1. INTRODUCTION

Early-type galaxies are known to comprise a two-parameter family in galaxy structure. In the three-dimensional (3D) parameter space of central stellar velocity dispersion ($\sigma$), galaxy effective radius ($R_e$), and mean central surface brightness ($I_e$), early-type galaxies occupy a 2D plane, known as the fundamental plane (FP; Faber et al. 1987; Dressler et al. 1987; Djorgovski & Davis 1987). The FP is relatively constant throughout the local universe (Jørgensen et al. 1996). There may be some variation with environment (Bernardi et al. 2003a), consistent with the FP in dense environments being offset toward lower $I_e$ than the FP in the field.

There is clear evolution in the FP with redshift, which is often interpreted as evolution in the stellar mass-to-light ratio ($M/L$). For field galaxies, most authors find consistent results, with $M/L$ evolution along and perpendicular to the fundamental plane (FP; Faber et al. 1997; Dressler et al. 1987; Djorgovski & Davis 1987). The FP is relatively constant throughout the local universe (Jørgensen et al. 1996). There may be some variation with environment (Bernardi et al. 2003a), consistent with the FP in dense environments being offset toward lower $I_e$ than the FP in the field.

The local FP should then be expected to include at least some galaxies that are relatively recent arrivals. This is supported by the results of Forbes et al. (1998) and Terlevich & Forbes (2002), who find that residuals from the FP correlate with age such that galaxies offset to higher (lower) surface brightness have younger (older) ages than those occupying the FP. The thickness of the FP may therefore be an age sequence, with the most recent arrivals lying at higher surface brightness than the midplane. This thickness may reveal a (narrow) third dimension to the structural parameters of early-type galaxies.

In contrast to the 2D structural space occupied by early-type galaxies, most studies of their stellar populations have stressed only a 1D space. Many previous authors have presented correlations between detailed stellar population properties and various measures of galaxy “size,” including $\sigma$ (e.g., Trager et al. 2000; Thomas et al. 2005; Nelan et al. 2005; Smith et al. 2007), stellar mass $M_*$ (e.g., Gallazzi et al. 2005), and luminosity ($L$) (e.g., Kuntschner & Davies 1998; Terlevich & Forbes 2002). However, considerable evidence suggests that early-type galaxy star formation histories (SFHs) in fact comprise a two-parameter family. Worthey et al. (1995) demonstrated an anticorrelation between age and metallicity among galaxies with similar $\sigma$ and showed that it helped explain the narrowness of the color–$\sigma$ and FP relations. Trager et al. (2000) quantified this anticorrelation, which they termed the “metallicity hyperplane.” The anticorrelation has been corroborated recently by Smith et al. (2008). Thomas et al. (2005) also found a range of ages for galaxies at fixed $\sigma$ although with no associated metallicity variation.

This is the second paper in a four-part series which demonstrates conclusively that early-type galaxies do span a 2D space in stellar population properties, implying that their SFHs must also occupy a two-parameter space. The goal of this series is to connect stellar population properties of early-type galaxies to their structural parameters in order to understand how galaxy structural evolution and mass assembly are related to star formation. In Graves et al. (2009, hereafter Paper I), we explored the variations in stellar populations along the color–magnitude relation of early-type galaxies and showed that galaxy stellar populations not only vary systematically with $\sigma$, but also vary with residuals from the $\sigma–L$ relation.

In this paper, we continue that approach but map out stellar populations along and through the FP rather than the $\sigma–L$ relation. The result is to parameterize the 2D space of stellar population variables in terms of the FP variables $\sigma$, $R_e$, and $I_e$. Briefly looking forward, Paper III presents a clear parameterization of the 2D family of early-type galaxy SFHs and
interprets the observed stellar population results as differences in the onset epoch and duration of star formation in galaxies. Paper IV compares various stellar ($M_\star/L$) and dynamical ($M_{\text{dyn}}/L$) mass-to-light ratios for the sample galaxies and demonstrates that the observed stellar population effects are not adequate to explain the variation in $M_{\text{dyn}}/L$ along or perpendicular to the FP.

This paper is organized as follows. Section 2 briefly reviews the selection criteria used to identify the early-type galaxy sample for this series of papers. In Section 3, we divide the FP into bins of similar galaxies, stack the spectra to obtain high signal-to-noise ratio (S/N) mean spectra for each point in FP-space, and compare the spectra to models in order to determine the mean stellar population properties along and through the FP. Section 4 presents these results. A major new result is that stellar populations, and therefore galaxy SFHs, appear to be independent of $R_e$, at fixed $\sigma$. Section 5 briefly discusses some possible explanations for why galaxy SFHs do not depend on $R_e$ at fixed $\sigma$. Finally, Section 6 summarizes our conclusions.

2. SAMPLE SELECTION

The sample of galaxies used in this work is identical to that of Paper I. A brief summary of the sample selection is included here. The sample consists of $\sim$16,000 galaxies from the Sloan Digital Sky Survey (SDSS; York et al. 2000) spectroscopic Main Galaxy Survey (Strauss et al. 2002) Data Release 6 (DR6; Adelman-McCarthy et al. 2008). Galaxies are chosen from a limited redshift range ($0.04 < z < 0.08$) and are selected to be quiescent galaxies based on the following criteria.

1. Galaxies have no detected emission in either the H$\alpha$ or [O iii] at 3727 lines.
2. Galaxies have centrally concentrated light profiles, as determined by the ratio of the Petrosian radii that enclose 90% and 50% of the total galaxy light ($R_{90}/R_{50} > 2.5$ in the $i$-band).
3. The likelihood of a de Vaucouleurs light profile fit is at least 1.03 times larger than the likelihood of an exponential light profile fit.

Paper I showed that, although no explicit color selection has been applied, these criteria define a sample of galaxies that populates the red sequence in the color–magnitude diagram, with very few color outliers (see Figure 1 of Paper I). Remaining color outliers are excluded from this analysis, as described in Section 3.

By requiring the sample galaxies to have no detectable emission, we remove four types of galaxies from the sample: actively star-forming galaxies, Seyfert hosts, low ionization nuclear emission-line region (LINER) hosts, and the so-called transition objects (TOs) whose spectra contain emission from both star formation and active galactic nuclei (AGNs). In galaxies with ongoing active star formation (star-forming galaxies and TOs), a small fraction of very young stars contribute disproportionately to the integrated light of the galaxy. These galaxies will therefore have significantly lower $M_\star/L$ than quiescent galaxies of comparable mass, which will change their location in FP space. These galaxies constitute about 11% of morphologically selected early-type galaxies (Schawinski et al. 2007). Excluding these galaxies removes the "youngest" early-type galaxies from the sample, leaving a sample of galaxies whose $M/L$ values and positions in FP space are not strongly biased by a small subpopulation of very young stars.

