On the origin of the scatter around the Fundamental Plane: correlations with stellar population parameters

A. Gargiulo,1* C. P. Haines,2 P. Merluzzi,3 R. J. Smith,4 F. La Barbera,3 G. Busarello,3 J. R. Lucey,4 A. Mercurio3 and M. Capaccioli5

1Physics Department, Università ‘Federico II’, Napoli, Italy
2School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT
3INAF – Osservatorio Astronomico di Capodimonte, via Moiariello, 1-80131 Napoli, Italy
4Department of Physics, Durham University, Durham DH1 3LE
5VSTceN, via Moiariello, 1-80131 Napoli, Italy

Accepted 2009 March 20. Received 2009 March 20; in original form 2009 January 16

ABSTRACT
We present a Fundamental Plane (FP) analysis of 141 early-type galaxies in the Shapley supercluster at z = 0.049 based on spectroscopy from the AAOMega spectrograph at the Anglo-Australian Telescope and photometry from the WFI on the European Southern Observatory/MPI 2.2-m telescope. The key feature of the survey is its coverage of low-mass galaxies down to σ ∼ 50 km s−1. We obtain a best-fitting FP relation re ∝ σe1.06±0.06 ⟨I⟩e−0.82±0.02 in the R band. The shallow exponent of σe0 is a result of the extension of our sample to low velocity dispersions. Considering the subsample of σe0 > 100 km s−1 galaxies, the FP relation is re ∝ σ1.35 ⟨I⟩e−0.81, consistent with previous studies in the high-luminosity regime. We investigate the origin of the intrinsic FP scatter, using estimates of age, metallicity and α/Fe. We find that the FP residuals anticorrelate (>3σ) with the mean stellar age in agreement with previous work. However, a stronger (>4σ) correlation with α/Fe is also found. These correlations indicate that galaxies with effective radii smaller than those predicted by the FP have stellar populations systematically older and with α overabundances larger than average, for their σ. Including α/Fe as a fourth parameter in the FP, the total scatter decreases from 0.088 to 0.075 dex and the estimated intrinsic scatter decreases from 0.068 to 0.049 dex. Thus, variations in α/Fe account for ∼30 per cent of the total variance around the FP, and ∼50 per cent of the estimated intrinsic variance. This result indicates that the distribution of galaxies around the FP are tightly related to the enrichment, and hence to the time-scale of star formation. Our results appear to be consistent with the merger hypothesis for the formation of ellipticals which predicts that a significant fraction of the scatter is due to variations in the importance of dissipation in forming merger remnants of a given mass.

Key words: galaxies: abundances – galaxies: ellipticals and lenticular, cD – galaxies: formation – galaxies: fundamental parameters – galaxies: structure.

1 INTRODUCTION

Early-type galaxies are observed to obey a set of scaling relations that connect their photometric and kinematic properties (e.g. Kormendy relation, Kormendy 1977; Faber–Jackson relation, Faber & Jackson 1976). Among these, the most notable, due to its surprising small scatter (∼0.1 dex), is the relation between effective radius re, mean surface brightness within the effective radius ⟨I⟩e and central velocity dispersion σe (Djorgovski & Davis 1987; Dressler et al. 1987). In the three-dimensional space (logre, logσe, log⟨I⟩e), elliptical galaxies populate a tight plane known as the Fundamental Plane (FP) and usually expressed in the form:

\[ \log r_e = \alpha \log \sigma_e + \beta \log \langle I \rangle_e + \gamma. \]  

(1)

If elliptical galaxies formed a homologous family, i.e. systems with density, luminosity and kinematical structures equal over the entire early-type sequence and with constant mass-to-light ratios (M/L), then the virial theorem predicts a correlation with \( \alpha = 2, \beta = -1 \). However, observations show that the plane is somewhat ‘tilted’ with respect to virial expectations, with best-fitting scalings \( \alpha \sim 1.3, \beta \sim -0.8 \) (e.g. Jørgensen, Franx & Kjægaard 1996, hereafter JFK96).
The origin of the FP tilt has been much debated and can be interpreted as the breakdown of either of the two assumptions in the virial expectation. A systematic variation in the mass-to-light ratio along the FP could be due to variations in the stellar content [age, metallicity or initial mass function (IMF)] and/or the amount of dark matter among ellipticals (Tortora et al. 2009). Performing detailed dynamical analysis of 25 galaxies with SAURON integral-field stellar kinematics to $r_e$, Cappellari et al. (2006) find the ‘tilt’ almost exclusively due to real M/L variations of the form $(M/L) \propto M_h^{0.27 \pm 0.03}$, while structural and dynamical non-homologies have negligible effects. They also find the variation of the dynamical M/L ratio to correlate with the Hβ line strength, and ascribe most of the tilt to stellar population (age) effects. On the other hand, other authors (e.g. Trujillo, Burkert & Bell 2004; La Barbera et al. 2008a) find that the tilt is not primarily driven by stellar populations, but instead results from other effects, such as non-homology.

Although the FP relation is quite tight, there is none the less a significant scatter around the plane that cannot be attributed to measurement errors. The origin of this intrinsic component has been investigated by many authors. JFK96 found that they were unable to reduce the scatter by introducing additional parameters, such as ellipticity or isophotal shape of the galaxies, into the FP relation. Variations in stellar populations along the sequence of early-type galaxies are found to be partially responsible for the intrinsic scatter (e.g. Gregg 1992; Guzman & Lucey 1993; Guzman, Lucey & Bower 1993). Prugniel & Simien (1996), studying the correlation between the residuals from the FP and the residuals from the colour and Mg$_b$ line strength versus luminosity relations, found that blue and low-Mg$_b$ elliptical galaxies deviate systematically from the value predicted by the FP. Following this evidence Forbes, Ponman & Brown (1998), studying a sample of non-cluster galaxies, found that the residuals of the FP correlate with the ages of the galaxies, i.e. the scatter of the FP is partly due to variation in galaxy age at a given mass, and in particular to variations in the time of the last starburst. On the contrary, they found that the effect of changes in metallicity is negligible. Similar results were obtained by Reda, Forbes & Hau (2005) analysing a sample of isolated galaxies: some objects deviate from the FP relation having lower M/L ratio and this was interpreted as due to their younger stellar populations, probably induced by recent gaseous merger. The same conclusions were reached by Wynts et al. (2004) for two high-redshift clusters. They found that the residuals from the FP correlate with the residuals from the Hβ–$\sigma_\text{e}$ relation. This confirms the role played by stellar populations in determining the appearance of the FP, with relations appearing more dispersed for samples of galaxies that are more dispersed in age.

The existence of the FP, its small observed scatter and the tilt have presented a long-standing challenge to theoretical models explaining the origin of early-type galaxies. In fact, whatever the scenario of formation and evolution of early-type galaxies is, it has to be able to explain the existence of such a tight correlation and its deviation from virial expectations and therefore to link galaxy structure and dynamics with their star formation histories.

In the recent years, observations and simulations have broadly supported the galaxy merging scenario which fits naturally into the C old dark matter hierarchical cosmology (e.g. Steinmetz & Navarro 2002). In the hierarchical scenario, ellipticals form through the merging of disc galaxies (Toomre & Toomre 1972; Toomre 1977). In the merging context, significant new insights have been made through large-scale gas dynamical simulations of galaxy mergers (Robertson et al. 2006), indicating that for lower mass galaxies dissipation becomes increasingly important, driving nuclear starbursts that contribute larger mass fractions and producing systematic trends with mass in both the structures and stellar populations of the remnant ellipticals (Hopkins, Cox & Hernquist 2008). The FP tilt then arises as a direct consequence of the systematic trends with mass of the importance of dissipation during mergers. In the same scenario of galaxy formation, the origin of the intrinsic scatter in the FP arises as a combination of the scatter in the total baryon-to-dark matter content of the progenitor galaxies, and variations in the dissipational fractions at fixed stellar mass. This latter factor should be observable as correlations between the residuals from the FP and the stellar population parameters, and represents a critical test of the merger scenario (Hopkins et al. 2008), through the predicted co-evolution of the stellar populations and structures of elliptical galaxies.

