Ages and metallicities for quiescent galaxies in the Shapley supercluster: driving parameters of the stellar populations

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ABSTRACT
We use high signal-to-noise spectroscopy for a sample of 232 quiescent galaxies in the Shapley supercluster, to investigate how their stellar populations depend on velocity dispersion ($\sigma$), luminosity and stellar mass. The sample spans a large range in velocity dispersion (30–300 km s$^{-1}$) and in luminosity ($M_R$ from $-18.7$ to $-23.2$). Estimates of age, total metallicity ($Z/H$) and $\alpha$-element abundance ratio ($\alpha$/Fe) were derived from absorption-line analysis, using single-burst models of Thomas and collaborators. Using the Rose Ca II index, we conclude that recent star formation (frosting) events are not responsible for the intermediate ages observed in some of the galaxies. Age, $Z/H$ and $\alpha$/Fe are correlated positively with velocity dispersion, but we also find significant residual trends with luminosity: at given $\sigma$, the brighter galaxies are younger, less $\alpha$-enriched and have higher $Z/H$. At face value, these results might suggest that the stellar populations depend on stellar mass as well as on velocity dispersion. However, we show that the observed trends can be reproduced by models in which the stellar populations depend systematically only on $\sigma$, and are independent of stellar mass $M_\ast$. For age, the observed luminosity correlation arises because young galaxies are brighter, at fixed $M_\ast$. For metallicity, the observed luminosity dependence arises because metal-rich galaxies, at fixed mass, tend also to be younger, and hence brighter. We find a good match to the observed luminosity correlations with age $\propto \sigma^{+0.40}$, $Z/H \propto \sigma^{+0.35}$, $\alpha$/Fe $\propto \sigma^{+0.20}$, where the slopes are close to those found when fitting traditional scaling relations. We conclude that the star formation and enrichment histories of galaxies are determined primarily by the depth of their gravitational potential wells. The observed residual correlations with luminosity do not imply a corresponding dependence on stellar mass.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution.

1 INTRODUCTION
Numerous studies have explored how the stellar content of passive galaxies1 depends systematically on ‘mass’. Along the passive sequence, more massive galaxies are observed to be redder, and have stronger metal absorption and weaker hydrogen features in their spectra (e.g. Faber 1973; Bower, Lucey & Ellis 1992). Physical explanations for these trends have been sought using increasingly sophisticated stellar population synthesis models (e.g. Worthey 1994; Thomas, Maraston & Bender 2003; Schiavon 2007), and ever im-

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1 By the terms passive/quiescent galaxies, we loosely include many partially overlapping definitions, i.e. galaxies which have ceased forming stars, lie in the red envelope of the optical colour distribution, have little or no line emission in their spectra, have early-type morphology, etc.
Because luminosity and velocity dispersion are mutually correlated through the Faber–Jackson (Faber & Jackson 1976, FJ) relation, and because stellar mass is inferred rather than measured directly, it is not trivial to distinguish the relative importance of these mass proxies in driving the relations. By exploiting the substantial scatter in the FJ relation, a number of previous works have indicated that luminosity and velocity dispersion are not interchangeable as predictors of the stellar populations (e.g. Bernardi et al. 2005; Gallazzi et al. 2006). In particular, Graves, Faber & Schiavon (2009, hereafter GFS09) recently analysed a sample of galaxies from the Sloan Digital Sky Survey (SDSS), concluding that important correlations with stellar mass persist after accounting for the trends with velocity dispersion.

In this paper, we address these issues using results from high signal-to-noise spectroscopy for galaxies in the Shapley supercluster. The observations were described in detail by Smith, Lucey & Hudson (2007, hereafter Paper I), which also presented measurements of absorption-line strengths for a sample of quiescent supercluster member galaxies. Here, we employ the data to determine ages, total metallicities (Z/H) and α-element abundance ratios (α/Fe) for each galaxy in the sample, and analyse their dependence on luminosity and velocity dispersion.

Section 2 provides a brief review of the sample definition and spectroscopic data, and describes the estimation of single-burst equivalent stellar population parameters. We also provide here a test for consistency with the broad-band colours, discuss the evidence against widespread recent secondary bursts of star formation, and describe the corrections for metallicity gradients. In Section 3, we present the correlations of age, Z/H and α/Fe with velocity dispersion and luminosity. In Section 4, motivated by the significant correlations of the stellar population parameters with luminosity, at fixed velocity dispersion, we investigate whether these require an underlying correlation with stellar mass. Section 5 compares the results to previous findings, especially focusing on the work of Graves, Faber & Schiavon (GFS09), and our main conclusions are summarized in Section 6.

The stellar population parameters as determined here have been used by Rawle et al. (2008a) to study the dependence of ultraviolet colours on the stellar populations, and by Gargiulo et al. (2009) to analyse stellar population effects in the Fundamental Plane residuals. An alternative analysis of a subset of the Paper I data, using the method of Graves & Schiavon (2008) has been presented by Smith et al. (2009a). A more thorough exploration of complex star formation history (SFH) models is provided by Allanson et al. (2009). A later paper will treat the correlations between stellar population parameters, e.g. the age–metallicity–mass relation.

Throughout this paper, we adopt cosmological parameters (ΩM, ΩΛ, h) = (0.3, 0.7, 0.7). For reference, at the redshift of Shapley (z = 0.048), one arcsecond corresponds to 0.97 kpc, and the distance modulus is m − M = 36.65.

## 2 Stellar Population Parameters

### 2.1 Data

Paper I provides a full description of the observations and data processing. Here, we provide only a summary of the main points.

The initial galaxy sample was drawn from photometric catalogues of the NOAO Fundamental Plane Survey (NFPS; Smith et al. 2004), covering the central 40 × 40 arcmin² region in each of three clusters, Abell 3556, Abell 3558 and Abell 3562, in the core of the Shapley supercluster. Spectra were obtained using the fibre-fed dual-beam AAOmega spectrograph at the Anglo–Australian Telescope. The fibres sample an aperture of 2 arcsec diameter. Within the region covered by the NFPS catalogue, we observed some 60 per cent of all R < 18 galaxies, with little dependence on the magnitude. In the blue arm of the spectrograph, the spectra cover the main emission lines, up to Fe5406 at the red end, with a spectral resolution of 3.2 Å full width at half-maximum (FWHM). The red arm was used to record the Hα region, at 1.9 Å resolution, for the purpose of detecting nebular emission. The total integration time was ∼8 h per galaxy, resulting in high signal-to-noise ratio (median S/N ≈ 60 Å⁻¹ at 4400–5400 Å).

The primary parameters measured from the spectra are the redshift, cz, the velocity dispersion, σ, equivalent widths of various emission lines after removing the stellar continuum, and the Lick absorption-line indices. For some galaxies, the velocity dispersion is ‘unresolved’, i.e. indistinguishable from zero in our spectra. The absorption-line indices were transformed to the spectral resolution of the Lick system and corrected for the effects of velocity broadening. A final sample for stellar population analysis was defined which excludes galaxies with Hα emission equivalent width above 0.5 Å (which indicates likely contamination of the Lick Balmer-line indices), and those which lie outside of the adopted redshift range for the supercluster (cz = 11 670–17 233 km s⁻¹). The final sample comprises 232 galaxies, of which 198 have measured velocity dispersion and 34 are unresolved. The analysis presented in this paper is based on the line strengths and supporting data provided in tables 2–4 of Paper I.

Note that the sample was not selected explicitly according to morphology at any stage, and is therefore representative of the passive population overall. Although no selection on colour was applied, our Hα selection very effectively restricts the sample to the red sequence in the B − R colour magnitude relation (see fig. 1 of Paper I).

### 2.2 Line strength diagrams

This and the following section describe the process of transforming the set of index measurements for each galaxy into a set of physical parameters, by comparison with stellar population models. This ‘grid-inversion’ approach has of course been applied by many other studies in the field, including some fairly sophisticated implementations (e.g. Proctor, Forbes & Beasley 2004; Kelson et al. 2006; Graves & Schiavon 2008). Here, the absorption-line data will be interpreted using simple stellar population (SSP) models by Thomas and collaborators (Thomas et al. 2003; Thomas, Maraston & Korn 2004, hereafter collectively TMBK). Constraints on non-SSP formation histories will be discussed in Section 2.5.