Removing galaxies with emission due to AGN activity (i.e., Seyferts and LINERS) is a less obvious choice, as these galaxies likely lack the very young stars that bias $M/L$ estimates in actively star-forming galaxies. However, host galaxies of strong AGNs have stellar light profiles intermediate between early-type and late-type galaxies (Kauffmann et al. 2003), as indicated by values of $R_{90}/R_{50}$. Furthermore, there is evidence that these galaxies have systematically different stellar populations from quiescent early-type galaxies of the same mass, with both Seyferts (Kauffmann et al. 2003) and LINERS (Graves et al. 2007) showing younger stellar population ages. In light of these differences, we defer an FP analysis of these galaxies to future work.

Defined in this way, the galaxy sample presented here contains bulge-dominated galaxies, some of which harbor significant disk components. Figure 2 in Paper I shows a selection of the sample galaxies illustrating this. Classical bulges of disk galaxies are known to lie on the FP defined by early-type galaxies (Fisher & Drory 2008; Kormendy & Fisher 2008) and are therefore relevant to this study. Because the SDSS images are fairly low resolution, high-quality automated bulge–disk decompositions are challenging. Assessing the quality of the decompositions and interpreting the output is a complicated topic and beyond the scope of the analysis presented here. We are engaged in ongoing work to assess and compare automated bulge–disk decompositions with by-eye morphologies (J. Y. Cheng et al. 2009, in preparation). We then intend to revisit the topic of morphological variation among quiescent galaxies and its effect on the FP and stellar population.

The FP explored in this work is defined by the galaxy central velocity dispersion ($\sigma$), galaxy effective radius ($R_e$), and galaxy effective surface brightness ($L_e$). Following Jørgensen et al. (1996, 2006), values of $R_e$ are derived using $r^{1/4}$ de Vaucouleurs fits to the galaxy light profiles (i.e., Sérsic 1968 fits with $n = 4$). It is likely that not all sample galaxies will have true Sérsic $n = 4$ profiles and that this will affect the derived FP correlations. However, it is not clear that a physically meaningful comparison can be made between values of $R_e$ derived from fitting profiles with different shapes. A separate study of the FP relationships presented here as a function of Sérsic $n$ will be included in the FP morphology-dependence study discussed above.

In this work, velocity dispersions are taken from the SDSS DR6 catalog and corrected to a “central” $\frac{1}{2} R_e$ aperture (see Paper I for details). Effective radii are from $r$-band de Vaucouleurs fits to the galaxy light profiles, converted to physical units using standard lambda cold dark matter (ΛCDM) cosmology with $\Omega_M = 0.7$, $\Omega_\Lambda = 0.3$, and $h_0 = 0.70$. Surface brightnesses are computed in the Johnson $V$ band as $I_e = L_V / 2\pi R_e^2$, where $L_V$ is the total $V$-band luminosity of the galaxy from a de Vaucouleurs fit to the light profile. The $K$-correction from observed SDSS $ugriz$ photometry to rest-frame $V$ band is performed using the IDL code kcorrect version 4.1.4 (Blanton et al. 2003). The de Vaucouleurs radii and luminosities are corrected for known problems with sky-subtraction around bright galaxies in the SDSS photometric pipeline, as described in Paper I. Luminosities are also corrected for Galactic extinction using the extinction values from the SDSS photometric pipeline.

The data used to identify the sample and to compute $\sigma$, $R_e$, and $I_e$ for each galaxy include the following parameters from the NYU Value-Added Catalog (Blanton et al. 2005) version of the SDSS DR4 (Adelman-McCarthy et al. 2006): redshift ($z$), de Vaucouleurs photometry in the $ugriz$ bands,
and Petrosian radii ($R_{90}$ and $R_{50}$). These are supplemented with the following parameters from the SDSS DR6 Catalog Archive Server:\(^3\) velocity dispersion as measured in the SDSS 3′ fiber ($\sigma_{90}$), $r$-band de Vaucouleurs radius ($r_{200}$) and axis ratio ($a/b$), and the likelihoods of de Vaucouleurs and exponential fits to the galaxy light profiles. The nondetection of emission lines is determined using the emission line measurements of Yan et al. (2006) by requiring galaxies to have emission line fluxes below a 2\(\sigma\) detection in both the H\(\alpha\) and the [O ii]\(\lambda 3727\) lines. The spectra used in this analysis are downloaded from the SDSS DR6 Data Archive Server.\(^4\)

The galaxy radii are critical measurements for this analysis, entering the FP determinations both directly through $R_e$ and indirectly through the calculation of $I_e$. We have attempted to correct for known problems in the SDSS photometry pipeline (see Paper I) but problems may remain. To check the validity of the de Vaucouleurs $R_e$ available in DR6, we compared these values to effective radii measured independently using the photometry package GALFIT version 2.0.3e (Peng et al. 2002), kindly provided by A. van der Wel. The GALFIT radii were measured from Sersic fits to the galaxy $r$-band light profile with $n = 4$ to match the SDSS de Vaucouleurs photometry. In comparison to the GALFIT radii, the SDSS radii are slightly underestimated for the largest galaxies (low by $\sim 0.07$ dex) and slightly overestimated for the smallest galaxies (high by $\sim 0.1$ dex). In addition to these systematic variations, there is scatter of $\sim 0.05$ dex between the two estimates of $R_e$. In Section 3.1, galaxies are sorted into bins based on $R_e$, with bin widths of 0.2 dex in $R_e$. Uncertainties on the order of 0.05 dex in $R_e$ should therefore have only modest effects on bin assignments. To make certain that our results are not strongly affected by possible errors in the DR6 values of $R_e$, we have performed the entire analysis presented in this paper using both the SDSS pipeline values of $R_e$ and the GALFIT fits to $R_e$ and compared the differences. All the results are qualitatively identical. We have chosen to present the results based on the SDSS DR6 pipeline photometry as these values are more easily accessible to the general astronomical community.

3. DECONSTRUCTING THE FUNDAMENTAL PLANE

The overarching goal of this project is to understand the relation between galaxy SFHs and their present-day structural properties, as categorized by their location in the FP space. To study systematic variations in SFHs with structure, galaxies are sorted into bins based on their location on the FP, then average spectra are constructed from the individual galaxies in each bin. The average spectra have very high S/N, allowing accurate stellar population modeling of the mean SFH of galaxies at each point in the FP space. This section defines the binning and describes the stellar population modeling process.

3.1. Binning in Fundamental Plane Space

In addition to studying stellar population trends over the FP, we also want to investigate variations through the thickness of the FP. We thus want to divide galaxies into bins in a 3D space. There are two obvious choices for binning coordinate systems. The first is to use two orthogonal vectors within the FP, together with a third vector defined perpendicular to the FP, similar to the $\kappa$-space of Bender et al. (1992). The second is to use the observed structural parameters $\log \sigma$, $\log R_e$, and $\log I_e$ directly, despite the fact that they are not truly orthogonal. We have chosen the latter approach because the resulting trends yield more readily to interpretation.

