THE EVOLUTION OF FIELD EARLY-TYPE GALAXIES TO $z \sim 0.7$1

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ABSTRACT

We have measured the fundamental plane (FP) parameters for a sample of 30 field early-type galaxies (E/S0s) in the redshift range $0.1 < z < 0.66$. We find that (i) the FP is defined and tight out to the highest redshift bin; (ii) the intercept $\gamma$ evolves as $d\gamma/dz = 0.58_{-0.10}^{+0.09}$ (for $\Omega = 0.3$, $\Omega_\Lambda = 0.7$) or, in terms of average effective mass-to-light ratio, as $d \log (ML_*/)dz = -0.72_{-0.14}^{+0.12}$, i.e., faster than is observed for cluster E/S0s ($-0.49 \pm 0.05$). In addition, we detect [O ii] emission greater than 5 Å in 22% of an enlarged sample of 42 massive E/S0s in the range $0.1 < z < 0.73$, in contrast with the quiescent population observed in clusters at similar $z$. We interpret these findings as evidence that a significant fraction of massive field E/S0s experiences secondary episodes of star formation at $z < 1$.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: structure

1. INTRODUCTION

The fundamental plane (FP) (Djorgovski & Davis 1987; Dressler et al. 1987) is a tight correlation between the effective radius ($R_e$), the effective surface brightness ($SB_e$), and the central velocity dispersion ($\sigma$),

$$\log R_e = \alpha \log \sigma + \beta SB_e + \gamma,$$

which is observed to hold for local early-type galaxies (E/S0s). Under the assumption that E/S0s are homogenous dynamical systems, the FP can be interpreted in terms of a power-law relation between mass ($M$) and mass-to-light ratio ($ML_*$) (Treu et al. 2001a and references therein). In recent years, it has been found that a tight FP exists in clusters out to redshift $z = 0.83$ (van Dokkum & Franx 1996; Pahre 1998; Bender et al. 1998; Kelson et al. 2000). The modest evolution of the intercept $\gamma$ and the tightness of the FP at $0.1 < z < 1$ can be explained in terms of passive evolution and an old age of the stellar populations in cluster E/S0s. The absence of a dramatic evolution in the slopes $\alpha$ and $\beta$ argues against the interpretation of the FP “tilt” resulting solely from a mass-age relation.

So far, most of the studies have been focused on the cluster environment. However, the population of galaxies in clusters is likely to evolve with redshift by accretion of field galaxies. Therefore, in order to obtain a complete and reliable picture, it is necessary to study the evolution of E/S0s both in clusters and in the field. In addition, hierarchical clustering models (e.g., Kauffmann 1996) predict the stellar populations of field E/S0s to be significantly younger than the ones of cluster E/S0s. The effects of age differences are difficult to observe in the local universe (Bernardi et al. 1998), when the typical population ages are large, but are greatly enhanced at intermediate redshift. For these reasons, we have embarked on a campaign aimed at measuring the evolution of the FP of field E/S0s with redshift. In previous papers (Treu et al. 1999; Treu et al. 2001a, 2001b, hereafter T01a, T01b), we have analyzed a sample of 19 E/S0s, finding that a tight FP exists in the field out to $z \approx 0.4$ and that the evolution of the intercept is marginally faster than in the clusters, indicating a marginally younger age for field galaxies (see also van Dokkum et al. 2001 and Kochanek et al. 2000).

Here we present results from a larger sample of 30 E/S0s extended to $z \sim 0.7$, increasing dramatically our sensitivity to differences between cluster and field environment, and show that field E/S0s evolve faster than cluster ones at the 95% confidence level. In addition, we report on the detection of [O ii] $\lambda 3727$ emission in a significant fraction of massive field E/S0s at intermediate redshift, which we interpret as evidence for secondary episodes of star formation.

We assume the Hubble constant, the matter density, and the cosmological constant to be, respectively, $H_0 = 50 h_{50}$ km s$^{-1}$ Mpc$^{-1}$ ($h_{50} = 1.3$ when necessary), $\Omega = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE SELECTION AND OBSERVATIONS

The sample of E/S0s was selected on the basis of Hubble Space Telescope (HST) images taken from the HST Medium Deep Survey (MDS; Griffiths et al. 1994). The selection criteria are identical to the ones extensively discussed in T01b, except for the color cut ($1.25 < V_{606} - I_{814}$), chosen to select higher redshift E/S0s; $V_{606}$ and $I_{814}$ indicate Vega magnitudes through HST filters F606W and F814W, respectively) and the magnitude range ($19.3 < I_{814} < 20.3$). The effects of color and magnitude selection are taken into account in the analysis presented here as discussed.