For the TMBK models, just three non-redundant index measurements are sufficient to invert the model grid and recover estimates of log(age), [Z/H] and [α/Fe]. If more indices are available, a χ² minimization provides an estimate of the SSP which best reproduces the observations. Such redundancy may be desirable both to suppress random errors, and to average over systematic error sources (e.g. the dependence of indices on chemical abundances beyond those allowed to vary in the models). For age-sensitivity, at least one index should measure one of the Balmer lines. In principle, any two metal lines with different α-sensitivity could be used to distinguish Z/H from [α/Fe] effects. With the advent of improved models which follow the light-element abundances separately (e.g. Schiavon 2007), it is important to be clear which elements are contributing to the measured α/Fe. Mgb5177 is the only index employed as an α-abundance indicator, and although we will use the notation
Figure 1. Index–index planes showing the α/Fe-sensitive index pair Fe5015 and Mgb5177. Each panel shows galaxies within a given interval in velocity dispersion. For clarity, we omit the ~4 per cent of galaxies having S/N < 20, and two other galaxies with large error bars in Fe5015 due to incomplete data. The model grids are from Thomas et al. (2003, 2004), with zero-points recalibrated from the most massive galaxies (see Section 2.3). The grids show lines of constant [\(\alpha/Fe\)] = 0.0, +0.2, +0.3, +0.5 (red) and of constant [\(Z/H\)] = −0.33, 0.00, +0.35, +0.67 (green). For this comparison, the grids are drawn for a fiducial age in each panel, as indicated in the legend. The fiducial ages are estimated from visual examination of Fig. 2.

[\(\alpha/Fe\)] in the context of the TMBK models, our measurements primarily reflect [Mg/Fe].

Our choice of Fe-sensitive index is limited because the widely used Fe5270 and Fe5335 features are contaminated by 5577 Å night-sky emission line in most of our spectra. The other red Fe index, Fe5406, may be unreliable because it is close to the spectrograph dichroic cut-off. Among the bluer lines, Fe4668 is also known as C\(_2\)4668 because it is dominated by the Swan C\(_2\) band. Since the abundance behaviour of C may be distinct from both Fe and Mg (e.g. Clemens et al. 2006; Sánchez-Blázquez et al. 2006a; Smith et al. 2009b), we prefer not to use Fe4668 here. Among the remaining indices, Fe4383 and Fe5015 are the most promising, with good sensitivity to Fe but not to the light elements (see Tripicco & Bell 1995).

Prior to describing the galaxy-by-galaxy grid inversion results, we present a visual impression of the data in the space defined by the Mgb5177, Fe5015, and HgF indices. Figs 1 and 2 show projections of the model grid and the data, divided into six bins according to the velocity dispersion. The first bin contains the galaxies with unresolved velocity dispersion, while the remaining bins represent roughly equal fractions of the galaxies with measured \(\sigma\). In Fig. 1, the Mgb5177 versus Fe5015 plane is displayed; the location of a galaxy in this diagram reflects primarily its metallicity and \(\alpha/Fe\), but also to a lesser extent its age. The over-plotted grids are extracted from the TMBK models, with age chosen as appropriate for each \(\sigma\) bin (determined by consideration of Fig. 2). From Fig. 1, the systematic increase of both \(Z/H\) and \(\alpha/Fe\) with increasing \(\sigma\) is apparent, although there is substantial intrinsic scatter within each bin. In particular, in each bin, there are galaxies spanning the full range 0.0–0.5 in [\(\alpha/Fe\)] covered by the models. The age effects are evident in Fig. 2, which shows HgF versus Fe5015. Again, the models are shown in two-dimensional projection with the third variable, in this case [\(\alpha/Fe\)], chosen to match the average value inferred from Fig. 1. The systematic trend of \(Z/H\) is visible as the tendency for the cloud of points to shift along the long axis of the grid with increasing velocity dispersion. A trend of increasing age is also seen in the averages. Within each bin there is substantial scatter, with galaxies spanning the age range 3–15 Gyr, clearly in excess of the measurement errors. In some of the panels, it can be seen that the galaxies which are younger than average also have higher metallicity than average, i.e. there is an anticorrelation of age and metallicity at fixed velocity dispersion (Trager et al. 2000).

2.3 Grid inversion

The formal grid inversions are performed using a non-linear \(\chi^2\) minimization over the six indices Mgb5177, Fe5015, Fe4383, Hbeta, HgF, HdF. The predicted values for each index are represented by a cubic-spline surface in the log(age)–[\(Z/H\)]–[\(\alpha/Fe\)] space, passing through all grid points and interpolating between. Using a spline...
interpolation ensures continuous derivatives at cell boundaries; the spline is constrained to reduce to linear extrapolation beyond the grid limits. Because the model grids are tilted with respect to the axes defined by the indices, the errors in recovered age and metallicity are correlated. We extract the full error covariance matrix from the χ² surface in order to propagate the correlated errors.

Recalling that the indices were measured on (approximately) flux-calibrated spectra, and that no attempt was made to match the Lick system response curve, we expect some small systematic offsets between the models and the observed indices. Because the galaxies are all at a common distance, the indices are always measured at approximately the same observed wavelength, and any offsets due to different flux calibrations should thus be similar for all galaxies. If uncorrected, the offsets would generate zero-point offsets. Instead, we adopt a practical strategy of calibrating the stellar library to establish corrections to the measured indices (usually limited to a constant zero-point shift). This is observationally expensive, and overlooks the possibility of zero-point uncertainties in the model predictions, which may be comparable to the observational offsets. Instead, we adopt a practical strategy of calibrating such that the most massive galaxies, on average, yield stellar population parameters that are similar to those obtained in previous studies. Specifically, we apply a rigid shift to the model grid, such that the median index-set for the 24 galaxies with σ > 200 km s⁻¹ corresponds to the prediction for (age, [Z/H], [α/Fe]) = (10.8 Gyr, 0.24, 0.28). These values are taken from the high-σ bin of Nelan et al. (2005), but they are characteristic of most other studies for giant ellipticals, including carefully Lick-calibrated work. The index shifts, applied to the models (not the observations), are: (Fe5015: −0.69), (Hβ: −0.10), (HgF: −0.01), (Mgb5177: −0.10), (Fe4383: −0.22), in the sense that the recalibrated indices are in all cases smaller than those predicted by the published models. We emphasize that only the average high-mass galaxy properties have been fixed in this way. Relative differences in their populations are preserved, so that measurements of the age scatter at high mass, for instance, are meaningful. Moreover, the relative properties of high- and low-mass galaxies are of course maintained, so that the slopes of the stellar population scaling relations are unchanged, to first order. The calibration scheme involves only six degrees of freedom, compared to ~200 × 6 independent data.

In Table 1, we present the derived stellar population parameters from the six-index inversion, as used in analysing the population

Figure 2. Index–index planes showing the age-sensitive index pair Fe5015 and HgF. Each panel shows galaxies within a given interval in velocity dispersion. For clarity, we omit the ~4 percent of galaxies having S/N < 20. The model grids are from TMBK, with zero-points recalibrated from the most massive galaxies (see Section 2.3). The grids show lines of constant [Z/H] = −0.33, 0.00, +0.35, +0.67 (blue) and of constant age $= 3, 6, 9, 12, 15$ Gyr (red). For this comparison, the grids are drawn for a fiducial $α/Fe$ for each bin, as indicated in the legend. The fiducial $α/Fe$ is estimated from visual examination of Fig. 1.
In this section, we consider whether the stellar populations inferred from spectroscopy are consistent with the broad-band colours observed for the same galaxies. We use $B - R$ colours from the Shapley Optical Survey (SOS) of Mercurio et al. (2006), measured within a fixed aperture of 4.4 arcsec diameter. To transform the spectroscopic age and metallicity to a predicted colour, we use the linear relation

$$ (B - R)_{\text{pred}} = 1.150 + 0.329 \log(\text{age}) + 0.297 [Z/H], $$

(1)

derived from a fit to Maraston (2005) models with age greater than 1 Gyr and $[Z/H] > -2$. Fig. 3 presents comparisons between observed and predicted colours, demonstrating the comparable roles played by age and metallicity in reproducing the colours (see also Gallazzi et al. 2006).