The parameters $\log \sigma$ and $\log R_e$ fortunately describe a relatively face-on view of the FP. It is furthermore attractive to choose them as fundamental binning parameters because neither depends explicitly on stellar population properties (in contrast to $I_e$) and because a combination of $\log \sigma$ and $R_e$ gives an estimate of the dynamical mass ($M_{\text{dyn}}$) of a galaxy, thus this binning scheme groups together the galaxies of similar total mass. The FP by definition has only two independent parameters. Once $\log \sigma$ and $\log R_e$ have been set, the mean value of $\log I_e$ for that bin is fixed.

We use the $\log I_e$ dimension to explore SFH variations through the thickness of the FP. Treating $\log I_e$ as the dependent variable, we fit the FP for $\log I_e$ as a function of $\log \sigma$ and $\log R_e$ using a simple least-squares fit that minimizes residuals in the $\log I_e$ direction (implemented as the IDL routine sfit.pro) and find the relation

$$\log I_e = 1.16 \log \sigma - 1.21 \log R_e + 0.55,$$

where $\sigma$, $R_e$, and $I_e$ are in units of $\text{km s}^{-1}$, kpc, and $L_\odot \text{pc}^{-2}$, respectively. The thickness of the FP can then be described as $\Delta \log I_e$, where $\Delta$ indicates the difference between the observed value of $\log I_e$ and the expected value of $\log I_e$ given the observed $\log \sigma$ and $\log R_e$. Figure 1 shows the observed $\log I_e$ plotted against the best-fitting FP relation given by Equation (1). By defining cuts in $\Delta \log I_e$, the FP is sliced into three layers: "low-SB" ($-0.3 < \Delta \log I_e < -0.1$), "midplane" ($-0.1 < \Delta \log I_e < 0.1$), and "high-SB" ($0.1 < \Delta \log I_e < 0.3$), as shown in Figure 1. Here, the terms "low-SB" and "high-SB" are relative terms which describe the value of $I_e$ with respect to the typical value of $I_e$ for galaxies of the same $\sigma$ and $R_e$.

More sophisticated statistical methods can be used to fit the FP relation, but the assignment of galaxies to bins is relatively insensitive to the exact equation used to describe the FP. The choice of $\log I_e$ as the dependent parameter in the binning process is motivated by three things: the first is the previously stated fact that $I_e$ is expected to vary most strongly with SFH. The second is that $\sigma$ and $R_e$ can be combined to estimate $M_{\text{dyn}}$ for a galaxy, thus producing groups of galaxies

\(^3\) http://cas.sdss.org/dr6/en
\(^4\) http://das.sdss.org/DR6-cgi-bin/DAS
of similar total mass. The third is that Paper I demonstrated that, at fixed $\sigma$, stellar populations vary substantially with $\Delta \log L_{\nu}$, which is related to $\Delta \log I_e$.

In each of the three surface brightness slices, galaxies are divided by a $6 \times 5$ grid in $\log \sigma$ and $\log R_e$, as shown in Figure 2. The grid is identical for all three slices. Sorting galaxies in this 3D space of $\log \sigma$–$\log R_e$–$\Delta \log I_e$ results in 90 different bins of galaxies. Within each bin, galaxies share similar values of these three parameters, and therefore also share similar values of $M_{\text{dyn}}$, total luminosity ($L_{\nu}$), and mass-to-light ratio ($M_{\text{dyn}}/L$). Within each bin, galaxies with colors more than 0.06 mag$^5$ from the mean $g-r$ color of the bin are excluded so that the stellar population properties measured in each bin are not biased by a small number of interlopers. The median values of $\log \sigma$, $\log R_e$, $\Delta \log I_e$, and $\log I_e$ for each of the 90 bins are listed in Table 1, along with the total number of galaxies in each bin.

Interestingly, Figure 2 shows that the galaxy distribution in $\log \sigma$–$\log R_e$ space is somewhat different in the various slices, with the high-SB slice showing a tail of high-$\sigma$, high-$R_e$ galaxies that are not present in the low-SB slice. This occurs because the FP of our sample galaxies has a small degree of curvature. This curvature is not necessarily real and may be due to selection effects. We have not attempted to correct for selection biases in this analysis, which spans a limited range in redshift and is therefore nearly volume-limited. Because galaxies are binned by surface brightness, selection effects should result in low-SB bins being incomplete but should not substantially bias the mean spectra.

Of the 90 bins described here, six bins do not contain enough galaxies to produce a reliable stacked spectrum (i.e., contain five or fewer galaxies), leaving a total of 84 stacked spectra for the analysis. Spectra are combined using a method that rejects outlier pixels, masks bright skylines, weights all galaxies equally, and smooths all spectra to the same resolution before combining (see Section 4.2 of Paper I for details). The result is a high S/N mean spectrum for each bin on the FP, as well as a corresponding error spectrum.

The bins are not evenly populated. As can be seen in Figure 2 and Table 1, some of the bins contain many hundreds of galaxies, while others contain a dozen or so. The typical S/N of the individual stacked spectra therefore varies substantially between bins. It is worth bearing in mind that the error bars are not uniform for the stacked spectra. In much of the subsequent analysis, we will indicate data derived from the lower S/N spectra and present typical error bars separately for the low-S/N and high-S/N data.

### 3.2. Lick Indices and Stellar Population Modeling

In each of the stacked spectra, we measure the full set of Lick indices as defined in Worthey et al. (1994) and Worthey & Ottaviani (1997). These include Balmer lines $H\beta$, $H_\gamma\alpha$, and $H_\delta\epsilon$ (as well as broad versions of the bluer Balmer lines, $H_\gamma\alpha$ and $H_\delta\epsilon$), a set of Fe-dominated lines ($Fe_{4383}$, $Fe_{4531}$, $Fe_{5015}$, $Fe_{5270}$, $Fe_{5335}$, $Fe_{5406}$, $Fe_{5709}$, and $Fe_{5782}$), and lines that are also sensitive to element abundances other than Fe ($Mg_1$, $Mg_2$, $Mg_b$, $CN_1$, $CN_2$, $Ca_{4227}$, $Ca_{4455}$, $NaD$, $TiO_1$, and $TiO_2$). Index measurements are performed by the automated IDL code $Lick\_EW$, which is part of the publicly available$^6$ $EZ\_Ages$ code package (Graves & Schiavon 2008). $Lick\_EW$ also computes errors in the Lick index absorption strengths from the associated error spectra following the formalism of Cardiel et al. (1998). It should be noted that the SDSS 3′′ spectral fibers sample roughly 2/3 $R_e$ for the redshift range of our sample. Index measurements and derived abundances in this work are therefore more nearly comparable to literature values measured within $R_e$ or $R_e/2$, rather than central or $R_e/8$ values.

Because many early-type galaxies show strong radial metallicity gradients, central index strengths and abundances tend to be higher than those measured from a substantial fraction of the galaxy light.