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Fig. 1.—Spectra of galaxies with measured central velocity dispersion. The shaded regions are affected by sky-line residuals and atmospheric absorption and have been masked out during the fit. Note [O\text{II}] in emission in galaxies B2 and A5.

in T01a.\textsuperscript{2} Morphological classification was performed independently by two of us (T. T., M. S.), based on visual inspection of the images, of the residuals from the fit, and of the luminosity profiles. In particular, since contamination from S\text{a} galaxies\textsuperscript{3} could bias our results toward a younger age of the stellar populations, we were extremely conservative in rejecting galaxies that showed sign of a spiral disk either in the direct images (F606W and F814W) or in the residuals from the r\textsuperscript{1/4} fit. As an independent check of our classification, the bulge-to-total luminosity ratio measured by the MDS group for our E/S0s is always larger than 0.6 and typically in the range 0.8–1.

Spectra for 16 galaxies were obtained in service mode from 2000 April to 2001 March, using the Focal Reducer and Spectrograph 2 (FORS2) at the Very Large Telescope (VLT). The adopted grism R600 with a 1'' wide slit gives a resolution of \( \sim 90–100 \) km s\(^{-1}\); exposure times ranged between 2 \( \times \) 1800 s and 2 \( \times \) 3600 s. For 10 out of 16 E/S0s observed (Fig. 1) we obtained a reliable central velocity dispersion (the success rate depending on observing conditions and redshift, since the observed wavelength range was optimized for the range \( z \approx 0.45–0.65 \)). The data reduction was very similar to the one described in T01b. Combined with the data of T01a, our total sample consists of 42 galaxies (in the range \( z = 0.10–0.73 \)), 30 of which with measured velocity dispersion (\( z = 0.10–0.66 \)).

3. THE EVOLUTION OF THE FUNDAMENTAL PLANE

Figures 2a–2e show the location in the FP-space of the galaxies in our sample, binned in redshift. The data (open symbols) in the rest-frame B band\textsuperscript{4} are compared with the local relation shown as solid line. The main result is that the brightening at fixed \( \sigma \) and \( R \) increases with redshift. By assuming constant slopes \( \alpha \) and \( \beta \) we obtain the average evolution of the intercept with redshift plotted as filled pentagons in Figure 2f.

Under the assumption of passive evolution and constant slopes (T01a), the evolution of \( \gamma \) can be converted into the evolution of the average \( M/L \) ratio, which can be read on the right-hand scale of Figure 2f. Modeling the evolution as

\textsuperscript{2} Images are available at the MDS Web site at http://www.archive.stsci.edu/ mds.

\textsuperscript{3} See, e.g., Smail et al. (1997) and van Dokkum et al. (1998a) for a discussion.

\textsuperscript{4} The analysis in the V band, or using different Coma FP, yields the same results; see T01a for discussion.
\[ \gamma(z) = \gamma(0) + \gamma'(0)z, \] where the prime indicates derivative with respect to \( z \), a least \( \chi^2 \) fit yields \( \gamma_0 = 0.64 \). However, in order to avoid biased results, it is crucial to take into account the selection process, for example, by applying the Monte Carlo–Bayesian method introduced in T01a, generalized by allowing the scatter to vary as a function of redshift, \( \sigma(z) = \sigma_0(0) + \sigma'(0)z \). In this way, we derive the posterior probability density given the set of observations, \( p(\gamma', \sigma'|[\gamma]) \) in the notation of T01a, shown in Figure 3a. The posterior probability peaks at \( \gamma'_p = 0.58 \) (0.45–0.67 68% limit), which corresponds to \( \log (M/L)_p \gamma = -0.49 \pm 0.05 \), i.e., \( \gamma = 0.39 \pm 0.04 \), which falls on the 95% contour in Figure 3a.

4. EMISSION-LINE PROPERTIES

At \( z \geq 0.3 \) the emission line [O \( \text{II} \) \( \lambda 3727 \)] is redshifted into the wavelength range covered by our instrumental setup. Six out of 27 E/S0s for which [O \( \text{II} \)] is detectable show significant emission (rest-frame equivalent width EW > 5 \( \AA \)). If attributed to star formation, the observed [O \( \text{II} \)] EWs correspond to star formation rates of order 0.5–5 \( M_\odot \) yr\(^{-1} \) (Kennicutt 1992). The fraction of E/S0s with sizable star formation in our sample is significantly larger than the one found for massive E/S0s in clusters at similar redshifts and in the local universe. In Figure 4 we plot the fraction of E/S0s with [O \( \text{II} \)] EW > 5 \( \AA \) as a function of redshift for field (pentagons) and cluster (squares) samples taken from the literature.