The measured colours exhibit a 1$\sigma$ scatter of 0.09 mag (estimated directly from the 68 per cent range of the data, to reduce the impact of outliers). If only the measured age is used to predict the colour (adopting a common value for the metallicity of all galaxies), the residual scatter is reduced to 0.07 mag. A similar scatter is obtained predicting colour from metallicity and using a common age for all galaxies. When the measured ages and metallicities are used together to predict the colours, a much tighter correlation is recovered, with the residual scatter reduced to 0.04 mag. The (anticorrelated) errors in the age and metallicity estimates account for much of this scatter, leaving only $\sim$0.02 mag unexplained.

Our predicted colours do not account for $a/Fe$ variations, since Maraston’s models are for solar abundance ratios. Fig. 4 shows that the residuals from the predicted versus observed colour relation are mildly anticorrelated with measured $a/Fe$. The slope, after rejecting a few outliers, is $\delta(B - R)/\delta[a/Fe] = -0.14 \pm 0.02$, indicating that $a$-enhanced populations are slightly bluer than solar-mixture populations. This result is qualitatively consistent with theoretical modelling by Coelho et al. (2007), who predict a slightly larger colour change $\delta(B - R)/\delta[a/Fe] \approx -0.2$ mag, when $Z/H$ is held constant. Allowing for the observed dependence on $a/Fe$, and for

| Galaxy ID | log $\frac{L_\odot}{L_r}$ | log $\sigma$ | log(age) | $[Z/H]$ | $[a/Fe]$ | C(age,$Z$) | C(age,$a$) | C($Z,a$) |
|-----------|----------------|-------------|----------|--------|---------|----------|----------|---------|
| NFPJ132328.9-314242 | 9.98 | 0.067 | 0.019 | 0.753 | 0.048 | +0.234 | +0.049 | +0.229 | +0.028 | -0.85 | +0.32 | -0.18 |
| NFPJ132330.8-314935 | 10.24 | 0.021 | 0.012 | 0.557 | 0.030 | +0.187 | +0.030 | +0.144 | +0.017 | -0.85 | +0.29 | -0.16 |
| NFPJ132335.5-315201 | 9.73 | 0.005 | 0.029 | 0.646 | 0.067 | +0.261 | +0.068 | -0.016 | +0.039 | -0.86 | +0.16 | +0.01 |
| NFPJ132337.1-315047 | 9.96 | 0.012 | 0.017 | 0.141 | 0.035 | -0.080 | +0.036 | +0.258 | +0.041 | -0.76 | +0.42 | -0.31 |
| NFPJ132345.0-314230 | 9.91 | 0.043 | 0.039 | 0.496 | 0.060 | +0.099 | +0.061 | +0.061 | +0.037 | -0.93 | +0.42 | -0.33 |
| NFPJ132348.3-314953 | 9.53 | 0.010 | 0.038 | 0.702 | 0.062 | +0.156 | +0.074 | +0.100 | +0.043 | -0.85 | +0.26 | -0.17 |
| NFPJ132355.5-313847 | 9.29 | 0.061 | 0.046 | 0.867 | 0.102 | +0.115 | +0.063 | +0.150 | +0.048 | -0.74 | +0.03 | +0.04 |
| NFPJ132406.9-314449 | 9.87 | 0.041 | 0.019 | 0.985 | 0.039 | -0.072 | +0.033 | +0.231 | +0.036 | -0.76 | +0.26 | -0.16 |
| NFPJ132412.7-314658 | 9.85 | 1.171 | 0.074 | 0.454 | 0.072 | +0.335 | +0.060 | +0.111 | +0.034 | -0.87 | +0.19 | -0.06 |
| NFPJ132418.2-314229 | 10.31 | 0.229 | 0.003 | 0.901 | 0.028 | +0.283 | +0.021 | +0.239 | +0.011 | -0.86 | +0.22 | -0.11 |
| NFPJ132423.0-313631 | 10.05 | 0.218 | 0.011 | 0.779 | 0.040 | +0.168 | +0.035 | +0.167 | +0.019 | -0.87 | +0.31 | -0.21 |
| NFPJ132425.9-314117 | 10.36 | 0.216 | 0.007 | 0.825 | 0.048 | +0.179 | +0.031 | +0.161 | +0.017 | -0.83 | +0.10 | +0.00 |
| NFPJ132426.5-315153 | 10.16 | 2.302 | 0.006 | 0.874 | 0.037 | +0.265 | +0.029 | +0.254 | +0.014 | -0.87 | +0.14 | -0.07 |
| NFPJ132430.6-314449 | 9.96 | - | 0.438 | 0.082 | -0.003 | +0.097 | +0.022 | +0.059 | -0.94 | +0.36 | -0.23 |
| NFPJ132440.7-314444 | 9.35 | - | 0.595 | 0.085 | -0.054 | +0.065 | +0.101 | +0.057 | -0.88 | +0.29 | -0.19 |
| NFPJ132440.7-314449 | 9.56 | - | 0.729 | 0.086 | -0.270 | +0.055 | +0.178 | +0.078 | -0.87 | +0.43 | -0.27 |
| NFPJ132457.0-314625 | 9.34 | - | 0.307 | 0.045 | +0.064 | +0.065 | +0.044 | +0.054 | -0.92 | +0.41 | -0.30 |
| NFPJ132520.0-313604 | 9.32 | - | 0.107 | 0.016 | +0.047 | +0.021 | +0.335 | +0.017 | -0.72 | +0.20 | -0.13 |
galaxies than for the most massive objects, so
Residual of the observed colour, relative to the colour predicted
1690–1705
α
α
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C
than the ages based on Hβ, by
σ
0.11 (the median value over the sample). In the centre panel, the measured ages are used, but a common age (6.5 Gyr) assumed. The right-hand panel
Comparison of colours predicted from the spectroscopic parameters against the observed colours from the SOS catalogue of Mercurio et al. (2006).
The observed colours, which are identical in all panels, are within an aperture of 4.4 arcsec diameter, i.e. larger than the 2 arcsec diameter spectroscopic aperture.

In the left-hand panel, the colours are predicted via the SSP models of Maraston (2005), using the measured age, but assuming a common metallicity of [Z/H] = 0.11 (the median value over the sample). In the centre panel, the measured ages are used, but a common age (6.5 Gyr) assumed. The right-hand panel uses the measured values for both age and metallicity to predict the colours. The solid line shows equality; the spread is quantified by the standard deviation (SD) and more robustly by the 68 per cent interval (iqr).

measurement errors, the colours show a residual intrinsic scatter of only 0.01 mag, compared to predictions from the spectroscopic parameters.

2.5 Constraints on composite stellar populations

We have so far been comparing observed galaxy spectra to idealized simple, i.e. single burst, stellar population (SSP) models. In a hierarchical galaxy formation model, real SFHs are expected to be extended, especially before incorporation into a cluster, and perhaps to have multiple bursts as new gas becomes available from mergers. In this case, we can still fit for an SSP-equivalent population, which best matches the observed parameters, but we need to be very careful regarding its interpretation. In general, the SSP-equivalent age is not a good approximation to the luminosity-weighted age. Rather, because the Balmer lines respond non-linearly with age, the SSP-equivalent age is even more heavily weighted to the youngest stars present. An excellent discussion of these issues, with extensive simulations of two-burst SFHs, is given by Serra & Trager (2007); the problem was discussed previously by Leonardi & Rose (1996) and Trager et al. (2000), among others. In this section, we briefly assess the evidence for composite stellar populations in the Shapley supercluster sample. Allanson et al. (2009) provide a more general analysis of our data using complex SFH models.

Using line indices alone, it is very difficult to distinguish between complex histories which have no star formation in the past ~1 Gyr, because changes in the spectrum are fairly linear in this regime. As a result, two widely separated star formation events can produce spectra that are indistinguishable from a single burst with intermediate age. For such cases, a single SSP-equivalent age still provides a convenient moment of the age distribution, that can be readily compared to galaxy formation models (e.g. Smith et al. 2009a; Trager & Somerville 2009). By contrast, subpopulations younger than 1 Gyr show spectral signatures of A-stars, which cannot be mimicked by intermediate-age SSPs.