The increasing importance of dissipation in the formation of low-mass galaxies and the different mechanisms that drive the evolution and the star formation histories for low- and high-mass galaxies (Haines et al. 2007) should be reflected in variations with the mass of the structural and kinematical properties and hence in variations both in the shape and orientation of the FP for these two families of galaxies. It should also be noted that non-merger origins may be important for lower mass galaxies, whose evolution turns out to be primarily driven by the mass of their host halo, probably through the combined effects of tidal forces and ram-pressure stripping (Haines et al. 2007).

To date, no large homogeneous sample of galaxies covering both the giant and dwarf regime exists. Although many FP data sets for systems as different as BCGs, normal Es, dEs, dSphs have been analysed and compared to look for changes in $\alpha$ (Zaritsky, Gonzalez & Zabludoff 2006), these studies suffer from the non-homogeneity of the samples both in terms of differences in measuring the quantities entering the FP (e.g. different fits to derive structural parameters, different apertures to measure the velocity dispersion) as well as the selection of galaxies themselves. The form of the FP obtained can be influenced by all of these criteria.

In this paper, we present a FP analysis of 141 early-type galaxies from the Shapley supercluster ($z \sim 0.049$) with both new R-band surface photometry measurements and published velocity dispersion measurements from Smith, Lucey & Hudson (2007, hereafter SLH). The sample is randomly selected down to $M_g + 3$ and represents the largest homogeneous sample of low-mass early-type galaxies with reliable velocity dispersions down to $\sim 50$ km s$^{-1}$. In Section 2, we present the photometric and spectroscopic data (including velocity dispersion measurements and spectral indices) and the catalogue of ‘newly derived’ structural parameters; the morphological classification is described in Section 3. Our FP fits for the overall and high-$\sigma$ ($\sigma > 100$ km s$^{-1}$) samples are presented in Section 4, which discusses how the selection criteria can affect the values of the FP coefficients and mimic a possible curvature of the plane. In Section 5, we quantify the contribution of stellar populations to the intrinsic scatter. We discuss our results in Section 6 and give a summary in Section 7. The origin of the tilt of the FP will be investigated in a forthcoming paper.

Throughout this paper, we use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. With this cosmology, 1 arcsec = 0.96 kpc at $z = 0.049$ and the distance modulus is 36.69.

2 THE DATA

The sample of galaxies used in this work consists of 141 early-type $R < 18$ galaxies (red points in Fig. 1) distributed throughout
Table 1. Spectroscopic sample: the first four lines indicate the criteria used to select the galaxy sample, and the number of galaxies remaining after each step. In the following lines, the 224 remaining galaxies are then divided into four classes, of which only the 141 early-type objects are used in our FP analysis.

| Sample selection                                      | 565 |
|--------------------------------------------------------|-----|
| Galaxies with spectra                                  | 565 |
| Cluster members (0.039 < z < 0.055)                     | 396 |
| Cluster members in SOS region                          | 378 |
| Cluster members in SOS region with surface photometry  | 224 |
| Galaxy classification                                  |     |
| Early type                                             | 141 |
| Late type                                              | 44  |
| Unresolved kinematically                               | 31  |
| With EW(Hα) > 3 Å                                      | 8   |

entire Shapley Optical Survey (SOS; Mercurio et al. 2006) area, but mainly located in high-density regions (i.e. cluster cores). The sample selection is summarized in Table 1. In the region covered by SOS, there are 378 confirmed supercluster members. Here, we analyse the sample of 141 galaxies which have all the following characteristics: (i) an early-type morphology (see Section 3), (ii) reliable surface photometry, (iii) a measured velocity dispersion and (iv) an insignificant Hα emission [EW(Hα) < 3 Å].

2.1 Spectroscopic data

Spectra were obtained using the AAOmega fibre-fed spectrograph at the Anglo-Australian Telescope. A full description is given by SLH; we summarize some key points here. The spectroscopic sample limit is \( R = 18 \) in the cluster cores, with galaxies selected from the NOAO (National Optical Astronomy Observatories) FP Survey (NFPS; Smith et al. 2004) images (green boxes in Fig. 1). Outside of these regions, brighter galaxies were selected from the Two-Mass All-Sky Survey Extended Source Catalogue (\( R \lesssim 15.7 \)). The fibre diameter of 2 arcsec corresponds to 1.9 kpc. Long integrations resulted in high signal-to-noise ratios, \( S/N \sim 45 \) per Å for \( \sigma < 100 \text{ km s}^{-1} \) and \( S/N \sim 90 \) per Å for \( \sigma > 100 \text{ km s}^{-1} \). Velocity dispersions were measured with respect to the best-matching simple stellar population (SSP) templates. The errors were estimated from Monte Carlo simulations, and are \( \sim 0.05 \text{ dex at } \sigma < 100 \text{ km s}^{-1} \) and \( \sim 0.01 \text{ dex at } \sigma > 100 \text{ km s}^{-1} \). The spectral resolution of 3.2 Å (82 km s\(^{-1}\) instrumental dispersion) allows the recovery of velocity dispersions as low as \( \sim 40 \text{ km s}^{-1} \). However, some galaxies in the sample remain kinematically unresolved, i.e. have velocity dispersions consistent with zero. When comparing the new velocity dispersion measurements with those previously obtained from the NFPS (having a factor of \( \sim 3 \) lower S/N), SLH find the new velocity dispersions of low-\( \sigma \) objects to be systematically lower by \( \sim 0.10 \text{ dex, which they attribute to a combination of higher S/N and the use of a range of SSP templates rather than individual K-giant stars.} \)

The absorption index data are tabulated by SLH. Here, we also make use of single-burst equivalent ages, metallicities (Z/H) and abundance ratios (\( \alpha/\text{Fe} \)). Typical errors for galaxies with \( \sigma \) in the range 50–100 km s\(^{-1}\) are 14 per cent in age, 0.05 dex in [Z/H] and 0.04 dex in \( \alpha/\text{Fe} \), while they reduce to half of these values for galaxies with \( \sigma > 150 \text{ km s}^{-1} \).

In this work, we refer to velocity dispersions measured into an aperture of \( r_{e}/8 \). We have corrected our velocity dispersions (\( \sigma_{ap} \)) acquired with fibres of 1 arcsec radius (\( r_{e} \)) to the apertures of \( r_{e}/8 \) following Jørgensen, Franx & Kjærgaard (1995):

\[
\log \frac{\sigma_{ap}}{\sigma_{r_{e}/8}} = -0.04 \log \frac{r_{ap}}{r_{e}/8}.
\]

Hereafter, we adopt the notation \( \sigma_{0} = \sigma_{r_{e}/8} \) for the velocity dispersion corrected to this fiducial aperture.
Starting from the sample of galaxies observed by SLH, we select those 396 galaxies belonging spectroscopically to the Shapley supercluster (0.039 < z < 0.056; blue and red points in Fig. 1).

2.2 Imaging data

For photometry, we refer to the SOS survey (Haines et al. 2006; Mercurio et al. 2006). The SOS is based on data acquired with the WFI camera (4 × 2 mosaic of 2k × 4k CCDs with a pixel scale of 0.238 arcsec pixel) mounted on the European Southern Observatory/MPG 2.2-m telescope at la Silla observatory. R-band imaging was acquired in good seeing conditions [full width at half-maximum (FWHM) ∼ 0.7 arcsec] for eight contiguous fields covering a region of 2 deg² centred on the Shapley supercluster core (see Fig. 1). Five exposures were obtained for each field giving a total exposure time of 1200 s for the mosaic images (240 s × 5). The reduction was carried out with the ALAMID pipeline (version 1.0; Vandame 2004) and the catalogue was produced with the SEXTRACTOR package (Bertin & Arnouts 1996), plus a set of procedures designed ad hoc to remove spurious detections (bad pixels, cosmic rays, etc.) and correct the photometry for blended sources. The survey is complete to $R = 22$ (≈ $M_r^* + 7$). For more details, see Mercurio et al. (2006). SOS photometry is available for 378 supercluster galaxies observed by SLH, all of which are detected at S/N levels greater than 100 in each exposure, such that reliable structural parameters can be derived.