All of the stacked spectra have been smoothed to match the highest-$\sigma$ galaxies in the sample (300 km s$^{-1}$) in order to compare all galaxies at the same effective spectral resolution. The combined smoothing due to $\sigma$ and the SDSS native resolution is lower than the resolution at which the Lick indices are defined ($\sim 210$ km s$^{-1}$ at SDSS resolution); thus the line strength measurements must be corrected to bring them onto the Lick system. We do this using corrections computed in

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$^5$ This is the typical color spread for galaxies with the same $\sigma$. See Section 4.1 of Paper I for details.

$^6$ [http://www.ucolick.org/~graves/EZ_Ages.html](http://www.ucolick.org/~graves/EZ_Ages.html)
| Bin R | Bin T | Bin L | Median R | Median L | Median Δ R | Median Δ L | Number | S/N |
|-------|-------|-------|-----------|-----------|-------------|-------------|--------|-----|
| 0.3   | 0.5   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 0.7   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 0.9   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 1.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 1.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 1.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 1.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 1.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 2.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 2.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 2.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 2.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 2.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 3.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 3.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 3.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 3.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 3.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 4.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 4.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 4.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 4.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 4.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 5.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 5.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 5.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 5.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 5.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 6.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 6.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 6.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 6.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 6.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 7.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 7.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 7.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 7.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 7.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 8.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 8.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 8.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 8.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 8.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 9.0   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 9.2   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 9.4   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 9.6   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 9.8   | -0.3  | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
| 0.3   | 10.0  | -0.3 | -0.3      | 0.1       | -0.1      | 0.1         | 0.0         | 2.5    | 14  |
Table 1
(Continued)

| σ Bin (km s⁻¹) | R_e Bin (kpc) | I_e Bin (L⊙ pc⁻²) | Median log σ (km s⁻¹) | Median log R_e (L⊙ pc⁻²) | Median Δ log I_e (L⊙ pc⁻²) | Median I_e (L⊙ pc⁻²) | Number | SNR² |
|----------------|---------------|---------------------|-----------------------|---------------------------|-----------------------------|-----------------------|--------|------|
| 66             | 0.1 < Δ log I_e < 0.3 | 2.30 | 0.24 | 0.13 | 3.08 | 53 | 235 |
| 67             | 0.3 < log R_e < 0.5 | 2.31 | 0.37 | −0.14 | 2.63 | 111 | 608 |
| 68             | −0.3 < Δ log I_e < −0.1 | 2.30 | 0.41 | −0.01 | 2.73 | 527 | 688 |
| 69             | 0.1 < Δ log I_e < 0.3 | 2.30 | 0.42 | 0.15 | 2.89 | 106 | 349 |
| 70             | 0.5 < log R_e < 0.7 | 2.32 | 0.56 | −0.13 | 2.42 | 54 | 186 |
| 71             | −0.1 < Δ log I_e < 0.1 | 2.31 | 0.59 | 0.01 | 2.53 | 504 | 675 |
| 72             | 0.1 < Δ log I_e < 0.3 | 2.31 | 0.61 | 0.14 | 2.65 | 161 | 422 |
| 73             | 0.7 < log R_e < 0.9 | 2.33 | 0.75 | −0.12 | 2.19 | 11 | 89 |
| 74             | −0.1 < Δ log I_e < 0.1 | 2.32 | 0.77 | 0.03 | 2.33 | 213 | 444 |
| 75             | 0.1 < Δ log I_e < 0.3 | 2.32 | 0.77 | 0.14 | 2.45 | 67 | 278 |
| 76             | 2.36 < log σ < 2.50 | −0.1 < log R_e < 0.1 | 2.38 | 0.02 | −0.15 | 3.17 | 19 | 100 |
| 77             | −0.1 < Δ log I_e < 0.1 | 2.40 | 0.03 | −0.03 | 3.28 | 37 | 168 |
| 78             | 0.1 < Δ log I_e < 0.3 | ... | ... | ... | ... | 3 | 53 |
| 79             | 0.1 < log R_e < 0.3 | 2.39 | 0.19 | −0.15 | 2.94 | 32 | 149 |
| 80             | −0.1 < Δ log I_e < 0.1 | 2.38 | 0.22 | −0.03 | 3.03 | 71 | 266 |
| 81             | 0.1 < Δ log I_e < 0.3 | ... | ... | ... | ... | ... | 58 |
| 82             | 0.3 < log R_e < 0.5 | 2.38 | 0.40 | −0.13 | 2.68 | 35 | 170 |
| 83             | −0.1 < Δ log I_e < 0.1 | 2.39 | 0.42 | −0.01 | 2.82 | 149 | 408 |
| 84             | 0.1 < Δ log I_e < 0.3 | 2.37 | 0.41 | 0.14 | 2.97 | 12 | 116 |
| 85             | 0.5 < log R_e < 0.7 | 2.38 | 0.56 | −0.13 | 2.49 | 26 | 152 |
| 86             | −0.1 < Δ log I_e < 0.1 | 2.39 | 0.61 | 0.01 | 2.61 | 242 | 527 |
| 87             | 0.1 < Δ log I_e < 0.3 | 2.39 | 0.63 | 0.13 | 2.70 | 43 | 244 |
| 88             | 0.7 < log R_e < 0.9 | −0.3 < Δ log I_e < −0.1 | ... | ... | ... | 3 | 50 |
| 89             | −0.1 < Δ log I_e < 0.1 | 2.39 | 0.76 | 0.02 | 2.42 | 153 | 420 |
| 90             | 0.1 < Δ log I_e < 0.3 | 2.40 | 0.77 | 0.12 | 2.54 | 26 | 190 |

Notes. I_e is computed in the V band.

a Total number of galaxies in the stacked spectrum.

b Effective median S/N of the stacked spectrum.

Table A2a of Schiavon (2007). The stellar population models used to interpret the line strength measurements are based on flux-calibrated spectra, and the SDSS spectra are themselves flux-calibrated; thus we do not apply a zero-point shift to bring our index measurements fully onto the Lick system. Because the data and the models are both flux-calibrated, zero-point offsets should be negligible.

To convert the set of line strength measurements into stellar population mean ages and abundances, the Lick indices are compared to the single stellar population models of Schiavon (2007). These models include the effects of multiple element abundance ratios and allow estimates of [Fe/H], [Mg/Fe], [C/Fe], [N/Fe], and [Ca/Fe], as well as mean luminosity-weighted stellar age. In Graves & Schiavon (2008), we created an IDL code package, EZ_Ages, which automates the process of determining stellar population mean age, [Fe/H], and abundance ratios for a set of Lick index measurements. We use EZ_Ages with the “standard set” of Lick indices ([Hβ], [Fe], Mg b, C4668, CN1, and C4227) to determine ages, [Fe/H], and abundance ratios for the 84 stacked spectra in our sample with adequate S/N (see Section 3.1). A detailed description of the modeling process is presented in Graves & Schiavon (2008), as well as rigorous testing of the method on Galactic globular clusters and a comparison with stellar population modeling results from Thomas et al. (2005). The interested reader is referred to that work for more information on the modeling process. It is worth noting here, however, that the models are computed at fixed [Fe/H], rather than at fixed total metallicity ([Z/H]) as in some stellar population models. Total metallicity is dominated by oxygen, which is unmeasurable in unresolved stellar populations with current techniques. In this analysis, we specifically discuss [Fe/H] and [Mg/Fe], elements which can be measured from low-resolution spectra, and avoid making statements about [Z/H].