As a test for ‘frosting’, i.e. young subpopulations representing low fractions of the total mass, we can compare the SSP-equivalent ages determined using different age indicators. The luminosity contribution from any younger subpopulation would be stronger at Hδ than at Hβ, for example, due to the bluer colour of their main-sequence turn-off stars. As a result, the Hδ-derived ages would be younger than the Hβ-derived ages. In Fig. 5, we compare the ages derived from an inversion using Hβ–Fe5015–Mgb5177 to those from Hδ–Fe5015–Mgb5177. The figure shows that the HδF ages are in fact older than the ages based on Hβ, by ~0.07 dex, the opposite of the offset expected from frosting. Moreover, the offset is larger for low-σ galaxies than for the most massive objects, so an increased incidence of frosting is apparently not the cause of the
The Rose Ca \textsc{ii} index for galaxies with errors smaller than 0.15, compared to the SSP-equivalent age. The blue grid indicates the expected behaviour for frosting by secondary bursts of age 1.0, 0.7 and 0.5 Gyr (solid lines), and mass fractions 5, 1 and 0.5 per cent (dotted lines), with the remaining mass in a 13 Gyr base population. The red track shows predictions for 2–12 Gyr SSPs, demonstrating the stability of Ca \textsc{ii} for intermediate ages. Although a few galaxies fall in the region of the frosted models, on average the SSP-equivalent ages of 'young' galaxies are not driven by secondary bursts in the past Gyr.

Figure 5. Comparison of age estimates using different Balmer indices. The upper panel shows the estimate based on H\text{d}F versus that using H\beta, while the lower left plots age difference against log $\sigma$. Small grey points are the individual data; large black points represent medians in $\sigma$ over the same bins as in Fig. 1. In the lower panel, galaxies with unresolved velocity dispersion have been placed to the left of the dotted line. If the younger ages at low mass were due to ‘frosting’ by a low-mass-fraction young subpopulation, the data would drift to lower H\text{d}F ages at low $\sigma$. In fact, a slight shift in the opposite direction is seen.

Figure 6. The Rose Ca \textsc{ii} index for galaxies with errors smaller than 0.15, compared to the SSP-equivalent age. The blue grid indicates the expected behaviour for frosting by secondary bursts of age 1.0, 0.7 and 0.5 Gyr (solid lines), and mass fractions 5, 1 and 0.5 per cent (dotted lines), with the remaining mass in a 13 Gyr base population. The red track shows predictions for 2–12 Gyr SSPs, demonstrating the stability of Ca \textsc{ii} for intermediate ages. Although a few galaxies fall in the region of the frosted models, on average the SSP-equivalent ages of 'young' galaxies are not driven by secondary bursts in the past Gyr.

cases shown are for a ~13 Gyr base population, with a secondary burst ages of 0.5, 0.7 and 1.0 Gyr. The mass fraction in the burst is 0.5, 1.0 and 5.0 per cent. Both populations are assigned solar Fe/H (metallicity effects on Ca \textsc{ii} are small enough to neglect for this test). For the horizontal axis, we compute the SSP-equivalent ages for the composite two-burst spectrum, by inverting the TMBK models using the same six indices that were used for the real data. (The mixing of different model sets is clearly undesirable, but cannot be avoided for this test; the results are probably fairly generic.) These simulations predict easily observable Ca \textsc{ii} offsets for galaxies with SSP-equivalent ages $\lesssim 5$ Gyr, if their ages are driven by minor bursts within the last $\lesssim 1$ Gyr. It is seen that a few galaxies indeed lie in the region occupied by the frosting models, and inconsistent with the cool-star Ca \textsc{ii} value of $\approx 1.1$. However, the overall distribution of points indicates that frosting is not responsible for the young derived ages on average. In particular, for 22 galaxies with inversion ages less than 4 Gyr, the mean Ca \textsc{ii} is $1.132 \pm 0.026$, indistinguishable from the value $1.135 \pm 0.005$ for 40 galaxies with inversion ages above 10 Gyr (the median values are 1.128 and 1.134, respectively).

In conclusion, we find no evidence that SSP ages are on the whole generated by frosting by small mass fractions of very recent star formation, although we cannot exclude this possibility for a small number of individual sample galaxies. The same conclusion holds for any other contribution from A-type stars, such as blue Horizontal Branch stars from an old, metal-poor subpopulation (e.g. Maraston & Thomas 2000). Allanson et al. (2009) show that frosting models

\footnote{See http://www.ucm.es/info/Astrof/miles/models/models.html}
(or exponential decay models, which similarly allow star formation within the past Gyr) are inconsistent with the dynamical mass-to-light ratios implied by the Fundamental Plane.

2.6 Corrections for stellar population gradients

The 2 arcsec diameter fibres enclose a larger fraction of the total light for small galaxies than for large ones. For galaxies in our sample, the effective (i.e. half-light) radii \( R_e \) range from 1 to 10 arcsec (Gargiulo et al. 2009). Since red galaxies in general exhibit internal metallicity gradients (e.g. Davies, Sadler & Peletier 1993), with higher metallicity in the central regions, a correction is needed to translate the central measurements to estimates of the metallicity at a common radius in terms of \( R_e \). Neglecting this correction could lead to systematic trends that can mimic correlations with galaxy mass.

To estimate the required corrections, we will assume metallicity gradients of the order of \( \Delta[Z/H]/\Delta \log R = -0.14 \) (Rawle et al. 2008b), for all galaxies. Weighted by an \( R^{1/4} \) luminosity profile, and integrated within circular apertures, this yields a correction of \( \sim 0.1 \) dex in \( Z/H \) between a measurement within 0.1 \( R_e \) and what would be observed within 1 \( R_e \) (Fig. 7).

Accounting for metallicity gradients is especially important when we attempt to disentangle the effects of luminosity and velocity dispersion on the stellar populations. The Fundamental Plane implies that at fixed velocity dispersion, more luminous galaxies are larger. In turn, this means the offset between metallicity at \( R_e \) and metallicity within the fibre is larger for more luminous galaxies. Conversely, at fixed luminosity, low-\( \sigma \) galaxies are larger than high-\( \sigma \) galaxies. If uncorrected, metallicity gradients would thus artificially boost the correlation of \( Z/H \) with luminosity at fixed \( \sigma \) and suppress its correlation with \( \sigma \) at fixed luminosity.

Effective radii have not been measured for all of our sample galaxies, but for the subset of 141 objects studied by Gargiulo et al.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Aperture effects on fibre measurements of \([Z/H]\). The curves show the difference between \([Z/H]\) measured within a circular fibre of radius \( R_{fib} \) and that measured at the effective radius, \( R_e \), as a function of the ratio between these radii. The solid curve is for an \( R^{1/4} \) luminosity profile, and the dashed curve is for an exponential profile. We assume a differential metallicity gradient of 0.14 dex per decade in radius. For our Shapley sample, the effective radii are in the range 1.0–10.0 arcsec, and \( R_{fib} = 1 \) arcsec. Over this range, indicated by the vertical dotted lines, a linear approximation to the aperture correction is justified.

3 OBSERVED SCALING RELATIONS OF THE STELLAR POPULATIONS

In this section, we examine the dependence of age, \( Z/H \) and \( \alpha/Fe \) as functions of velocity dispersion, \( \sigma \), and luminosity, \( L_e \). We start with one-parameter descriptions, e.g. the age–\( \sigma \) relation, then test for residual correlations, and finally consider bivariate fits in which \( \sigma \) and \( L_e \) are used simultaneously to predict the stellar populations. We defer a discussion of the correlation among stellar population parameters, e.g. the age–metallicity and age–\( \alpha/Fe \) relations, to a subsequent paper in this series.

3.1 Biases and choice of the mass proxy

Velocity dispersion has traditionally been the mass proxy used most widely for stellar population studies, because it is independent of the stellar mass-to-light ratio and reflects the depth of the gravitational potential well. However, when galaxy samples are selected by luminosity, the use of \( \sigma \) as a mass proxy is biased: with decreasing \( \sigma \), such samples become increasingly dominated by galaxies with unusually high luminosity given their \( \sigma \).