2.3 Structural parameters

Structural parameters were derived using the software 2DPHOT described by La Barbera et al. (2008b). This is an automated tool measuring both integrated and surface photometry of galaxies and is furnished with several tasks to carry out reliable star–galaxy separation, point spread function (PSF) modelling and estimation of catalogue completeness. The main steps of the 2DPHOT algorithm are: (i) creation of a clean catalogue of the input image with SEXTRACTOR; (ii) estimation of the FWHM and the definition of ‘sure stars’; (iii) construction of an accurate PSF model taking into account both possible spatial variations as well as deviation of stellar isophotes from circularity; (iv) derivation of structural parameters (effective radius $r_e$, mean surface brightness $⟨μ_e⟩$, Sersic index $n$, total magnitude $m_{tot}$, etc.) by fitting galaxy images with two-dimensional PSF-convolved Sersic models, as well as the measure of the fit accuracy ($\chi^2$).

The measurement of structural parameters is strictly dependent both on the PSF model and on the S/N. Since the mosaic SOS images are obtained by stacking jittered images to cover the gap regions between the eight CCDs, the S/N is not constant among the images being lower in the overlapping gap area. Moreover, in the gap area the PSF turns out to be poorly defined due to its spatial variations. We removed the galaxies in these regions from our sample and performed the surface photometry only for galaxies in highest S/N regions (224 galaxies), where the PSF is well defined. We correct our mean surface brightnesses for cosmological dimming ($d(μ_e) = 0.208$ mag arcsec⁻²), galactic extinction ($dm = 0.147$ mag; Schlegel et al. 1998) and k-correction ($dm = 0.05$; Poggianti 1997) and convert from mag arcsec⁻² to log(I)_e, expressed in physical units $L_{K⊙}$ pc⁻² through log(I)_e = $−0.4[⟨μ_e⟩ − M_{K⊙}] − 5 \log(206265 \text{ pc/10 pc})$ where $M_{K⊙} = 4.42$ is the solar absolute magnitude (Binney & Merrifield 1998).

2.4 Measuring the uncertainties in effective radius and mean surface brightness

To derive the errors, we measure the structural parameters on the five single exposures ($r_e^i$, $⟨μ_e⟩^i$ with $i = 1$, 5), assuming that the observed spread of their values is directly related to the S/N on the final mosaic used to derive the structural parameters entering the FP.

Due to the size of the sample (five exposures), only two scale estimators can be considered reliable (Beers, Flynn & Gebhardt 1990): the classical standard deviation and that obtained by the gapper algorithm $σ_{gap}$. The gapper is a robust scale indicator (Wainer & Thissen 1976) based on the gaps between ordered statistics which has a high level of efficiency for samples as small as five objects. If we have $n$ measures of a quantity $x$ ranked in increasing order ($x_1$, $x_2$, ..., $x_{n−1}$, $x_n$), according to the gapper algorithm we can measure a robust scale indicator as

$$σ_{gap} = \frac{\sqrt{n}}{n(n−1)} \sum_{i=1}^{n} w_i g_i,$$  \hspace{1cm} (4)

where

$$g_i = x_{i+1} − x_i, \; i = 1, \ldots, n−1 \; \text{and} \; w_i = i(n−i).$$  \hspace{1cm} (5)

To avoid an overestimation of the errors due to the presence of outliers, we first compute the $σ_{gap}$ of the $\log(I)_e$ and $\log(⟨μ⟩_e)$ distributions and reject all values that deviate more than $3σ_{gap}$ from the median value, before subsequently computing the classical standard deviation as well as the covariance matrices of the clipped sample for both variables ($σ_{log(I)_e}$, $σ_{log(⟨μ⟩_e)}$, $\text{cov}[\log(I)_e, \log(⟨μ⟩_e)]$).

The errors on the mosaic value of $\log(I)_e$ and $\log(⟨μ⟩_e)$ are $\delta_{log(I)_e}$ and $\delta_{log(⟨μ⟩_e)}$, respectively) are given by $σ_{log(I)_e}/\sqrt{n}$ and $σ_{log(⟨μ⟩_e)}/\sqrt{n}$, where $n$ is the number of measures available. The typical errors on the logarithms of effective radius ($\log r_e$) and mean surface brightness ($\log(⟨μ⟩_e)$ are 0.03 and 0.04, respectively. These errors explicitly include the effects of noise in the galaxy, but not the presence of neighbouring objects. We have estimated the effect of the latter, by repeatedly placing copies of the galaxies one by one at random positions across the same CCD image (where the PSF should remain constant) and reapplying 2DPHOT, finding the variations in the structural parameters to be consistent with the previously obtained errors, albeit with a small number (~2 per cent) of >5σ outliers when the galaxy is placed very close to a bright star or galaxy.

3 MORPHOLOGICAL CLASSIFICATION

We have morphologically classified the 224 galaxies with available surface photometry, by inspection of the residual maps provided by 2DPHOT. We denote as ‘late type’ all galaxies showing signs of spiral arms or asymmetric disturbance and as ‘early type’ all those with no such structures. The resolution of SOS images does not allow any finer classification, for example into elliptical and lenticular galaxies, since the presence of a residual disc can be seen only in particular cases, i.e. when it is very bright, widespread or edge-on. In Fig. 2, we show some illustrative examples of galaxies classified as early and late types, covering the full range of magnitudes studied here. We have checked this classification by comparing our results with those of Thomas & Katgert (2006) for a subsample of 54 galaxies, since the presence of a residual disc can be seen only in particular cases, i.e. when it is very bright, widespread or edge-on. In Fig. 2, we show some illustrative examples of galaxies classified as early and late types, covering the full range of magnitudes studied here. We have checked this classification by comparing our results with those of Thomas & Katgert (2006) for a subsample of 54 galaxies belonging to A3558 and A3562, finding perfect agreement. In their classification, galaxies were subdivided into E, S0, Se and SI classes (the latter being early and late spirals). Our early-type
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The samples contain only galaxies classified as E and S0 by Thomas & Katgert (2006).

The strong correlation between the Sersic index $n$ and luminosity (Caon, Capaccioli & D’Onofrio 1993; Young & Currie 1994) prevents any morphological classification based on the Sersic index alone. Graham & Guzman (2003) show that the values of the Sersic index $n$ of dE, ordinary E/S0 galaxies, and BCGs follow a continuous trend from $n < 0.5$ to $n \sim 10$, whereby brighter galaxies have larger values of $n$. In Fig. 3, we demonstrate the equivalent trend for our galaxy sample, plotting the Sersic index distribution as a function of morphological type and magnitude. The median value of $n$ for early-type (filled circles) and late-type (open circles) galaxies are shown for each magnitude bin (chosen to contain the same number of galaxies), while the error bars indicate the interquartile values.

As pointed out by Graham & Guzman (2003), the distribution of $n$ for early-type galaxies is shifted towards higher values with increasing luminosity. Late-type galaxies have lower values of $n$ at all magnitudes, but there is not a clean a priori separation between the two morphological classes.

The morphological classification results in a sample of 141 early-type galaxies and 44 late-type or irregular galaxies, while 31 galaxies are removed from the sample since they are not kinematically resolved, and eight are removed as having significant Hα emission [EW(Hα) > 3 Å]. We summarize the characteristics of the sample in Table 1, while in Table 2 we report structural and kinematical parameters with the corresponding errors for the 141 galaxies used in the following section.