Figure 3 shows the measured values of (Fe) and Hβ for the stacked spectra plotted over a set of model grids from Schiavon (2007). Data points are color-coded by σ as indicated in the figure key. Crosses, filled circles, and open triangles represent the low-SB, midplane, and high-SB data, respectively. The various bins in R_e are not indicated. Two trends emerge clearly from the data. As σ increases, galaxies tend to have stronger (Fe) and weaker Hβ. At fixed σ, as ΔI_e increases, galaxies tend to have stronger (Fe) and stronger Hβ. We will discuss the detailed implications of these trends in Section 4, here they are merely presented to illustrate the line strength data.

The solid lines in Figure 3 show models of constant [Fe/H], from −0.7 to +0.2, as labeled. The dotted lines show models of constant age, from 2.2 to 14.1 Gyr. As can be seen from the orientation of the grid lines, Hβ is predominantly sensitive to stellar population age such that younger populations have stronger Hβ, while (Fe) is dominated by [Fe/H] such that more Fe-rich populations have stronger (Fe). The effects of the age–metallicity degeneracy are apparent in the fact that Hβ is (mildly) sensitive to [Fe/H] and (Fe) is sensitive to age. Because of the degeneracy, there is no one-to-one mapping between Hβ and age, or (Fe) and [Fe/H]; the grid lines are not perfectly...
vertical and horizontal. However, the model grids in these particular indices are close enough to orthogonal that they serve to break the age–metallicity degeneracy. Other combinations of indices (e.g., Hβ and Fe4383, see Figure 9 of Graves & Schiavon 2008) are more affected by the degeneracy, causing the model grids to collapse down on top of one another and making them less robust indicators of age and metallicity.

\(\text{EZ}_\text{Ages}\) computes statistical errors in each of the stellar population parameters, determined from the measurement errors in the Lick indices. The black cross in the upper left corner of Figure 3 illustrates the median error bars in the line strength measurements. The nonorthogonality of the model grids due to the age–metallicity degeneracy causes the derived errors to be correlated. For example, an overestimate of (Fe) will result in both a higher derived value of \([\text{Fe/H}]\) and \([\text{Mg/Fe}]\) as a function of the median log \(\sigma\) in each galaxy bin. We have divided the data into “low-S/N” and “high-S/N” subsamples in order to indicate the range of error values, where low-S/N data points are those whose statistical error estimates are > 0.015 dex higher than the median error value for the data as a whole. The black data points and error bars indicate the values associated with high-S/N data. Low-S/N data are indicated in gray, along with the appropriate median error bar. Age, total Fe, and Mg abundances, and the \([\text{Mg/Fe}]\) abundance ratio all increase with increasing \(\sigma\). These relations are very similar to those demonstrated in Paper I, where galaxies were binned first by \(\sigma\) and then by \(L\) and color at fixed \(\sigma\). The dashed lines indicated linear least-squares fits of the stellar population parameters as functions of \(\sigma\), computed using only the high S/N data (i.e., excluding the gray points).

The age–\(\sigma\) and [Fe/H]–\(\sigma\) relations both show substantial scatter. Quantitatively, the spread around the mean relations (dashed lines) is \(~4\)–5 times larger than the scatter expected due to the statistical errors in both age and [Fe/H], indicating that there is substantial spread in the SFHs of galaxies at fixed \(\sigma\). The [Mg/Fe]–\(\sigma\) and [Mg/H]–\(\sigma\) relations show less scatter, with the observed spread representing only \(~2\) times the expected statistical scatter. The Mg abundance shows both the steepest correlation with \(\sigma\) and the least intrinsic scatter about the mean relation as compared to the observational errors, indicating that [Mg/H] varies only slightly at fixed \(\sigma\).

Unlike the strong stellar population trends observed with \(\sigma\), neither \(R_e\) nor \(I_e\) shows strong correlations with stellar population properties. Figure 5 shows the results of the stellar population modeling as a function of the median \(R_e\) for each galaxy bin. There are no strong trends with \(R_e\) in any of the properties modeled here. There is some evidence for slight increases in [Fe/H] and [Mg/H] with increasing \(R_e\), but the dependence is weak and the scatter is large. Also, at large \(R_e\) there do not appear to be any “young” galaxies with mean ages < 7 Gyr. However, it is evident from Figure 2 that there are very few galaxies with large \(R_e\) and low \(\sigma\). Since Figure 4 showed that low-\(\sigma\) galaxies are most likely to have young ages, the lack of “young” galaxies with large \(R_e\) may be due to the way galaxies populate the FP, rather than any genuine relation between larger \(R_e\) and older ages.

4. STELLAR POPULATIONS IN FUNDAMENTAL PLANE SPACE

4.1. Age, [Fe/H], [Mg/H], and [Mg/Fe] as Functions of \(\sigma\), \(R_e\), and \(I_e\) Separately

We begin by examining the variations in stellar population properties with each of the FP parameters \(\sigma\), \(R_e\), and \(I_e\) individually.

Figure 4 shows the \(\text{EZ}_\text{Ages}\) results for mean luminosity-weighted age, [Fe/H], [Mg/H], and [Mg/Fe] as a function of the median log \(\sigma\) in each galaxy bin. We have divided the data into “low-S/N” and “high-S/N” subsamples in order to indicate the range of error values, where low-S/N data points are those whose statistical error estimates are > 0.015 dex higher than the median error value for the data as a whole. The black data points and error bars indicate the values associated with high-S/N data. Low-S/N data are indicated in gray, along with the appropriate median error bar. Age, total Fe, and Mg abundances, and the [Mg/Fe] abundance ratio all increase with increasing \(\sigma\). These relations are very similar to those demonstrated in Paper I, where galaxies were binned first by \(\sigma\) and then by \(L\) and color at fixed \(\sigma\). The dashed lines indicated linear least-squares fits of the stellar population parameters as functions of \(\sigma\), computed using only the high S/N data (i.e., excluding the gray points).

The age–\(\sigma\) and [Fe/H]–\(\sigma\) relations both show substantial scatter. Quantitatively, the spread around the mean relations (dashed lines) is \(~4\)–5 times larger than the scatter expected due to the statistical errors in both age and [Fe/H], indicating that there is substantial spread in the SFHs of galaxies at fixed \(\sigma\). The [Mg/Fe]–\(\sigma\) and [Mg/H]–\(\sigma\) relations show less scatter, with the observed spread representing only \(~2\) times the expected statistical scatter. The Mg abundance shows both the steepest correlation with \(\sigma\) and the least intrinsic scatter about the mean relation as compared to the observational errors, indicating that [Mg/H] varies only slightly at fixed \(\sigma\).