The most obvious mechanism for such a bias is that old galaxies are fainter than otherwise identical galaxies with younger populations (because stellar mass-to-light ratio increases with age) and are hence lost at low-velocity dispersion in a luminosity-selected sample (as discussed by Kelson et al. 2006, for example). If not

we find

\[
R_e = 2.15 \text{arcsec} \left( \frac{L_e}{10^{10} L_\odot} \right)^{1.03} \left( \frac{\sigma}{100 \text{ km s}^{-1}} \right)^{1.09},
\]

with a 1σ scatter of 0.13 dex. Applying this relation (simply a statement of the Fundamental Plane) to calculate a predicted effective radius \( R_{e,\text{pred}} \) for all galaxies in our sample, we can correct the metallicity to \( R_{e,\text{pred}} \) via

\[
\Delta[Z/H] = -0.1 \log \left( \frac{R_{e,\text{pred}}}{R_{\text{fib}}} \right).
\]

The corrections to \( Z/H \) range from \( -0.09 \) dex to \( +0.06 \) dex, with median \(-0.02 \) dex.\(^7\) The error in the correction, associated with scatter around the Fundamental Plane, is \( 0.1 \times 0.13 \approx 0.01 \) dex, which is much smaller than the formal error on \( Z/H \) (typically \( \sim 0.05 \) dex), and is neglected in what follows. The strength of the internal gradients, i.e. the factor \(-0.1 \) above, is uncertain to perhaps 50 per cent. In Section 3, we consider explicitly how our results for \( Z/H \) would change if the adopted aperture corrections are altered within this range.

The evidence for internal age gradients in red galaxies is inconclusive, with small positive (Rawle et al. 2008b) and negative (Sánchez-Blázquez, Gorgas & Cardiel 2006b) gradients having been reported. Similarly, gradients in \( \alpha/Fe \) appear to be small. No corrections are imposed here for either parameter. For the velocity dispersions, the usual correction is adopted, with

\[
\log \left( \frac{\sigma^{R_{e,\text{pred}}}}{\sigma^{R_{\text{fib}}}} \right) = -0.04 \log \left( \frac{R_{e,\text{pred}}}{R_{\text{fib}}} \right)
\]

(e.g. Jørgensen, Franx & Kjærgaard 1995). The corrections range from \(-0.04 \) dex to \(+0.02 \) dex in \( \sigma \).
corrected for, this generates an artificial steepening of the age–σ
relation. To a lesser extent, the same effect steepens the Z/H–σ
relation, since the stellar mass-to-light ratio also increases slightly
with metallicity.

A second cause of bias can be identified, which is distinct from
the above. Consider a parameter P, which is positively correlated
both with stellar mass (and hence luminosity), and with σ. If we
construct the P–σ relation from a luminosity-selected sample, the
observed low-σ galaxies are unrepresentative of the population at
large, being unusually bright for their σ. In turn, they have unusually
high values of P, and the slope of the P–σ relation will be artificially
flattened. This is irrespective of any direct causality between P and
L_R. A bias of this type was considered by Graves et al. (2007) when
deriving composite spectra for SDSS galaxies binned by velocity
dispersion. They found that within a given σ interval, certain metal-
line indices showed a strong correlation with luminosity. As a result,
at low σ, their sample was biased to objects with unrepresentatively
high metallicity, and they introduced a correction method to account
for the bias. In the following section, we will instead include the
apparent luminosity dependence explicitly in our analysis of the
scaling relations.

3.2 Correlations with luminosity and velocity dispersion

We begin by considering qualitatively the distribution of measured
stellar population parameters, and their correlation with either the
R-band luminosity L_R or with velocity dispersion σ. We use only
the set of 193 galaxies which have reliable stellar population fits
and resolved velocity dispersions. When fitting the correlations, we
weight galaxies according to the quadrature sum of their measure-
ment errors and the intrinsic scatter in the fit. In practice, this is
done by iteratively reweighting the points, updating the estimate
of intrinsic scatter in each step. The errors in predictors (σ, L_R)
are ignored in the fits. Table 2 presents the coefficients of the fits
described in this section.

The correlations with luminosity are shown in the upper panels
of Fig. 8. The metallicity Z/H exhibits a very strong (∼σ) correla-
tion with L_R, while age and α/Fe are more weakly correlated
(∼3σ). Because the sample is luminosity limited, the selection cut
is diagonal in these diagrams, and does not explicitly bias the slopes
of the relationships. However, because stellar mass-to-light ratios
depend on age, and to a lesser extent on metallicity, lines of constant
stellar mass run diagonally across the panels. In the lower panels
of Figure 8, we show the correlations with central velocity dispersion.
The Z/H–σ relation is slightly weaker than the Z/H–L_R relation
(∼σ), while the relations for age and α/Fe are much steeper (∼8σ)
than the equivalent L_R correlations. The trends with σ are in good
agreement with the estimates made in Paper I based on the slopes
of the index–σ relations (i.e. Z/H σ0.34, age σ0.52, α/Fe σ0.23
from table 7 of Paper I), although the new age slope is slightly
shallower. We note that the fit to the α/Fe–σ relation seems to be
flattened by the presence of high-α/Fe outliers at relatively low
σ. The ‘core’ of the relation would favour a slope ∼50 per cent
steadier, which would be in closer agreement with previous work
(slopes of 0.3–0.4 were derived by Nelan et al. 2005; Thomas et al.
2005; Bernardi et al. 2006; Graves et al. 2007). The fairly shallow
α/Fe–σ relation derived in Paper I is possibly influenced in the
same way.

Fig. 9 shows the residual correlations. In the upper panels, we
plot the residuals from the Z/H–σ, age–σ and α/Fe–σ relations,
as a function of luminosity. Fairly weak residual luminosity trends
(2–4σ) are found for all three parameters: Z/H increases with lumi-

Table 2. Observed scaling relation fits, adopting the default aperture cor-
rection model. For each parameter Z/H, age, and α/Fe, we provide fits with
velocity dispersion σ, R-band luminosity L_R, and to both parameters simulta-
aneously. In fits to the residuals from one of the relations (indicated by
Δ), the fixed coefficient is given in parentheses. The tabulated scatter is the
estimated intrinsic dispersion around the fit. The first line in each section
gives the scatter around the null model, e.g. the total metallicity scatter of
the sample as a whole.

| Relation | Coeff. of log σ | Coeff. of log L_R | Scatter |
|----------|-----------------|------------------|---------|
| [Z/H]–σ  | +0.307 ± 0.043  | –                 | 0.151   |
| [Z/H]–L_R| –               | +0.216 ± 0.028   | 0.133   |
| Δ[Z/H]–σ | +0.067 ± 0.042  | (+0.216)         | 0.130   |
| Δ[Z/H]–L_R| (+0.307)      | +0.064 ± 0.028   | 0.131   |
| [Z/H]–σ | +0.149 ± 0.062  | (+0.143) ± 0.042 | 0.129   |
| log(age) | –               | –                 | 0.194   |
| log(age)–σ| +0.437 ± 0.053  | –                 | 0.165   |
| log(age)–L_R| –               | +0.112 ± 0.041   | 0.191   |
| Δlog(age)–σ | +0.312 ± 0.056 | (+0.112)         | 0.176   |
| Δlog(age)–L_R| (+0.437)      | –0.106 ± 0.035   | 0.161   |
| log(age)–σ | +0.698 ± 0.075  | –0.235 ± 0.050   | 0.156   |
| [α/Fe] | –               | –                 | 0.091   |
| [α/Fe]–σ | +0.210 ± 0.026  | –                 | 0.076   |
| [α/Fe]–L_R| –               | +0.047 ± 0.020   | 0.089   |
| Δ[α/Fe]–σ | +0.156 ± 0.027  | (+0.047)         | 0.081   |
| Δ[α/Fe]–L_R| (+0.210)      | –0.053 ± 0.017   | 0.074   |
| [α/Fe]–σ | +0.341 ± 0.035  | –0.117 ± 0.024   | 0.070   |
relative to the other parameters (contours aligned mainly with \( \sigma \)). A somewhat comparable illustration, for age, is shown by Gallazzi et al. (2006) in their figure 15a.

### 3.3 Bivariate scaling relation for the broad-band colour

Using the bivariate scalings of age and metallicity with velocity dispersion and luminosity, it is now possible to predict the equivalent correlations for broad-band colours, and compare to the observed trends.