4 THE FUNDAMENTAL PLANE OF $R < 18$ SHAPLEY GALAXIES

For the FP, we use the representation of equation (1) where $r_e$ is the effective radius measured in kpc, $\sigma_0$ is the central velocity dispersion
corrected to an aperture of radius r_e/8 in km s^{-1} (see Section 2.1) and 
\langle I_e \rangle is the mean surface brightness within r_e expressed in L_\odot pc^{-2}.
To derive the value of α, β and γ, we adopted the orthogonal fit which minimizes the quantity:
\[ \sum_{i=1}^{N} w_i [\log r_e - (\alpha \log \sigma_0 + \beta \log \langle I_e \rangle + \gamma)], \]
which is the sum of the absolute residuals perpendicular to the plane. This is less sensitive to outliers than the classic least-squares method (JFK96). For the full sample of 141 galaxies, we found
\log r_e = 1.03 \pm 0.06 \log \sigma_0 - 0.82 \pm 0.02 \log \langle I_e \rangle + 0.33, \quad (7)
where the errors on coefficient are computed via a bootstrap procedure. The above relation presents a scatter of 0.088 dex in the intrinsic scatter orthogonal to the FP, \( \delta_{\text{int}} \). The fitting function to be minimized is
\[ w_i^{-2} = \delta_{\text{int}}^2 + (\alpha \log \sigma_0 + \beta \log \langle I_e \rangle)^2 - 2 \beta \log r_e \log \langle I_e \rangle. \]
\[ (9) \]
where the sum is extended over all sample galaxies and where \( w_i^{-2} \) is adjusted to give the expected value of 0.8 per degree of freedom (the mean absolute value of a standardized Gaussian distribution is 0.8). The resulting equation for the FP is
\log r_e = 1.06 \pm 0.06 \log \sigma_0 - 0.82 \pm 0.02 \log \langle I_e \rangle + 0.28. \quad (10)\]
The orthogonal and weighted fits are consistent, demonstrating that the results are robust to the effects of the larger \( \sigma_0 \) uncertainties (0.01 dex for \( \sigma_0 > 100 \kms \) and 0.05 for \( \sigma_0 < 100 \kms \) for the lowest mass galaxies. The scatter in the log \( r_e \) direction is now equal to 0.092, while its intrinsic component is 0.070. Fig. 4 shows the two edge-on FP views (left-hand and central panels) and its trend along the direction of luminosity (right-hand panel).

The value of the \( \alpha \) coefficient, obtained for the Shapley sample, is significantly lower than the typical values of 1.2–1.3 reported for samples dominated by giant galaxies (e.g., JFK96). If we restrict our sample to galaxies with \( \sigma_0 > 100 \kms \) (high-\( \sigma_0 \) sample, 91 galaxies), we obtain the FP relation:
\log r_e = 1.35 \pm 0.11 \log \sigma_0 - 0.81 \pm 0.03 \log \langle I_e \rangle - 0.40, \quad (11)\]

Table 2. Structural and kinematical parameters for the FP galaxy sample.

| ID                     | RA(J2000) | Dec.(J2000) | R_e | log\( \sigma_0 \) (km s^{-1}) | log\( \log r_e \) | log\( \log \langle I_e \rangle \) (L_\odot pc^{-2}) | \( \delta_{\log r_e} \) | \( \delta_{\log \langle I_e \rangle} \) | n  | \chi^2 |
|------------------------|-----------|-------------|-----|-------------------------------|-----------------|---------------------------------|----------------|----------------|-----|--------|
| TMASSJ1327466-3059237  | 13:27:46.6| -30:59:24   | 15.1 | 2.201                         | 0.010           | 0.904                           | 0.042          | 1.766          | 0.070 | 10.708 1.25 |
| NFPJ132828.6-313205    | 13:28:28.6| -31:32:04   | 15.4 | 2.112                         | 0.012           | 0.308                           | 0.002          | 2.861          | 0.004 | 1.589  6.43 |
| NFPJ132738.0-313041    | 13:27:38.0| -31:30:41   | 16.5 | 2.044                         | 0.016           | 0.038                           | 0.004          | 2.943          | 0.008 | 2.283  1.31 |
| NFPJ133408.0-314735    | 13:34:08.1| -31:47:34   | 16.8 | 2.175                         | 0.097           | 0.682                           | 0.044          | 1.842          | 0.059 | 3.518  2.03 |
| NFPJ1332945-3201001    | 13:32:54.2| -32:00:59   | 15.2 | 2.153                         | 0.010           | 0.475                           | 0.005          | 2.597          | 0.007 | 4.617  1.17 |
| NFPJ132656.0-312528    | 13:26:36.0| -31:25:27   | 14.8 | 2.031                         | 0.007           | 0.797                           | 0.007          | 2.118          | 0.011 | 5.452  1.99 |
| NFPJ1329483-311558     | 13:29:48.3| -31:15:58   | 14.0 | 2.296                         | 0.004           | 0.984                           | 0.023          | 2.043          | 0.035 | 6.945  1.15 |
| NFPJ132810.5-312310    | 13:28:10.5| -31:23:09   | 13.8 | 2.267                         | 0.004           | 1.108                           | 0.043          | 1.875          | 0.067 | 7.796  1.48 |
| NFPJ133246.5-315153    | 13:24:26.5| -31:51:53   | 14.8 | 2.302                         | 0.006           | 0.506                           | 0.036          | 2.685          | 0.051 | 8.414  1.38 |
| NFPJ132923.8-314832    | 13:29:23.2| -31:48:32   | 15.0 | 1.718                         | 0.062           | 0.972                           | 0.046          | 1.673          | 0.073 | 9.545  1.77 |

Note. Column 1: ID (SLH), Columns 2 and 3: RA(J2000) and Dec.(J2000), Column 4: total R-band magnitude, Columns 5 and 6: log \( \sigma_0 \) referred to an aperture of r_e/8 radius and \( \log \sigma_0 \), Columns 7 and 8: log \( r_e \) and \( \log r_e \), Columns 9 and 10: log \( \langle I_e \rangle \) and \( \log \langle I_e \rangle \), Column 11: n, Column 12: reduced \( \chi^2 \). This is a sample of the full catalogue, which is available in the electronic version of the paper (see Supporting Information).

Figure 4. Left-hand and central panels: the edge-on views of the Shapley R < 18 FP. Right-hand panel: the edge-on view of the FP as it appears along the direction of luminosity. Black lines are the best-fitting relations. α, β and γ values are reported in the left-hand panel.
with the overall scatter in \( \log \sigma_r \) reduced to 0.090. In Fig. 5, we plot the FP as fitted for the high-\( \sigma_0 \) sample (black points). Galaxies with \( \sigma_0 < 100 \) km s\(^{-1} \) are also reported for comparison (red dots). The \( \alpha \) value of the high-\( \sigma_0 \) sample is closer to those of other authors. The lower \( \alpha \) value found for the total sample is thus probably due to the extension of our sample to very low mass galaxies, down to \( \sigma_0 \sim 50 \) km s\(^{-1} \). The improved method used to obtain the velocity dispersions, as well as the high S/N levels of the spectra, can produce systematic effects on the resultant values of \( \sigma_0 \), particularly for low-\( \sigma_0 \) objects. SLH find that velocity dispersions obtained using single, old, solar-metallicity models instead of templates with different metallicities (as used in this paper) are overestimated by \( \sim 6 \) per cent for \( \sigma_0 = 75 \) km s\(^{-1} \) galaxies and by \( \sim 18 \) per cent for \( \sigma_0 = 50 \) km s\(^{-1} \). As a result, in our sample the low-\( \sigma_0 \) values are systematically lower than those of previous samples (e.g. NFPS sample), causing an increase of the FP tilt of about 10–15 per cent. The impact of the low-\( \sigma_0 \) limits is explored further in Section 4.2.

We note that results presented in Section 5 and discussed in Section 6 has been checked to be independent of \( \sigma_0 \) cuts.

