformations, the procedure is very different from a $K$-correction, and is independent of the spectral types of the galaxies. Using spectral energy distributions from Pence (1976), we estimate the error induced by the transformations is $\lesssim 0.03$ magnitudes for all spectral types. Because the scatter in the FP is very small, the errorbars in Fig. 4.3 are mainly due to systematic errors. We have assumed that the systematic errors in the dispersions, in the photometric zeropoints, and the errors caused by the sample selection (see vDF) can be added in quadrature. The $M/L$ ratio evolves as
Figure 4.3: Evolution of the $M/L$ ratio with redshift, for $q_0 = 0.15$ (a), $q_0 = 0.5$ (b), and for a non-zero cosmological constant (c). The open symbols are Coma at $z = 0.02$ (JFK), CL 1358+62 at $z = 0.33$ (KvDFIF), CL 0024+16 at $z = 0.39$ (vDF), and MS 2053+03 at $z = 0.58$ (KvDFIF). The solid symbol is MS 1054−03 at $z = 0.83$ (this paper). Model predictions for different formation redshifts of the stars are shown, assuming a Salpeter IMF ($x = 2.35$) and a range of metallicities. The data favor high formation redshifts and a low value of $q_0$. The broken line in (b) indicates a model with $z_{\text{form}} = 2$ and a steep IMF ($x = 3.35$). The conclusions are very sensitive to the IMF.

\[ \Delta \log M/L_B \propto (-0.40 \pm 0.04)z \] if \( \Omega_m = 0.3 \), or \[ \Delta \log M/L_B \propto (-0.31 \pm 0.04)z \] if \( \Omega_m = 1 \). This is consistent with other measurements of the luminosity evolution of early-type galaxies to $z \approx 0.8$ (e.g., Schade et al. 1997). However, our measurement has a much smaller uncertainty, due to the low scatter in the FP.

4.5 Discussion

The observed evolution of the $M/L$ ratio with redshift can be compared to predictions for the evolution of single age stellar populations formed at redshift $z_{\text{form}}$. The luminosity evolution of a single age stellar population behaves as a power law: $L \propto (t - t_{\text{form}})^\kappa$. The evolution depends on $\kappa$, the cosmology, and $z_{\text{form}}$ (vDF). The value of $\kappa$ depends on the passband, the IMF, and the metallicity. The models of Bruzual & Charlot (1999), Vazdekis et al. (1996) and Worthey (1999) give $0.86 < \kappa_B < 1.00$ for a Salpeter (1955) IMF ($x = 2.35$) and $-0.5 < [\text{Fe}/\text{H}] < 0.5$. Model predictions are shown in Fig. 4.3(a) for $z_{\text{form}} = 2$ (open area) and $z_{\text{form}} = \infty$ (shaded area), for a universe with $\Omega_m = 0.3$ and no cosmological constant ($q_0 = 0.15$). Note that the models as well as the data points in Fig. 4.3 are independent of the value of $H_0$. The formal 95% confidence lower limit on the formation redshift is $z_{\text{form}} > 2.8$, for solar metallicity, a Salpeter IMF and $q_0 = 0.15$.

The slow evolution of massive galaxies in clusters not only provides a constraint on their formation redshift, but also on cosmological models (e.g., Bender et al. 1998). This is illustrated in Fig. 4.3(b), which shows the same models as in Fig. 4.3(a) for $\Omega_m = 1$ ($q_0 = 0.5$) rather than $\Omega_m = 0.3$. The models fail to fit the data in this cosmology, and we find $\Omega_m < 0.86$ (95% confidence). The constraint on $\Omega_m$ is considerably stronger than the constraint derived by Bender et al. (1998) from the combination of the Mg$_b - \sigma$ relation and the fundamental plane at $z = 0.375$, due to the higher redshift of MS 1054−03.

These results are based on the assumption that massive early-type galaxies in clusters have a Salpeter IMF. There is considerable uncertainty in the slope and form of the IMF in the mass range around $\sim 1M_\odot$ (Scalo 1997), and there are only indirect constraints on the
The IMF of massive ellipticals in clusters (e.g., Gibson & Matteucci 1997). The value of $\kappa$, and hence the rate of evolution, is quite sensitive to the logarithmic slope of the IMF: the Worthey (1999) models give $\Delta \kappa_B = -0.22 \Delta x$.

Since the IMF is very uncertain, we express our results as a combined constraint on $\Omega_m$ and the slope of the IMF in Fig. 4.4. The IMF is steep if $\Omega_m = 1$. The 95% confidence lower limit on the slope is $x > 3.5$ for $\Omega_m = 1$. As an illustration, the broken line in Fig. 4.3(b) indicates a model with $\Omega_m = 1$, $z_{\text{form}} = \infty$ and $x = 3.35$. This model fits the data very well. The case $z_{\text{form}} = \infty$ is extreme; the dependence on the formation redshift of the constraints on $\Omega_m$ and $x$ is indicated with an arrow in Fig. 4.4. For lower formation redshifts (or higher metallicities) the constraints are stronger. As an example, for $z_{\text{form}} = 5$ rather than $\infty$ we find that $\Omega_m < 0.60$ for $x = 2.35$, and $x > 3.0$ for $\Omega_m = 1$.

We note that if $\Omega_\Lambda > 0$, as is indicated by distant supernovae (Riess et al. 1998), the constraints on $z_{\text{form}}$ and the slope of the IMF are much weaker. Figure 4.3(c) shows the evolution of the $M/L$ ratio if $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The lower limit on the formation redshift is $z_{\text{form}} > 1.7$. In this cosmology, the data provide no meaningful constraint on the slope of the IMF.

The implicit assumption in this type of study that the set of high redshift early-types is similar to the set of low redshift early-types (e.g., Kauffmann 1995, van Dokkum & Franx 1996) is probably justified for the high mass galaxies considered here. It seems unlikely that a significant fraction of the high mass galaxies in clusters at $z = 0$ was added to the sample between $z = 0.83$ and $z = 0$, given the tightness of the color-magnitude relation of luminous galaxies in intermediate $z$ clusters (e.g., Ellis et al. 1997, van Dokkum et al. 1998), and the low masses of the E+A galaxies (Franx 1993b, KvDFIF). However, our conclusions may not hold for low mass galaxies: there is good evidence that a significant fraction of the low luminosity early-type galaxies at $z = 0$ was accreted from the field at $z < 1$ (e.g., Abraham et al. 1996, van Dokkum et al. 1998). The two E+A galaxies in our sample may be galaxies that were recently accreted. Larger samples to fainter magnitudes are needed to assess the fraction of galaxies with young populations in $z \approx 0.8$ clusters, and their masses.

In conclusion, the luminosity evolution of massive early-type galaxies to $z \approx 0.8$ has now been determined to sufficient accuracy to place strong constraints on the epoch of formation of the galaxies, and on cosmological models. The main uncertainty in the interpretation is the poor understanding of the IMF in the mass range around one solar mass. Other applications of the FP suffer from the same uncertainty (e.g., Bender et al. 1998). Nevertheless, our current
measurement can be used directly to correct the evolution of the luminosity function for the brightening of the stellar populations with redshift. This can provide direct constraints on the mass evolution of galaxies.

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References

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