A bivariate fit to the observed \( B - R \) colours from SOS, within an aperture of 4.4 arcsec diameter, yields a correlation primarily with velocity dispersion: \( \Delta (B-R)_{\text{obs}} = (0.19 \pm 0.03) \Delta \log \sigma - (0.01 \pm 0.01) \Delta \log L \). This agrees with the findings of Bernardi et al. (2005) who showed that a strong colour–\( \sigma \) relation holds after controlling for luminosity, but that there is no colour–luminosity relationship at fixed \( \sigma \) (their fig. 4).

We can readily explain this behaviour using our spectroscopically determined age and metallicity scaling relations. Since the observed colours are within a fixed aperture, we use the scalings derived for the ‘no aperture correction’ case. The factor-of-two mismatch between the photometry aperture and spectrograph fibre size should yield only a constant correction factor, and will not affect the slopes of the correlation. Using equation (1), which was derived from the Maraston (2005) models, predicted colour differences can be expressed as \( \Delta (B-R)_{\text{pred}} = 0.33 \Delta \log(\text{age}) + 0.30 \Delta [Z/H] \).

The small effects of \( \alpha/Fe \) on broad-band colours will be neglected here. Inserting the \( L, \sigma \) dependences of age and metallicity, this gives \( \Delta (B-R)_{\text{pred}} = 0.23 \Delta \log \sigma - 0.08 \Delta \log L \) from the age change and \( \Delta (B-R)_{\text{pred}} = 0.01 \Delta \log \sigma + 0.07 \Delta \log L \) from \( [Z/H] \) variations. We see that the age and metallicity contributions to the \( L \) dependence cancel almost precisely, leaving \( \Delta (B-R)_{\text{pred}} = 0.24 \Delta \log \sigma - 0.01 \Delta \log L \), dominated by the change in \( \sigma \), as observed.

This test confirms the consistency between the derived spectroscopic parameters and the observed broad-band colours. Where Section 2.4 demonstrated this on a galaxy-by-galaxy basis, here we have shown that the derived systematic behaviour is also reflected in the colours.

### 4 NO CORRELATIONS WITH STELLAR MASS?

We noted in Section 3.1 that simple fits for correlations with \( \sigma \) are compromised for samples selected by luminosity, and that although introducing luminosity as a second ‘predictor’ leads to unbiased fits, these are difficult to interpret because luminosity itself depends on the stellar populations. A physically more meaningful quantity to use as a predictor of age, etc, is the stellar mass, \( M_\star \). In this section, we develop a Monte Carlo modelling approach to constrain the relative importance of \( M_\star \) and \( \sigma \) in driving the stellar population scaling relations.

![Figure 8](image-url)
4.1 Modelling the scaling relations

To construct a simulated galaxy sample, we first draw stellar masses from a Schechter function, with characteristic mass $M^* = 10^{10.7} M_\odot$, and low-mass slope $\alpha_M = -0.5$, and assign velocity dispersions with mean value following $\log \sigma = 1.85 + 0.50 \log \frac{M^*}{10^{10.0} M_\odot}$, and a Gaussian scatter of 0.125 in $\log \sigma$ around the mean. The numeric coefficients here are chosen (but not rigorously fitted) to match the luminosity distribution and the observed FJ relation of our galaxy sample. The adopted stellar mass function is in fact similar to that derived for early-type (concentration-selected) galaxies by Bell et al. (2003), where $M^*_* = 10^{10.6} M_\odot$ and $\alpha_M = -0.6$. We attempt to reproduce the observed stellar population scaling relations $P = P_0 \sigma^\alpha L^\beta$ in terms of underlying models of the form $P = P_0 \sigma^\alpha L^\beta$, where the $P$ are age, $\mathcal{Z}/\mathcal{H}$ and $\alpha/\mathcal{F}e$. For given choices of model parameters $(P_0, \alpha, \beta, \rho)$, we assign ages and metallicities, with a fixed scatter $s_P$ around the model. We allow the deviations from the mean scaling relation for age to be anticorrelated with those from the $\mathcal{Z}/\mathcal{H}$ scaling relation, as proposed by Trager et al. (2000). The $\alpha/\mathcal{F}e$ deviation is assumed to be correlated with the age deviation. We consider cases of uncorrelated, moderately correlated and perfectly correlated deviates.

Using the Maraston (2005) SSP models, we next determine the stellar mass-to-light ratio for each simulated galaxy, based on its age and $\mathcal{Z}/\mathcal{H}$, and from this compute the luminosity $L_\mathcal{E}$, (Abundance ratio effects on the mass-to-light ratio are neglected here.) Finally, we impose selection criteria, $\log (L/L_\odot) > 9.2$ and $\log \sigma > 1.55$ to reproduce the approximate limits of the observed galaxy sample.

To estimate the correlations of age and metallicity with stellar masses from a Schechter function, with characteristic mass $M^* = 10^{10.7} M_\odot$, and low-mass slope $\alpha_M = -0.5$, and assign velocity dispersions with mean value following $\log \sigma = 1.85 + 0.50 \log \frac{M^*}{10^{10.0} M_\odot}$, and a Gaussian scatter of 0.125 in $\log \sigma$ around the mean. The numeric coefficients here are chosen (but not rigorously fitted) to match the luminosity distribution and the observed FJ relation of our galaxy sample. The adopted stellar mass function is in fact similar to that derived for early-type (concentration-selected) galaxies by Bell et al. (2003), where $M^*_* = 10^{10.6} M_\odot$ and $\alpha_M = -0.6$. We attempt to reproduce the observed stellar population scaling relations $P = P_0 \sigma^\alpha L^\beta$ in terms of underlying models of the form $P = P_0 \sigma^\alpha L^\beta$, where the $P$ are age, $\mathcal{Z}/\mathcal{H}$ and $\alpha/\mathcal{F}e$. For given choices of model parameters $(P_0, \alpha, \beta, \rho)$, we assign ages and metalicities, with a fixed scatter $s_P$ around the model. We allow the deviations from the mean scaling relation for age to be anticorrelated with those from the $\mathcal{Z}/\mathcal{H}$ scaling relation, as proposed by Trager et al. (2000). The $\alpha/\mathcal{F}e$ deviation is assumed to be correlated with the age deviation. We consider cases of uncorrelated, moderately correlated and perfectly correlated deviates. Using the Maraston (2005) SSP models, we next determine the stellar mass-to-light ratio for each simulated galaxy, based on its age and $\mathcal{Z}/\mathcal{H}$, and from this compute the luminosity $L_\mathcal{E}$, (Abundance ratio effects on the mass-to-light ratio are neglected here.) Finally, we impose selection criteria, $\log (L/L_\odot) > 9.2$ and $\log \sigma > 1.55$ to reproduce the approximate limits of the observed galaxy sample.
and $L$ depends only \( \propto \) relation, and the correlation structure of the $\sigma$ $P$ 1690–1705 $\alpha / \text{Coef. of log relations can now be fit for the selected simu-
s$ Marked FJ relations, showing the distribution of SSP parameters in the space of luminosity and velocity dispersion. The colours are assigned and $C$ are correlated, the errors on their coefficients are anticorrelated. The unshaded grey ellipses indicate the $M$ log but also decreasing with luminosity.

The $P = P_0 \sigma^\alpha L^\beta$ relations can now be fit for the selected simulated galaxies, and compared to the observed correlations. Ideally, the model would be optimized to obtain confidence intervals for the parameters which describe the underlying correlations (i.e. $P_0$, $\alpha_p$, $b_p$, $s_p$, for each parameter $P$), marginalizing over the ‘nuisance parameters’ (i.e. those describing the stellar mass distribution function, the $M_* - \sigma$ relation, and the correlation structure of the deviations from the mean scalings). In practice however, the high dimensionality precludes a full exploration of the solutions, at least within this paper. Here, we simply test whether suitable solutions exist for underlying relations having no intrinsic dependence on stellar mass, i.e. all stellar population parameters are determined only by their velocity dispersion. Table 4 and Fig. 12 summarize the results obtained for input correlations of $Z/H \propto \sigma^{0.35}$, $\text{age} \propto \sigma^{+0.40}$ and $\alpha / \text{Fe} \propto \sigma^{+0.20}$. As we will show, these input slopes are able to reproduce all of the observed trends with $\sigma$ and $L$, without invoking intrinsic stellar mass dependence. The required slopes were determined using a three-parameter grid search, with the parameters of the stellar mass distribution and the $M_* - \sigma$ relation held fixed, and adopting the case with ‘moderate’ anticorrelation of age and metallicity residuals (see below). The scatter in parameters around the input model is constrained in all cases to reproduce the age, metallicity and $\alpha / \text{Fe}$ scatter around the observed scaling relations.