### 4.1 Comparison with Coma

Besides the range of velocity dispersions, the determination of the three FP coefficients is strictly dependent on other factors such as the selection criteria of the sample, the fit algorithm and the procedure used to derive structural and kinematical parameters (Kelson et al. 2000). We address this problem comparing our FP with the previous work by JFK96. Their sample consists of 81 early-type galaxies down to the Gunn \( r \sim 15.3 \) in the central region of the Coma cluster. For this section, we have corrected our velocity dispersions to their standard fixed aperture of 0.595 kpc of radius. To analyse the consistency of the two samples, in Fig. 6 we plot the spectroscopic completeness functions (CFs) of the Coma (open circles) and Shapley (filled circles) FP samples as a function of magnitude. The magnitudes of the Shapley galaxies are converted from \( R \) to the Gunn-\( r \) photometric system according to the typical colour of \( r - R = 0.35 \) for elliptical galaxies (Fukugita, Shimasaku & Ichikawa 1995). The Coma CF is computed using the JFK96 FP sample and the complete photometric catalogue of early-type Coma galaxies published by Jørgensen & Franx (1994). The limiting magnitude of the Coma sample is \( M_r = -19.79 \) (dashed line). The Coma sample is complete at bright magnitudes, but the completeness declines rapidly towards zero at the faint magnitude limit.

In contrast, about 30 per cent of Shapley galaxies are spectroscopically observed and have available velocity dispersion measurements independent of magnitude down to \( M_r = -19.79 \). In the magnitude bins fainter than \( M_r = -20 \), the Shapley CF declines slightly due to an increasing fraction of galaxies with surface brightnesses and velocity dispersions too low for successful \( \sigma_0 \) measurements, before dropping rapidly in the faintest bin. Green triangles represent the CF of Shapley galaxies observed spectroscopically with no regards to successful velocity dispersion measurements: the decline at the faintest magnitude has now disappeared except for the faintest bin (\( M_r > -18.5 \)). The distribution reflects well the random selection criteria of our spectroscopic survey for \( R < 18 \) galaxies. To compare the FPs of the two samples, we have selected from Shapley only early-type galaxies with \( M_r < -19.79 \) and \( \sigma_0 > 100 \) km s\(^{-1} \) (hereafter ‘matched’ sample) corresponding roughly to the limits of the Coma FP sample. This new sample consists of 88 galaxies. The

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**Figure 5.** Left-hand and central panels: the edge-on views of the Shapley \( R < 18, \sigma_0 > 100 \) km s\(^{-1} \) (black dots) FP. Right-hand panel: the edge-on view of the Shapley \( R < 18 \) galaxies. To compare the FPs of the two samples, we have selected from Shapley only early-type galaxies with \( M_r < -19.79 \) and \( \sigma_0 > 100 \) km s\(^{-1} \) (hereafter ‘matched’ sample) corresponding roughly to the limits of the Coma FP sample. This new sample consists of 88 galaxies. The
FP of the ‘matched’ sample is
\[
\log r_e = 1.21 \pm 0.08 \log \sigma_0 - 0.75 \pm 0.02 \log \langle I \rangle_e - 0.19, 
\]
with a scatter equal to 0.08 dex in log \( r_e \) direction. In Fig. 7, we plot the edge-on view of the FP for the ‘matched’ sample (filled circles). Coma galaxies (open symbols) are reported for comparison. Since in JFK96 the value of \( H_0 \) is set equal to 50 km s\(^{-1}\) Mpc\(^{-1}\), the effective radii of Coma galaxies have been shifted by a factor of 0.146 dex. Both the distributions and the dispersions of the two samples are consistent, in fact the FP for the Coma sample, as found by JFK96, is
\[
\log r_e = 1.31 \pm 0.07 \log \sigma_0 - 0.84 \pm 0.02 \log \langle I \rangle_e - 0.082. 
\]
The possible reasons for the remaining slight differences between the two FP's could be the different sampling at the brightest magnitudes of the two data sets, and the different procedures used to obtain the structural parameters, since JFK96 fit their early-type galaxies with de Vaucouleurs profiles.

### 4.2 A curved surface or a selection effect?

Observing the high-\( \sigma_0 \) fit (see Fig. 5), it is notable that all galaxies with velocity dispersions less than 100 km s\(^{-1}\) (low-mass galaxies) are systematically displaced above (left-hand panel) or below (central panel) the best-fitting plane as defined by the high-\( \sigma_0 \) sample. In particular, the \( \log \sigma_0 \) edge-on view suggests that low-mass galaxies do not follow the same relation as massive galaxies. Thus, at face value, the FP appears curved, as suggested also by other studies (JFK96; Zaritsky et al. 2006; D’Onofrio et al. 2008; Nigoche-Netro, Ruelas-Mayorga & Franco-Balderas 2008) investigating the curvature of the FP as a function of mass and/or luminosity. Studying a sample of 69 faint early-type galaxies in the core of the Coma cluster, Matković & Guzmán (2005) find a similar behaviour for the

\[ L - \sigma \] relation, with dwarf galaxies having a trend \( (L \propto \sigma^{2.01 \pm 0.36}) \) shallower than that observed for elliptical giant systems \( (L \propto \sigma^4) \).

In Fig. 8, we investigate this possible curvature by analysing the dependence of \( \alpha \) as a function of different low-\( \sigma_0 \) limits. We cut the galaxy sample at various values of \( \sigma_0 \) and estimate the FP coefficients through the weighted orthogonal fit procedure. One can see that \( \alpha \) increases systematically as the \( \sigma_0 \) cut moves to higher values, removing more galaxies from the sample. The values of \( \alpha \) for the whole sample \( (\alpha = 1.06 \pm 0.06) \) and for the highest \( \sigma_0 \) cuts \( (\alpha = 1.72 \pm 0.28) \) differ by more than twice the standard errors, indicating a possible curvature of FP. To investigate, if these observed variations of \( \alpha \) with the sample selection are due to a real curvature of the FP, or induced by selection effects, a set of simulations were performed. We constructed 1000 mock catalogues using the observed values of \( \log \langle I \rangle_e \) and \( \log \sigma_0 \) and the value of \( \log r_e \) assigned using the relation
\[
\log r_e = \alpha \log \sigma_0 + \beta \log \langle I \rangle_e + \gamma + N(0, \delta), 
\]
where, in this case, \( \alpha = 0.92, \beta = -0.78 \) and \( \gamma = 0.496 \) are the coefficients obtained by fitting the FP of the overall Shapley sample with \( \log r_e \) as the dependent variable, \( \delta = 0.099 \) is the observed scatter in the \( \log r_e \) direction and \( N(0, \delta) \) is a Gaussian random variable with zero mean and standard deviation of \( \delta \). For each mock catalogue, we evaluate the relative change in \( \alpha (\delta \alpha / \alpha) \) between the orthogonal fits obtained for the whole sample and after applying a cut at \( \sigma_0 = 100 \) km s\(^{-1}\). The resulting histogram of \( \delta \alpha / \alpha \) values is shown in Fig. 9, where the dashed line indicates the \( \delta \alpha / \alpha \) computed directly for the Shapley sample. This shows that the observed change in \( \alpha \) is fully consistent with that expected for a linear relation. Moreover, in Fig. 10 we compare the FP edge-on projection (equation 11) for the observed high-\( \sigma_0 \) sample (solid symbols) and a simulated sample obeying the overall Shapley FP relation (open symbols). The two samples show similar behaviour, with the same apparent curvature such that galaxies with low velocity dispersions are placed systematically below the FP relation. Given that the simulated sample is defined to follow a linear relation, this suggests that the apparent curvature in Fig. 5 can be explained solely by selection biases. Hence, in spite of the wide range in velocity dispersions covered by our sample, this is not sufficient to distinguish between either a linear or curved FP relation, but there is no convincing evidence for the latter in our data.
intrinsic scatter of the FP analysing the correlations between both spectral indices (Mgb, Fe5015, Fe4383, Hβ, HgF, HdF) and stellar population parameters (age, metallicity, α-enhancement) and the residuals from the FP.

5.1 FP residuals versus single spectral indices

All of the many spectral indices are known to correlate with σ0, which, if not corrected for, could produce spurious correlations with the FP residuals. To avoid this problem, rather than use the spectral indices themselves, we consider their residuals with respect to the index–log σ0 relation. For each index, we fitted first the index–log σ0 relation, shown in Figs 11 and 12 (bottom panels) for metallicity- and age-sensitive indices, respectively, and then determine the residuals with respect to that relation (middle panels).