Unlike the strong stellar population trends observed with \(\sigma\), neither \(R_e\) nor \(I_e\) shows strong correlations with stellar population properties. Figure 5 shows the results of the stellar population modeling as a function of the median \(R_e\) for each galaxy bin. There are no strong trends with \(R_e\) in any of the properties modeled here. There is some evidence for slight increases in [Fe/H] and [Mg/H] with increasing \(R_e\), but the dependence is weak and the scatter is large. Also, at large \(R_e\) there do not appear to be any “young” galaxies with mean ages < 7 Gyr. However, it is evident from Figure 2 that there are very few galaxies with large \(R_e\) and low \(\sigma\). Since Figure 4 showed that low-\(\sigma\) galaxies are most likely to have young ages, the lack of “young” galaxies with large \(R_e\) may be due to the way galaxies populate the FP, rather than any genuine relation between larger \(R_e\) and older ages.
## Table 2
Lick Indices and Stellar Population Properties of Stacked Spectra

| Hδ (Å) | (Fe) (Å) | Mg b (Å) | Age* (Gyr) | [Fe/H] (dex) | [Mg/H] (dex) | [Mg/Fe] (dex) |
|--------|---------|---------|------------|-------------|-------------|--------------|
| 1.82 ± 0.08 | 2.11 ± 0.09 | 3.29 ± 0.08 | 10.3 ± 1.5 | -0.48 ± 0.05 | -0.22 ± 0.08 | 0.26 ± 0.06 |
| 2.00 ± 0.04 | 2.24 ± 0.05 | 3.10 ± 0.04 | 7.1 ± 0.5 | -0.33 ± 0.03 | -0.18 ± 0.03 | 0.15 ± 0.02 |
| 2.23 ± 0.06 | 2.50 ± 0.07 | 2.93 ± 0.06 | 4.1 ± 0.5 | -0.09 ± 0.04 | -0.06 ± 0.05 | 0.03 ± 0.03 |
| 1.81 ± 0.05 | 2.25 ± 0.05 | 3.21 ± 0.05 | 10.1 ± 0.9 | -0.39 ± 0.03 | -0.23 ± 0.03 | 0.16 ± 0.02 |
| 1.99 ± 0.03 | 2.40 ± 0.03 | 3.27 ± 0.03 | 6.9 ± 0.3 | -0.22 ± 0.01 | -0.10 ± 0.03 | 0.12 ± 0.02 |
| 2.20 ± 0.03 | 2.35 ± 0.04 | 3.02 ± 0.03 | 4.7 ± 0.3 | -0.19 ± 0.02 | -0.09 ± 0.03 | 0.10 ± 0.02 |
| 1.86 ± 0.05 | 2.36 ± 0.05 | 3.30 ± 0.04 | 8.9 ± 0.7 | -0.29 ± 0.03 | -0.15 ± 0.04 | 0.14 ± 0.03 |
| 2.07 ± 0.03 | 2.36 ± 0.03 | 3.27 ± 0.03 | 5.8 ± 0.3 | -0.23 ± 0.02 | -0.07 ± 0.03 | 0.16 ± 0.02 |
| 2.17 ± 0.05 | 2.37 ± 0.05 | 3.37 ± 0.04 | 4.9 ± 0.4 | -0.17 ± 0.03 | 0.02 ± 0.04 | 0.18 ± 0.03 |
| 1.86 ± 0.09 | 2.48 ± 0.11 | 3.36 ± 0.09 | 8.8 ± 1.4 | -0.22 ± 0.05 | -0.14 ± 0.07 | 0.08 ± 0.05 |
| 1.96 ± 0.05 | 2.45 ± 0.06 | 3.55 ± 0.05 | 7.2 ± 0.6 | -0.19 ± 0.03 | -0.03 ± 0.04 | 0.16 ± 0.02 |
| 2.12 ± 0.08 | 2.27 ± 0.09 | 3.13 ± 0.08 | 5.4 ± 0.7 | -0.26 ± 0.05 | -0.09 ± 0.07 | 0.17 ± 0.05 |

...
Table 2 (Continued)