4.2 Results
In the case where the age and metallicity deviates are uncorrelated (solution 1 in Fig. 12 and Table 4), we find that although age does not depend explicitly on stellar mass, the recovered fit has age increasing very steeply with $\sigma$ but also decreasing with luminosity. This is primarily an effect of the variation in $M_* / L$; younger galaxies are brighter. For $Z/H$ and $\alpha / \text{Fe}$, the recovered scaling relations are much closer to the input relations, because $M_* / L$ depends only weakly on $Z/H$ and not at all in our modelling on $\alpha / \text{Fe}$. Thus, if we do not allow for correlated deviations, our models with no intrinsic stellar mass dependence cannot match the observed trends in these

![Figure 10](image1.png) Bivariate model coefficients. The shaded ellipses show the 1, 2, 3 $\sigma$ intervals on the coefficients of fits $\log (\text{age}) = a_0 + a_1 \log \sigma + a_2 \log L_*$, and similarly for $[Z/H]$ and $[\alpha / \text{Fe}]$. For the metallicity panel, triangles indicate the fits obtained adopting 50 per cent stronger (red, upward-pointing) and 50 per cent weaker (blue, downward-pointing) aperture corrections for metallicity gradients (see Table 3). The open circle shows the fit when no aperture correction is applied at all. Because the predictors $\sigma$ and $L_*$ are correlated, the errors on their coefficients are anticorrelated. The unshaded grey ellipses indicate the correlations obtained from fitting the SDSS data from Graves et al. (2009), as discussed in Section 5.

![Figure 11](image2.png) Marked FJ relations, showing the distribution of SSP parameters in the space of luminosity and velocity dispersion. The colours are assigned according to rank in each parameter shown. The contours show lines of equal parameter rank, with a heavy smoothing applied.

---

**Table 3.** Effect of varying the aperture correction scheme on the coefficients obtained for $[Z/H]$ as a function of $\sigma$ and $L_*$.

| Scheme | $\Delta Z/H \, \Delta \log R$ | Coeff. of $\log \sigma$ | Coeff. of $\log L_*$ |
|--------|-------------------------------|-------------------------|----------------------|
| None   | 0.00                          | +0.044                  | +0.241               |
| Weaker | $-0.07$                       | +0.097                  | +0.192               |
| Default| $-0.15$                       | $+0.149$                | $+0.143$             |
| Stronger| $-0.23$                      | $+0.201$                | $+0.093$             |
The observed correlations (yellow ellipses, as in Fig. 10) compared to the outputs from simulations that assume no intrinsic dependence on stellar mass. The velocity dispersion dependence of the input models is indicated by the blue square on the horizontal axis. The correlations with σ and L, obtained by fitting the simulated data set, are shown by the numbered red circles, for three cases described in the text: 1 for uncorrelated age/metallicity deviations; 2 for moderately anticorrelated scatter; 3 for perfectly anticorrelated scatter. The figure demonstrates that the observed luminosity dependences can be recovered without any intrinsic correlation with stellar mass, provided that the age/metallicity scatter is anticorrelated.

Finally, noting that the observed trends lie intermediate between the results for uncorrelated and perfectly anticorrelated age-metallicity deviates, we assign stellar populations to the simulated galaxies using moderately anticorrelated scatter (ρ = −0.75). With this prescription, we are able to match the observed scaling relations for all three stellar population parameters. Fig. 13 shows the simulated one-parameter scaling relations (i.e. equivalent to Fig. 8), for a realization of our model, with moderate anticorrelation of the age/metallicity deviates. Exactly as in the observed galaxy sample, we recover metallicity scaling tightly both with luminosity and with σ, while age and α/Fe follow σ much more closely than luminosity. We emphasize that these predictions are derived from an underlying model in which stellar populations depend only on σ, and are independent of stellar mass. This result is robust to changes in the strength of the assumed metallicity gradients: e.g. if stronger aperture corrections are preferred, the degree of residual anticorrelation required is reduced. Note also that the scalings with velocity dispersion in the Monte Carlo models (e.g. age ∝ σ^{+0.44} are not substantially different from the single-parameter fits of Section 3.2 (where age ∝ σ^{+0.44±0.05}). In principle, the modelling here explicitly takes into account the biases described in Section 3.1. The similarity to the one-parameter scalings confirms that selection biases do not strongly influence the simpler fitting method (as found also by Allanson et al. 2009).

With the simulations in hand, we can assess the apparently simpler approach of fitting scaling relations using stellar masses estimated directly from the measured ages and metallicities. As noted above, this is complicated by the very strong correlation between age and metallicity, which occurs primarily in our model due to the assumed age/metallicity relationship.

We estimate that to match the Z/H trends in the absence of correlated deviation, we would require approximately Z/H ∝ σ^{+0.2}M_σ^{+0.2}.

### Table 4. Results for Monte Carlo modelling of the underlying scaling relations. The input model assumes that the stellar populations depend intrinsically on velocity dispersion (σ), and are not systematically related to stellar mass (M_σ). The recovered correlations with σ and luminosity (L_σ) are comparable to the observed relations, when correlated residuals (the Z-plane) are allowed for. Solutions (1), (2) and (3) are as labelled in Fig. 12.

| Input model σ, M_σ scalings | Recovered σ, L_σ scalings | Observed σ, L_σ scalings |
|-----------------------------|---------------------------|---------------------------|
| Z/H ∝ σ^{+0.35} M_σ^{0.00} | age ∝ σ^{+0.40} M_σ^{0.00} | Z/H ∝ σ^{+0.15} L_σ^{0.14} |
| α/Fe ∝ σ^{+0.20} M_σ^{0.00} | α/Fe ∝ σ^{+0.20} L_σ^{0.00} | α/Fe ∝ σ^{+0.34} L_σ^{0.12} |
| No M_σ dependence          | Uncorrelated age–Z residuals (1) | (default aperture correction) |

Figure 12. The observed correlations (yellow ellipses, as in Fig. 10) compared to the outputs from simulations that assume no intrinsic dependence on stellar mass. The velocity dispersion dependence of the input models is indicated by the blue square on the horizontal axis. The correlations with σ and L, obtained by fitting the simulated data set, are shown by the numbered red circles, for three cases described in the text: 1 for uncorrelated age/metallicity deviations; 2 for moderately anticorrelated scatter; 3 for perfectly anticorrelated scatter. The figure demonstrates that the observed luminosity dependences can be recovered without any intrinsic correlation with stellar mass, provided that the age/metallicity scatter is anticorrelated.

parameters. Indeed, the recovered Z/H scaling would yield a luminosity slope opposite to that observed, because higher metallicity galaxies have lower luminosities, other factors being equal.

Next we impose an anticorrelation between the age and metallicity deviations at fixed mass, such that galaxies that are younger than average are also more metal rich than average. This is consistent with the ‘Z-plane’ in our own data (Smith, Lucey & Hudson 2008) and with the conclusions reached in other work (e.g. Trager et al. 2000; Smith et al. 2009a). We also allow a positive correlation of the α/Fe and age deviates. In the first instance, we assume perfect anticorrelation among the residuals. In this case, the age trends are only slightly altered from the uncorrelated-deviation solution. However, the recovered metallicity scalings are dramatically different: instead of the input pure σ dependence, the observed scaling is almost purely with luminosity, in the sense that more luminous galaxies have higher Z/H. The explanation is that more luminous galaxies at given σ and M_σ are younger, and the Z-plane now implies that they are also more metal rich. This indirect brightening effect is much larger than the direct dimming effect of higher Z/H. A similar effect holds for α/Fe. The recovered scaling relations are now in much better agreement with the observed correlations, although for Z/H they ‘overshoot’, producing slightly too strong a luminosity trend. Adjusting the input σ scaling does not much improve the match.