In the figures, the upper panels show the index–log σ0 residuals versus the residuals from the FP in the log r_e direction. For each relation, we quantify the product–moment correlations between the residuals and spectral index through the correlation factor r and the bisector least-squares fit, assuming that the distributions are both Gaussian. Uncertainties in r and the fits are estimated through 10000 Monte Carlo realizations, taking into account the errors on each value. These values together with the probability p that two quantities with correlation factor r are not correlated are reported in Figs 11 and 12.

Among the primarily metal-sensitive indices (Fig. 11), the strongest dependence is found for Fe4383, which is correlated with FP residuals at the 4σ level. A similar but weaker correlation is obtained for Fe5015. For Mgb, however, a weak correlation is obtained in the opposite sense. Thus, galaxies which are more compact than expected from the FP have lower Fe4383 indices than expected for their σ0, but higher Mgb indices than expected for their σ0. This already provides a hint that the physical driver for the residual trends is not the total metallicity, but instead the ratio between Mg and Fe abundances. The Balmer lines show weak positive correlations, such that galaxies with strong index values (for their σ0) are more diffuse than predicted by the FP. This could be caused either by age or by metallicity effects, since the Balmer lines are sensitive to both parameters to some extent.

5.2 FP residuals versus stellar population parameters

Using a single spectral index, it is not possible to disentangle between the effects of age and metallicity. In this section, we use estimates of age, metallicity and α-enhancement (α/Fe) derived from the index measurements by means of a multi-index procedure, to provide more physically meaningful information (Smith et al. 2009).

As for the single spectral indices, the three stellar population parameters age, metallicity and α/Fe correlate strongly with σ0 as shown by the scaling relations of equation (2), therefore we first compute the residuals of stellar population parameters (age, metallicity, α-enhancement (α/Fe)) derived from the index measurements by means of a multi-index procedure, to provide more physically meaningful information (Smith et al. 2009).

For the single spectral indices, the three stellar population parameters age, metallicity and α/Fe correlate strongly with σ0 as shown by the scaling relations of equation (2), therefore we first compute the residuals of stellar population parameters with respect to these relations. The lower panels of Fig. 13 show the stellar population residuals against logσ0 characterized, by construction, by the absence of correlations between the residuals and log σ0 itself. The top panels show the resultant correlations between the age, metallicity and α/Fe residuals (left-hand, middle and right-hand panel, respectively) and the FP residuals along the log r_e projections.

Both age and α/Fe are seen to be strongly anticorrelated (at >3σ and >4σ, respectively) with the residuals computed in the logr_e direction, while metallicity shows a positive correlation with the FP residuals along the same axis. We find these correlations to
be independent of the range of \( \sigma \) covered, for example obtaining consistent results when using only the high-\( \sigma_0 \) sample. In Table 3, we summarize the probability \( p \) for all the cases.

We note that in the Figs 11–13 the velocity dispersion enters into both axes, since each quantity is a residual from a relation involving \( \sigma_0 \). The errors are hence correlated which will produce a bias towards positive correlations. For each of the primary stellar population parameters, we measure the level of this bias through Monte Carlo simulations, based on fake data in which there are no intrinsic correlations. First, for each galaxy we assign fake stellar population values (age, Z/H, \( \alpha/Fe \)) following the previously derived index–\( \sigma_0 \) relations, and having the same rms intrinsic scatter in the SSP value about the relation. We then perturb each of the values log \( \sigma_0 \), log \( r_e \) and log \( (I_e) \) by their uncertainties for each galaxy, and recalculate the residuals about the FP and the index–\( \sigma_0 \) relation as before. Through these simulations, we measure this bias \( (\Delta r) \), i.e. the difference in the correlation coefficient, due to the correlated measurement errors in \( \sigma_0 \) and find

\[
\Delta r(\log \text{age}) = 0.03, \quad \Delta r(Z/H) = 0.02, \quad \Delta r(\alpha/Fe) = 0.04. \tag{15}
\]

We see that this bias contributes to the observed correlation between the metallicity and FP residuals, but acts to oppose the anticorrelations seen for age and \( \alpha \)-enhancement. In each case, the effect of the bias is small, being at a level of \( \sim 10 \) per cent of the observed correlation. The relation between residuals obtained taking into account this bias is shown in Fig. 13 by the red dot–dashed line.

It should be remembered that the stellar population parameters presented here are derived through fixed apertures covering only the galaxy centres. Therefore, if galaxies have significant population gradients, the observed trend could be due to sampling the central stellar populations at different radii. In the case of metallicity, this may be a factor, as early-type galaxies are observed to have negative metallicity gradients (Kuntschner et al. 2006; Rawle et al. 2008) of the order \(-0.20 \pm 0.05 \) dex in [Z/H]. However, spatially resolved spectroscopy of early-type galaxies show that they generally have flat radial trends in age and \( \alpha/Fe \) (Sánchez-Blázquez et al. 2007; Rawle et al. 2008), indicating that the anticorrelation of age and abundance ratios with the FP residuals in the log \( r_e \) and log \( (I_e) \) directions is robust.

The strong correlations found between the stellar population parameters, principally the \( \alpha/Fe \), and the residuals of the FP suggest

\begin{figure}
\centering
\begin{tabular}{ccc}
\includegraphics[width=0.3\textwidth]{fig11a} & \includegraphics[width=0.3\textwidth]{fig11b} & \includegraphics[width=0.3\textwidth]{fig11c} \\
\includegraphics[width=0.3\textwidth]{fig11d} & \includegraphics[width=0.3\textwidth]{fig11e} & \includegraphics[width=0.3\textwidth]{fig11f} \\
\end{tabular}
\caption{Low-left panel: the Fe 4383–log\( \sigma_0 \) relation. In all the panels, the solid (dashed) lines indicate the mean (and 1\( \sigma \) confidence limits) bisector least-squared fits after 10 000 Monte Carlo realizations. The corresponding correlation coefficient \( r \) (and uncertainty) is indicated. Middle-left panel: the corresponding Fe 4383–log\( \sigma_0 \) residuals in Fe 4383 direction with respect to the fit (solid line in low-left panel) plotted against log\( \sigma_0 \). Top-left panel: correlations between the residuals of the Fe 4383–log\( \sigma_0 \) relation in Fe 4383 direction with the residuals from the best-fitting FP in the log\( r_e \) direction. The probability \( p \) that two quantities with correlation factor \( r \) are not correlated is also reported. Central panels: the same for Fe 5015. Right-hand panels: the same for Mgb.}
\end{figure}
that its scatter is in part due to variations in the stellar populations at fixed galaxy $\sigma_0$. To this aim, we fit the modified FP relation:

$$\log r_e = \alpha \log \sigma_0 + \beta \log \langle I \rangle_e + \kappa_{spp} + \gamma,$$

where the stellar population parameter $spp$ is, in turn, $\alpha$ enhancement, age and metallicity of the galaxies, and study the variation induced in the scatter by keeping $\alpha$ and $\beta$ fixed as in equation (14) and allowing $\kappa$ to vary to minimize the FP scatter. It is necessary to keep $\alpha$ and $\beta$ fixed as each of the stellar population parameters correlate strongly with $\sigma_0$, and hence would introduce spurious variations in $\alpha$. The results obtained are listed in Table 4, where the second column indicates the estimated strength of the $spp$ term $\kappa$, the following two columns indicate the overall scatter in the $\log r_e$ direction after the addition of the $spp$ term, and the relative intrinsic scatter, and the final column the rms contribution of the $spp$ term to the scatter in $\log r_e$. The fit with the most significant $\kappa$ coefficient ($4.5\sigma$) is the fit with the $\alpha/Fe$ as fourth parameter. In the case of age and metallicity, the new coefficient is non-zero at just the $\sim 3\sigma$ level, indicating the weaker impact of these parameters on the fundamental relation.