| Hβ   | (Å)  | (Fe) | (Å)  | Mg b | Agea | (Gyr)   | [Fe/H] | (dex)   | [Mg/H] | (dex)   | [Mg/Fe] | (dex)   |
|------|------|------|------|------|------|---------|--------|---------|--------|---------|---------|--------|
| 65   | 1.66 ± 0.02 | 2.61 ± 0.02 | 4.40 ± 0.02 | 11.4 ± 0.3 | −0.15 ± 0.01 | 0.13 ± 0.01 | 0.28 ± 0.01 |
| 66   | 1.82 ± 0.03 | 2.79 ± 0.04 | 4.19 ± 0.03 | 8.4 ± 0.5 | −0.01 ± 0.01 | 0.17 ± 0.03 | 0.16 ± 0.02 |
| 67   | 1.58 ± 0.03 | 2.59 ± 0.03 | 4.44 ± 0.03 | 13.3 ± 0.7 | −0.19 ± 0.02 | 0.09 ± 0.03 | 0.28 ± 0.02 |
| 68   | 1.70 ± 0.01 | 2.69 ± 0.01 | 4.34 ± 0.01 | 10.5 ± 0.2 | −0.09 ± 0.01 | 0.14 ± 0.01 | 0.23 ± 0.01 |
| 69   | 1.88 ± 0.02 | 2.73 ± 0.02 | 4.13 ± 0.02 | 7.5 ± 0.3 | −0.00 ± 0.01 | 0.18 ± 0.02 | 0.18 ± 0.02 |
| 70   | 1.60 ± 0.04 | 2.58 ± 0.04 | 4.47 ± 0.04 | 12.9 ± 0.9 | −0.19 ± 0.02 | 0.11 ± 0.03 | 0.30 ± 0.02 |
| 71   | 1.69 ± 0.01 | 2.69 ± 0.01 | 4.39 ± 0.01 | 10.7 ± 0.2 | −0.10 ± 0.01 | 0.14 ± 0.02 | 0.24 ± 0.02 |
| 72   | 1.87 ± 0.02 | 2.76 ± 0.02 | 4.20 ± 0.02 | 7.6 ± 0.2 | 0.01 ± 0.01 | 0.19 ± 0.01 | 0.18 ± 0.01 |
| 73   | 1.60 ± 0.08 | 2.46 ± 0.09 | 4.68 ± 0.07 | 13.1 ± 1.8 | −0.24 ± 0.05 | 0.17 ± 0.08 | 0.41 ± 0.06 |
| 74   | 1.65 ± 0.02 | 2.67 ± 0.02 | 4.35 ± 0.02 | 11.5 ± 0.3 | −0.12 ± 0.01 | 0.11 ± 0.02 | 0.24 ± 0.02 |
| 75   | 1.84 ± 0.02 | 2.74 ± 0.03 | 3.22 ± 0.02 | 8.2 ± 0.4 | −0.05 ± 0.01 | 0.03 ± 0.02 | 0.08 ± 0.02 |
| 76   | 1.47 ± 0.08 | 2.50 ± 0.10 | 4.59 ± 0.08 | ... ± ... | −0.19 ± 0.06 | 0.20 ± 0.08 | 0.38 ± 0.05 |
| 77   | 1.62 ± 0.04 | 2.71 ± 0.05 | 4.58 ± 0.04 | 11.8 ± 0.8 | −0.09 ± 0.03 | 0.18 ± 0.04 | 0.27 ± 0.03 |
| 78   | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... |
| 79   | 1.53 ± 0.05 | 2.68 ± 0.06 | 4.72 ± 0.05 | 14.0 ± 1.4 | −0.14 ± 0.03 | 0.16 ± 0.05 | 0.30 ± 0.04 |
| 80   | 1.62 ± 0.03 | 2.75 ± 0.03 | 4.60 ± 0.03 | 11.7 ± 0.5 | −0.07 ± 0.02 | 0.19 ± 0.03 | 0.26 ± 0.03 |
| 81   | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... |
| 82   | 1.55 ± 0.04 | 2.55 ± 0.05 | 4.67 ± 0.04 | 13.7 ± 1.1 | −0.20 ± 0.03 | 0.17 ± 0.04 | 0.37 ± 0.04 |
| 83   | 1.58 ± 0.02 | 2.74 ± 0.02 | 4.67 ± 0.02 | 12.4 ± 0.3 | −0.09 ± 0.01 | 0.19 ± 0.01 | 0.28 ± 0.01 |
| 84   | 1.79 ± 0.07 | 2.87 ± 0.08 | 4.60 ± 0.06 | 8.4 ± 1.0 | 0.05 ± 0.03 | 0.27 ± 0.04 | 0.22 ± 0.03 |
| 85   | 1.55 ± 0.05 | 2.66 ± 0.05 | 4.63 ± 0.05 | 13.5 ± 1.2 | −0.15 ± 0.03 | 0.15 ± 0.04 | 0.30 ± 0.02 |
| 86   | 1.63 ± 0.01 | 2.76 ± 0.02 | 4.57 ± 0.01 | 11.5 ± 0.3 | −0.06 ± 0.01 | 0.19 ± 0.01 | 0.25 ± 0.01 |
| 87   | 1.71 ± 0.03 | 2.80 ± 0.03 | 4.47 ± 0.03 | 9.9 ± 0.5 | −0.02 ± 0.02 | 0.19 ± 0.03 | 0.21 ± 0.02 |
| 88   | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... | ... ± ... |
| 89   | 1.60 ± 0.02 | 2.80 ± 0.02 | 4.64 ± 0.02 | 11.9 ± 0.3 | −0.05 ± 0.01 | 0.20 ± 0.01 | 0.25 ± 0.01 |
| 90   | 1.74 ± 0.04 | 2.83 ± 0.04 | 4.36 ± 0.03 | 9.4 ± 0.6 | 0.01 ± 0.01 | 0.19 ± 0.03 | 0.18 ± 0.02 |

**Notes.**

* Ages are determined from Hβ for all stacked spectra with the exception of spectrum 76, whose weak Hβ absorption falls outside the parameter space covered by the models. For this index, Hγ is used in the fitting process to determine abundances. For consistency, the age measured for this spectrum is not used in the analysis here, as ages derived from Hγ are typically somewhat younger than those derived from Hβ (see Graves & Schiavon 2008).

**Figure 4.** Stellar population modeling results, showing mean luminosity-weighted stellar age, [Fe/H], [Mg/Fe], and [Mg/H] as a function of galaxy σ. The black (gray) points and error bars indicate high (low) S/N measurements and their associated median errors. The dashed lines show linear least-squares fits of the stellar population properties as a function of σ, based on the high S/N (black) data only. Mean stellar age, [Fe/H], [Mg/Fe], and [Mg/H] all increase with increasing σ. Age and [Fe/H] both show substantial scatter at fixed σ, with total spread 4–5 times the expected spread due to measurements errors, indicating genuine underlying population variations at fixed σ. [Mg/H] and [Mg/Fe] show less scatter, only ~ 2 times that expected due to measurement errors. The [Mg/H]–σ relation is particularly strong and tight, nearly consistent with measurement errors, particularly at the high-σ end.

Finally, Figure 6 shows age, [Fe/H], [Mg/Fe], and [Mg/H] plotted against the median log I, for each galaxy bin. Again, there are no strong correlations between log I, and any of the stellar population parameters. There is some indication of weak correlations between log I, and [Fe/H] and [Mg/H] such that the high-SB galaxies have higher Fe and Mg abundances. There
is also some evidence for a weak anticorrelation between \(I_e\) and age such that low-SB galaxies have older ages, but none of these trends is compelling. The \([\text{Mg/Fe}]\) abundance ratio is completely flat with \(\log I_e\).

A clear result from Figures 4–6 is that stellar populations on the FP vary primarily with \(\sigma\). Neither \(R_e\) nor \(I_e\) appears to be closely related to stellar population properties. However, the lack of general trends with \(R_e\) and \(I_e\) may hide weak correlations with residuals from the strong \(\sigma\) relationships. Although Figure 4 shows clear correlations with \(\sigma\) in all stellar population parameters, there is some scatter at fixed \(\sigma\), particularly in age and \([\text{Fe/H}]\). The next section examines how stellar populations vary throughout the FP as a function of all three FP parameters simultaneously.

4.2. Mapping Stellar Populations Along and Through the Fundamental Plane

By binning galaxies along and through the thickness of the FP, then stacking their spectra and performing stellar population modeling on the high S/N average spectra, we have measured the typical age, \([\text{Fe/H}]\), \([\text{Mg/Fe}]\), and \([\text{Mg/H}]\) for galaxies at each point on, above, and below the FP. Each of these properties can be mapped throughout the 3D space of the FP, thereby associating information about typical SFHs with the structural properties of galaxies. This is a somewhat challenging exercise in data visualization, as we are trying to understand the variations and co-variations of four different stellar population parameters throughout a 3D structure space. This effectively
The figure is constructed to be similar to Figure 2, which illustrates the bin definitions for the 3D FP space. The three lower panels show the three slices in surface brightness, as in Figure 2. Within each slice, galaxy $\sigma$ and $R_e$ are plotted, with gray points showing individual galaxies in the sample. The overplotted color contours show the typical stellar population age at each point on the FP (see Section 4.2 for details). The dashed lines show lines of constant $M_{\text{dyn}}$, assuming $M_{\text{dyn}} \propto \sigma^2 R_e$. Within each slice, age increases with increasing $\sigma$, as seen in Figure 5. Lines of constant age run approximately vertically, indicating that mean stellar population age is independent of $R_e$ at fixed $\sigma$. The upper panels show stellar population age as a function of $\sigma$ for each FP slice. Different values of $R_e$ are indicated by different line styles. Comparing the typical ages between the various slices in $I_e$, it is clear that galaxies with lower surface brightness than the FP (left panels) have older ages than those on the FP midplane (center panels), while galaxies with higher surface brightness than the FP (right panels) have younger ages, at the same value of $\sigma$ and $R_e$. Despite the lack of strong stellar population trends with absolute galaxy $I_e$ (cf. Figure 6), stellar population age at fixed $\sigma$ does appear to depend on $I_e$ residuals from the FP, such that low-SB (high-SB) galaxies are older (younger) than those on the FP midplane.