E/S0s with similar [O \( \text{II} \)] EWs, or similarly with relatively blue colors, have been reported previously, suggesting that secondary episodes of star formation are common at intermediate redshift (Schade et al. 1999; Menanteau, Abraham, & Ellis 2001). Im et al. (2001) measured the width of the [O \( \text{II} \)] line for a sample of blue E/S0s at intermediate redshift, finding velocity dispersions \( \sigma \approx 80 \text{ km s}^{-1} \); on the basis of this measurement they argue that most blue E/S0s are not the progenitors of present-day massive E/S0s but rather less massive spheroids, for which star formation is observed also in the local universe (Jansen et al. 2000). Our sample adds further information, because it is made of bright (\( I < 20.3 \)) and massive E/S0s. The velocity dispersions we obtained via absorption-line kinematics are typical of massive field E/S0s. In particular, the three objects with significant [O \( \text{II} \)] emission for which
velocity dispersions are available have \( \sigma = 118, 179, \) and 233 km s\(^{-1}\). From the FP relationship, as measured from our sample, we estimate for the other three galaxies with [O \( \text{II} \)] emission \( \sigma = 105, 171, \) and 261 km s\(^{-1}\).

We can estimate the amount of stellar mass assembled in these secondary bursts in the following way. The probability of observing a burst is given by

\[
p(O \text{ II}) = \langle n \rangle \langle \dot{t} \rangle / \Delta t,
\]

where \( \langle n \rangle \) is the average number of bursts per galaxy, \( \langle \dot{t} \rangle \) is the average duration of the burst, and \( \Delta t \) is the interval in cosmic time between \( z = 0.73 \) and \( z = 0.26 \) when the burst was observable. The total average mass in secondary bursts is then

\[
M_{\text{OII}} = \langle n \rangle \langle \dot{t} \rangle \langle \dot{\mathcal{M}} \rangle = p(O \text{ II}) \Delta t \langle \dot{\mathcal{M}} \rangle.
\]

By using the observed values for \( p(O \text{ II}) = 6/27 \) and \( \langle \dot{\mathcal{M}} \rangle = 0.5–5 \, M_\odot \text{ yr}^{-1} \), we estimate that the average stellar mass formed in these bursts is of the order of \( M_{\text{OII}} \sim 5 \times 10^{-8} – 5 \times 10^3 \, M_\odot \).

5. CONCLUSIONS

Our sample of 30 field E/S0s defines a tight FP out to \( z = 0.66 \), with no or modest increase of the scatter with redshift. The intercept \( \gamma \) evolves with redshift as \( \gamma' = 0.58 \), which, interpreted in terms of passive evolution of the stellar populations, implies \( \log (M/L_\odot) \gamma' = -0.72 \pm 0.11 \), i.e., faster than that observed in clusters by other groups (e.g., \(-0.49 \pm 0.05\); van Dokkum et al. 2001). In addition, 22% of the galaxies show [O \( \text{II} \)] in emission, with EW > 5 \AA. Assuming the emission is due to star formation, we estimate that such bursts produce of order \( M_{\text{OII}} \sim 5 \times 10^{-5} – 5 \times 10^9 \, M_\odot \) of stellar mass between \( z = 0.73 \) and \( z = 0.26 \).

The existence and tightness of the FP suggest that no major structural changes occur between \( z = 0.7 \) and \( z = 0 \). However, we find evidence that some stellar mass is formed at relatively recent time during secondary bursts. Although these bursts contribute only a small fraction of the total stellar mass, they contribute significantly to the evolution of the observable luminous component. For example, a scenario in which most of the stars formed at \( z > 1 \) and secondary star formation occurs at \( z < 1 \) not only could explain the evolution of the FP (T01a) and the observed [O \( \text{II} \)] emission, but could also reconcile the modest evolution of the number density of E/S0s observed to \( z \sim 1 \) (Schade et al. 1999; Im et al. 2001) with the paucity of red E/S0s observed in some infrared surveys (Menanteau et al. 1999; Treu & Stiavelli 1999; see also Jimenez et al. 1999 and Daddi et al. 2000).

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