While it seems that none of the additional $spp$ terms reduce the overall scatter significantly, the relative impact of the three $spp$ terms becomes clearer when considering the intrinsic scatter (i.e. after accounting for the measurement uncertainties). Both the relation including the effect of age and metallicity have an intrinsic scatter of $\sim 0.06$, only marginally lower than the value without the $spp$ term, while in the case of $\alpha/Fe$ the intrinsic scatter is reduced to 0.049. This is comparable to the rms contribution from the $\alpha/Fe$ term (0.047), i.e. $\alpha/Fe$ contributes around half of the intrinsic scatter, and indicates that the distribution of galaxies around the FP is tightly related to the enrichment, and hence to the time-scale of star formation. The $\alpha/Fe$ dependence of the FP scatter is illustrated further in Fig. 14 which demonstrates also the reduction in total scatter despite the introduction of measurement errors in $\alpha/Fe$. We split the Shapley sample into three groups (shown as red, grey and blue points in Fig. 14) according to the position of each galaxy with respect to the $\alpha/Fe$–$\log \sigma_0$ relation (see left-hand panel): the 50 per cent of galaxies closest to the relation are plotted in grey, while the 25 per cent with $\alpha/Fe$ higher (lower) than expected for their $\sigma$ are plotted in red (blue). A modest reduction in total scatter is seen, despite the introduction of uncertainty due to $\alpha/Fe$ measurement errors.

Furthermore, the total FP scatter is reduced by including the extra terms, in spite of the fact that the stellar population parameters are subject to their own substantial uncertainties. This implies there must be a still greater reduction in the intrinsic FP scatter.

Figure 12. As for Fig. 11, but now showing correlations for the Balmer line indices Hα (left-hand panels), HgF (central panels) and Hβ (right-hand panels).
Figure 13. As for Fig. 11, but now showing correlations for the stellar population parameters, age (left-hand panels), total metallicity (central panels) and $\alpha$/Fe (right-hand panels). The red dot–dashed line shows the relation obtained taking into account the correlated errors (see the text).

Table 3. Probability that two quantities with correlation factor $r$ as in Figs 11–13 are not correlated.

|          | Mgb | Fe5015 | Fe4383 | Hβ | HgF | HdF | Log age | Z/H | $\alpha$/Fe |
|----------|-----|--------|--------|----|-----|-----|---------|-----|-------------|
| (per cent) | (per cent) | (per cent) | (per cent) | (per cent) | (per cent) | (per cent) | (per cent) | (per cent) | (per cent) |
|          | 11.3 | 5.3    | 0.092  | 2.3 | 14.9 | 4.0 | 0.056   | 0.38 | 0.001       |

Table 4. The impact on the overall and intrinsic FP scatter of adding a further term (spp) to the orthogonal fit of the FP.

|          | $\kappa$ | rms in log $r_e$ dir. | intrinsic FP rms | spp rms contribution |
|----------|-----------|----------------------|------------------|----------------------|
| $\alpha$/Fe | 0.88      | 0.068                |                  |                      |
| Log age   | +0.582 ± 0.128 | 0.075              | 0.049            | 0.047                |
| Z/H       | −0.160 ± 0.061 | 0.087              | 0.066            | 0.016                |

Note. Column 1: the $\kappa$ value which minimizes the overall FP scatter along the log $r_e$ direction to equation (16), Column 2: total scatters around the FP; Column 3: estimated intrinsic FP scatter; Column 4 estimated rms contribution of the spp term in the log $r_e$ direction.

6 THE ORIGIN OF THE INTRINSIC SCATTER

JFK96 pointed out that the dispersion around the FP relation is not completely due to the measurement errors but has an intrinsic scatter whose nature is not yet understood. The existence of this intrinsic scatter was interpreted as due to another ‘fundamental’ parameter characterizing the family of early-type galaxies. In many of the previous works on the FP (see Section 1), a strong effort has been made to find correlations between the FP residuals and different line indices considered to be representative of a particular stellar population parameter (for example, Hβ for age, Mgb2 for metallicity, etc.).

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In Section 5, we showed that the FP residuals are strongly correlated with estimated stellar population parameters especially with the $\alpha$/Fe abundance ratio ($\alpha$/Fe). Given that age and $\alpha$/Fe are known to correlate strongly for galaxies of a given mass, while age and metallicity anticorrelate (e.g. Proctor & Sansom 2002; SLH), it is not clear which of the three parameters drives the correlations. However, the fact that the strongest correlation is observed for the $\alpha$/Fe suggests that this parameter is playing the major role, while age and metallicity trends just reflect their mutual correlations. The trends observed for the metallicity indices also suggest that the $\alpha$/Fe is driving the correlations. In fact, the positive correlations between the $Z/H$-dependent indices Fe4383 and Fe5015 combined with the negative correlation for Mg$b$ is consistent with an anticorrelation for the abundance ratio $\alpha$/Fe. Moreover, we found that about half of the FP intrinsic variance is due to variations in the stellar populations as described by the $\alpha$-enhancement trend, while the other stellar population parameters seem to contribute rather less to the intrinsic scatter.

It has long been realized (Tinsley 1980) that in the study of galaxy formation and evolution a major role can be played by the analysis of the abundance ratios, due to them being relatively model independent and primarily affected by stellar nucleosynthesis and the IMF (Matteucci 1996). In particular, the ratio between the so-called $\alpha$ elements [synthesized in Type II supernovae (SNe)] and iron (mainly from delayed type Ia events) is widely accepted to be affected by the characteristic time-scale of star formation, the $\alpha$ elements and iron having different production time-scales (Greggio & Renzini 1983). According to the simplest and widely accepted scenario, a galaxy with a high value of $\alpha$/Fe has experienced many Type II SNe events, but almost no SNe of Type Ia during the major epoch of star formation: this constrains the time-scale for this epoch of stellar formation to be shorter than $3 \times 10^8$ yr.

Our results suggest that the galaxies which formed their stars over a shorter duration (high $\alpha$/Fe) are also those which are more compact. Such a pattern may be expected in a dissipational merger inducing a nuclear starburst. Vazdekis, Trujillo & Yamada (2004), studying 21 early-type galaxies already claimed the existence of a correlation between the Sersic index and Mg/Fe ratio (i.e. between galaxy structure and stellar population), even if they did not correct for correlations with $\sigma$. They interpreted their results as more massive galaxies having their star formation quenched on shorter time-scales. Although, in agreement with our finding, their analysis is based on a smaller sample spanning, a narrower range of velocity dispersions and luminosities as compared to our Shapley sample making any comparisons difficult.

Hopkins et al. (2008) make specific predictions for the effects of varying the dissipational fraction on the remnant spheroids of a given mass, resulting in correlations between the structural and stellar population parameters. By considering identical progenitor discs (at $t = 0$) with initial gas fractions $f_{\text{gas}} = 1$ following an exponential star formation history with time-scale $\tau$, we have that the gas fraction at the time of the merger $t_{\text{in}}$ (and hence dissipational fraction in the merger-induced starburst) will scale as $f_{\text{gas}} = \exp(-t_{\text{in}}/\tau)$. If the remaining gas is then consumed in the central starburst, producing a passively evolving spheroid remnant, then the dissipational fraction will increase for earlier mergers, and hence mean stellar age. Hopkins et al. (2008) also show that ellipticals formed through mergers with higher dissipation fractions should be more $\alpha$-enriched. As merger remnants involving more dissipation, like those between more gas-rich discs, are expected to yield larger mass fractions formed in nuclear starbursts, which reduce significantly the effective radii of the remnant, we should expect both mean stellar age and $\alpha$/Fe to anticorrelate with the residuals in the $r_e$ direction.

We observe clear correlations between the FP residuals and age and $\alpha$/Fe, with those galaxies of a given mass with effective radii smaller than predicted by the FP to have stellar populations systematically older and with higher abundances than average, fully consistent with the predictions of Hopkins et al. (2008).