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age and spectroscopic stellar mass, and by the luminosity selection limit, which translates into a sharp diagonal cut in the age–$M_\ast$ plane. Fig. 14 shows the age–$M_\ast$ relation for the observed sample, and for a realization of our simulation, in which there is no explicit dependence on stellar mass. In both cases, a strong correlation is observed, but this primarily reflects the correlation with velocity dispersion, and bias from the luminosity limit. Fitting simultaneously using $\sigma$ and $M_\ast$, the observed data yield age $\propto 2.0^{+0.10}_{-0.13} \, M_\ast^{+0.05}$, which is indistinguishable from the measured trends. In both the simulated and the observed samples, the apparent dependence on $M_\ast$ (at fixed velocity dispersion) arises from error correlations and from the luminosity selection bias.

We conclude that for reasonable assumptions about the galaxy population (mass distribution, $M_\ast$–$\sigma$ relation, Z-plane anticorrelation of age and metallicity residuals at fixed $\sigma$), we can reproduce the observed scaling relations from a model in which stellar populations depend only on velocity dispersion, and not on stellar mass. A residual correlation with $M_\ast$ cannot be excluded, since the assumptions entering into the model are uncertain to an extent, and a full exploration of the parameter space has not yet been performed. Rather, our conclusion is that the data do not at present require any stellar mass dependence, in contrast to recent claims, which we discuss in the following section.

5 DISCUSSION

During the preparation of this paper, GFS09 published an analysis of composite spectra from the SDSS which addresses some of the issues that are discussed here. At an observational level, the results of GFS09 agree closely with the fits we obtain from our sample of galaxies in Shapley. However, our interpretation of the results, and especially our conclusion that no residual dependence on $M_\ast$ is required, differ from that of GFS09, as we discuss in this section. GFS09 constructed composite spectra for 16 000 SDSS galaxies with $0.04 < z < 0.08$, binned by $\sigma$, $L$ and optical colour. The high S/N stacked spectra for each bin were used to derive SSP-equivalent parameters, via comparison to models from Schiavon (2007), which were then used to explore how the stellar populations are correlated with luminosity and velocity dispersion. Their galaxy sample was selected to have concentrated $r^{1/4}$-like luminosity profiles, as well as to have no detected emission lines, contrasting with the absence of explicit morphological cut in our sample. The total range of galaxy mass is narrower in GFS09 than here, with $\log \sigma > 1.86$ and $\log (L/L_\odot) > 9.4$. Moreover, the sample is drawn from the general galaxy population, rather than being explicitly a cluster-galaxy sample as here. GFS09 did not apply any correction for metallicity gradients, stating that the SDSS 3 arcsec fibres are `not nuclear spectra but sample a substantial fraction of the galaxy light’.

Using the stellar population parameters for the stacked spectra, GFS09 recover positive correlations of age, Fe/H and Mg/Fe both with velocity dispersion and with luminosity. In agreement with our
The age versus stellar mass relation in the observed sample
\( \sigma L \propto Z \) can give rise to luminosity dependence
but there is no intrinsic dependence on \( Z \).

For the observations, stellar masses have been estimated using the observed ages and metallicities. The dashed line in each panel indicates the \( 10^{10} \, \text{M}_\odot \) luminosity limit, assuming a fixed metallicity. For the simulated data, the figure assumes realistic measurement errors in the age and metallicity. The stellar masses shown are those which would be computed from the spectra by an observer, and hence include the effects of these measurement errors. Grey points indicate simulated galaxies excluded by the luminosity and \( \sigma \) limits.

For a fair comparison to our results for metallicity, we use the translation derived by Smith et al. (2009a) to convert from Fe/H in a representative realization from the simulation (below) compared to a representative realization from the simulation (below), in which age \( \propto \sigma^{-0.40} \) but there is no intrinsic dependence on \( M_* \).

The observed correlations appear to be primarily metallicity correlations, with luminosity correlations can be recovered from an underlying model in simulations including the effects of sample selection, as well as intrinsic correlations between age and metallicity at fixed mass. We showed that, for our observational strategy, stellar populations which depend only on \( \sigma \) can give rise to luminosity dependence consistent with that observed. It seems plausible that the similar trends found by GFS09 can be explained similarly, but to confirm this would require equivalent Monte Carlo modelling tuned to the different strategy used in their work.

Moreover, we have seen that the effect of metallicity gradients can be substantial when deriving trends with \( \sigma \) and \( L \) simultaneously, because the Fundamental Plane implies that the brightest galaxies at a given velocity dispersion have larger effective radius, and are thus subject to larger aperture corrections. The range of aperture corrections at fixed \( \sigma \), over a given interval in luminosity, is independent of fibre size and independent of distance to the galaxy. Thus, despite GFS09 using larger fibres, and covering a significant range in distance, we expect that uncorrected metallicity gradients will generate a bias in their Fe/H scaling relations, in favour of a steeper slope with \( L \), and a shallower dependence on \( \sigma \).

Finally, we note that our results partly disagree with those of Gallazzi et al. (2006), who found that the anticorrelation of age and luminosity at fixed \( \sigma \) in an SDSS-based sample could not be entirely accounted for by variations in \( M_*/L \) and hence some residual dependence with \( M_* \) was required. For metallicity, however, Gallazzi et al. conclude that dynamical mass is more important than stellar mass, in accordance with our results.

**6 CONCLUSIONS**

In this paper, we have used previously reported absorption-line strengths for passive galaxies in the Shapley supercluster to obtain estimates of SSP-equivalent age, metallicity and \( \alpha \)-element abundance ratios. Typical formal errors on the derived ages and metallicities are \( \sim 10 \) per cent. The derived population parameters reproduce the observed broad-band colours, with a weak residual colour dependence on \( \alpha/Fe \) in the sense predicted by stellar evolution models. Using the Rose Ca II index, we have shown that the young (2–5 Gyr) SSP-equivalent ages in some galaxies do not, in general, result from a low mass-fraction ‘frosting’ of star formation within the past Gyr.

We investigated the variation of stellar population parameters as a function of both velocity dispersion and luminosity. Examining both the residual correlations after fitting one variable, and the bivariate fits, we find strikingly different behaviours for the different parameters. Age and \( \alpha/Fe \) are correlated primarily with \( \sigma \), but with an additional trend with luminosity such that at given \( \sigma \), the more luminous galaxies are younger and less \( \alpha \)-enriched. For total metallicity \( Z/H \), the observed correlations appear to be primarily with luminosity. These observed trends, for galaxies in rich cluster cores, are in close agreement with the recent results of GFS09 for a general sample of galaxies from SDSS. Thus, it is unlikely that the results are strongly dependent on the environments that are sampled.

The luminosity trends would naively suggest that metallicity, in particular, may be primarily correlated with stellar mass, rather than with the depth of the potential well. Such a result appears contrary to galactic wind models for the mass–metallicity relation. However, using Monte Carlo simulations, we showed that the apparent luminosity correlations can be recovered from an underlying model in which stellar populations depend only on velocity dispersion, and not at all on stellar mass. Thus, the observed luminosity trends do not imply corresponding trends of stellar population parameters.

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**Figure 14.** The age versus stellar mass relation in the observed sample (above) compared to a representative realization from the simulation (below), in which age \( \propto \sigma^{-0.40} \) but there is no intrinsic dependence on \( M_* \). For the observations, stellar masses have been estimated using the observed ages and metallicities. The dashed line in each panel indicates the \( 10^{10} \, \text{M}_\odot \) luminosity limit, assuming a fixed metallicity. For the simulated data, the figure assumes realistic measurement errors in the age and metallicity. The stellar masses shown are those which would be computed from the spectra by an observer, and hence include the effects of these measurement errors. Grey points indicate simulated galaxies excluded by the luminosity and \( \sigma \) limits.
Driving parameters of stellar populations

with stellar mass. For age, the luminosity correlation arises because young galaxies are brighter, at fixed $M_*$. For metallicity, the observed luminosity dependence arises because metal-rich galaxies, at fixed mass, tend also to be younger, and hence brighter. The presence of metallicity gradients also boosts the apparent luminosity dependence, if aperture corrections are not applied.

After accounting for these effects, we conclude that the stellar populations of passive galaxies are fundamentally correlated with velocity dispersion, and hence with the depth of their gravitational potential well. There is no convincing evidence for additional dependence on the stellar mass, after accounting for the velocity dispersion correlations.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Model inversion results.

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