7 SUMMARY AND CONCLUSIONS

We have derived the FP of a sample of 141 early-type $R < 18$ galaxies in the Shapley supercluster at $z = 0.049$. Velocity dispersions and stellar population parameters were derived from the spectroscopic data of SLH, while R-band photometry is from the SOS (Mercurio
et al. 2006). The final sample extends down to $M_g + 3$ in magnitude and 50 km s$^{-1}$ in $\sigma_0$. Using the software 2Dphot (La Barbera et al. 2008b), we derived for each galaxy the structural parameters $r_e$, $\langle \mu_e \rangle$, $n$ and $m_{170}$ by fitting a two-dimensional PSF-convolved Sersic model. The morphological classification was performed by eye and checked with those of Thomas & Katgert (2006) for a subsample of 54 galaxies finding complete agreement.

Adopting a weighted fit (see equation 8), we derived the FP: $r_e \propto \sigma^{0.105} (I_e^{-0.8})^{0.052}$ for the 141 early-type R galaxies. The low $\sigma$ value between the total and the $I_e$ effect, since $C_{\sigma} > 75$–89 $18$ galaxies. The low $\sigma$ results due to $\alpha$-abundances, and $\alpha$ abundances due to high-mass systems. The most important result of this work is our demonstration that the FP residuals are correlated with stellar population characteristics (line strength indices and derived SSP parameters). In particular, FP residuals are anticorrelated both with the $\alpha$-element abundance ratio, $\alpha/Fe$, and with galaxy age resulting in trends whereby galaxies more compact than expected from the FP relation have stellar populations systematically older and with higher abundances than average. Previous studies have reported correlations of the FP residuals with stellar age (e.g. Forbes et al. 1998; Reda et al. 2005). Although our FP residual do show a correlation with age, we recover a much stronger signal for $\alpha/Fe$ than for age, suggesting that this is the more fundamental dependence. Indeed, a multiple regression analysis suggests there is no age correlation at fixed $\alpha/Fe$ and FP residuals. The most important result of this work is our demonstration that the FP residuals are correlated with stellar population characteristics (line strength indices and derived SSP parameters). In particular, FP residuals are anticorrelated both with the $\alpha$-element abundance ratio, $\alpha/Fe$, and with galaxy age resulting in trends whereby galaxies more compact than expected from the FP relation have stellar populations systematically older and with higher abundances than average. Previous studies have reported correlations of the FP residuals with stellar age (e.g. Forbes et al. 1998; Reda et al. 2005). Although our FP residual do show a correlation with age, we recover a much stronger signal for $\alpha/Fe$ than for age, suggesting that this is the more fundamental dependence. Indeed, a multiple regression analysis suggests there is no age correlation at fixed $\alpha/Fe$ and FP residuals does not indicate a direct causal effect, since varying $\alpha/Fe$ at fixed age and $Z/H$ has little effect on the stellar $M/L$. Instead, the correlation suggests that the structural properties and the star formation history are both dependent on some unobserved aspect of the galaxy assembly process. At face value, our results are broadly consistent with recent galaxy merger simulations, which predict a sequence of formation mechanisms governed by the varying importance of dissipation (Hopkins et al. 2008). In this scenario, mergers with a higher initial gas fraction trigger more centrally concentrated starbursts, and higher $\alpha$ abundances due to the short duration of star formation in the burst.

ACKNOWLEDGMENTS

AG gratefully acknowledges the hospitality of the University of Birmingham during her stays there, where some of the work was performed. CPH acknowledges financial support from STFC. RJS is supported by STFC rolling grant P/PC051568/1 ‘Extragalactic Astronomy and Cosmology’ at Durham 2005–2010.

This work was carried out in the framework of the collaboration of to the FP7-PEOPLE-IRSES-2008 project ACCESS ‘A Complete Census of Star formation and nuclear activity in the Shapley super-cluster’.

We thank the anonymous referee for his/her comments which helped to improve this work.

REFERENCES

Beers T. C., Flynn K., Gebhardt K., 1990, AJ, 100, 32
Bertin E., Arnouts S., 1996, A&A, 117, 393
Binney J., Merrifield M., 1998, Galactic Astronomy. Princeton Univ. Press, Princeton, NJ
Caon N., Capaccioli M., D’Onofrio M., 1993, MNRAS, 265, 1013
Cappellari M. et al., 2006, MNRAS, 366, 1126
Dreschers L. B., Quataert E., Ma C. P., West A. A., 2007, MNRAS, 377, 402
Djorgovski S., Davis M., 1987, ApJ, 313, 59
D’Onofrio M. et al., 2008, ApJ, 685, 875
Dressler A., Faber S. M., Burstein D., Davies R. L., Lynden-Bell D., Terlevich R. J., Wagner G., 1987, ApJ, 313, 42
Faber S. M., Jackson R. E., 1976, ApJ, 204, 668
Forbes D. A., Ponnun T. J., Brown R. J. N., 1998, ApJ, 508, 43
Fukugita M., Shimasaku K., Ichikawa T. A. W., 1995, PASP, 107, 945F
Graham A. W., Guzmán R., 2003, AJ, 125, 2936
Gregg M., 1992, ApJ, 384, 43
Greggio L., Renzini A., 1983, A&A, 118, 217
Guzman R., Lucey J. R., 1993, MNRAS, L47.
Guzman R., Lucey J. R., Bower R. G., 1993, MNRAS, 265, 731
Haines C. P., Merluzzi P., Mercurio A., Kruzanov N., Busarello G., La Barbera F., Capaccioli M., 2006, MNRAS, 371, 55
Haines C. P., Gargiulo A., La Barbera F., Merluzzi P., Busarello G., 2007, MNRAS, 381, 7
Hopkins P. F., Cox T. J., Hernquist L., 2008, ApJ, 689, 17
Hyde J. B., Bernardi M., 2008, preprint (arXiv:0810.4924)
Jørgensen I., Franx M., 1994, ApJ, 433, 553
Jørgensen I., Franx M., Kjægaard P., 1995, MNRAS, 276, 1341
Jørgensen I., Franx M., Kjægaard P., 1996, MNRAS, 280, 167 (JK96)
Kelson D. D., Illingworth G. D., van Dokkum P. G., Franx M., 2000, ApJ, 531, 184
Kormendy J., 1977, ApJ, 213, 333
Kuntschner H. et al., 2006, MNRAS, 369, 497
La Barbera F., Busarello G., Merluzzi P., de la Rosa I., Coppola G., Haines C. P. 2008a, ApJ, 689, 913
La Barbera F., de Carvalho R. R., Kohl-Moreira J. L., Gal R. R., Soares-Santos M., Capaccioli M., Santos R., Sant’Anna N., 2008b, ASP, 120, 681
Matković A., Guzmán R., 2005, MNRAS, 362, 289
Matteucci F., 1996, Fundam. Cos. Phys., 17, 283
Mercurio A. et al., 2006, MNRAS, 368, 109
Nigoche-Netro A., Ruelas-Mayorga A., Franco-Balderas A., 2008, A&A, 491, 731
Poggianti B. M., 1997, A&AS, 122, 399
Proctor R. N., Sansom A. E., 2002, MNRAS, 333, 517
Prugniel P., Simien F., 2002, A&A, 309, 749
Rawle T. D., Smith R. J., Lucey J. R., Swinbank A., 2008, MNRAS, 389, 1891
Reda F. M., Forbes D. A., Hau G. K. T., 2005, MNRAS, 360, 693
Robertson B., Cox T. J., Henquist L., Franx M., Hopkins P. F., Martini P., Springel V., 2006, ApJ, 641, 21
Sánchez-Blázquez P., Forbes D. A., Strader J., Brodie J., Proctor R., 2007, MNRAS, 377, 759
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 252
Smith R. J. et al., 2004, AJ, 128, 1558
Smith R. J., Lucey J. R., Hudson M. J., 2007, MNRAS, 381, 1035 (SLH)
Smith R. J., Lucey J. R., Hudson M. J., Bridges T. J., 2009, preprint (arXiv:0903.2473)
Steinmetz M., Navarro J. F., 2002, New Astron., 7, 155

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Table 2. Structural and kinematical parameters for the FP galaxy sample.

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