(A color version of this figure is available in the online journal.)

Figure 7 shows the results for mean luminosity-weighted age. The figure is constructed to be similar to Figure 2, which illustrated the bin definitions for the 3D FP space. The three lower panels show the three slices in $\Delta \log I_e$, with the center panel showing the midplane slice through the FP, while the left and right panels show respectively the low-SB and high-SB slices from Figure 1. Within each FP slice, $\log \sigma$ and $\log R_e$ are plotted for the individual galaxies as gray points (as in Figure 2). The dashed lines show lines of constant $M_{\text{dyn}}$. The color overlay indicates the mean stellar population age at each point in the parameter space, with numerical values given by the color bar in the top of the leftmost panel. The age overlay was constructed as follows: for each stacked spectrum, the median values of $\log \sigma$ and $\log R_e$ are plotted for the galaxies in the bin, color-coded by the age measured in the stacked spectrum. Ages are then interpolated between the median points to create a continuous map of stellar population age across the $\log \sigma$–$\log R_e$ diagram. High-S/N and low-S/N data are all included in the interpolation.

The upper three panels of Figure 7 show mean luminosity-weighted age as a function of $\sigma$ for each FP slice. Different bins in $R_e$ are indicated by different line styles.

Look first at the central panels of Figure 7, which show the midplane of the FP. The trend from Figure 4 is visible: galaxies with larger $\sigma$ are older (red) than galaxies with lower $\sigma$ (blue). Although there are significant changes in age as a function of $\sigma$, there seems to be little if any variation in age as a function of $R_e$. Lines of constant age run roughly vertically in the diagram. This is consistent with Figure 5, which showed no clear systematic variation in stellar population age as a function of $R_e$, independently of the other FP parameters. Here, we see directly that, at fixed $\sigma$, there is no substantial dependence of stellar population age on $R_e$. If the best predictor of stellar population age were $M_{\text{dyn}}$, rather than $\sigma$, lines of constant age should follow the dashed line of constant $M_{\text{dyn}}$. The near-verticality of the age contours indicates that $\sigma$ is a better predictor of stellar population age than is $M_{\text{dyn}}$.

If we look now at the galaxies from the low-SB (left panels) and high-SB (right panels) slices above and below the FP, we see essentially the same trends: age increases systematically with increasing $\sigma$, but lines of constant age run nearly vertically, indicating that stellar population age is independent of $R_e$ at fixed $\sigma$. However, comparing the age ranges (indicated by the color scale) between the different panels, there are systematic differences. These are illustrated clearly in the upper panels. Galaxies in the low-SB slice of the FP (left panels) are systematically older than galaxies in the midplane of the FP (center panels), which are in turn systematically older than galaxies in the high-SB slice (right panels). There are substantial overlaps in the age ranges in the three panels, but at fixed $\sigma$ the low-SB galaxies are older and the high-SB galaxies are younger than the typical galaxies in the FP. This means that, although there are no clear trends in stellar population age with $I_e$ alone (Figure 6), typical galaxy ages do vary with $\Delta \log I_e$ at a fixed point in $\sigma$ and $R_e$. This is similar to the results of Forbes et al. (1998) and Terlevich & Forbes (2002), who found that surface brightness residuals from the FP correlate with stellar population age, although they explored only the general trend over all galaxies, not as a function of $\sigma$ and $R_e$. Our higher-resolution map is made possible through the large sample of 16,000 galaxies in this study.

A similar map for $[\text{Fe/H}]$ is shown in Figure 8. As seen in Figure 4, $[\text{Fe/H}]$ increases systematically with $\sigma$. Like stellar population age, $[\text{Fe/H}]$ appears to depend weakly or negligibly on $R_e$–contours of constant $[\text{Fe/H}]$ are roughly vertical rather than following the lines of constant $M_{\text{dyn}}$. Also similar to the age variations, there appear to be systematic variations in $[\text{Fe/H}]$ between the different slices in $\Delta \log I_e$. This trend,
however, runs opposite to the one seen in age: at fixed $\sigma$, the low-SB galaxies (left panels) tend to be Fe-poor and the high-SB galaxies (right panels) tend to be Fe-rich. The general conclusion is that, not only do age and [Fe/H] increase with $\sigma$, they also vary systematically with $\Delta \log I_e$, with low-SB galaxies showing older mean ages and lower [Fe/H], while high-SB galaxies show younger mean ages and higher [Fe/H]. This implies that, at fixed $\sigma$, age and [Fe/H] are anticorrelated, as first shown by Trager et al. (2000). Section 4.3 will directly examine the correlations between various stellar population residuals from the mean trends with $\sigma$.

Figure 9 shows the map for [Mg/H]. As expected from Figure 4, [Mg/H] varies strongly with $\sigma$. Like stellar population age and [Fe/H], [Mg/H] shows no dependence on $R_e$. Unlike age and [Fe/H], [Mg/H] varies only mildly with $\Delta \log I_e$. To the extent that [Mg/H] does vary at fixed $\sigma$ between the different panels, it follows the same trend as [Fe/H], with low-SB galaxies showing slightly lower [Mg/H] and high-SB galaxies showing slightly higher [Mg/H] than their counterparts in the midplane FP slice. However, the variation in [Mg/H] with $\Delta \log I_e$ is only about half that seen in [Fe/H]. Figure 4 showed that [Mg/H] has the strongest and tightest trend with $\sigma$. This 4D map both confirms that there is little spread in [Mg/H] at fixed $\sigma$ and illustrates that the small existing spread is correlated with $\Delta \log I_e$.

Finally, Figure 10 shows the map of [Mg/Fe] across the FP slices. As with the other stellar population parameters, [Mg/Fe] depends strongly on $\sigma$ and is independent of $R_e$. Comparison
between the panels shows that it also varies with $\Delta \log I_e$. Unlike $[\text{Fe/H}]$ and $[\text{Mg/H}]$, both of which increase with increasing surface brightness, $[\text{Mg/Fe}]$ decreases on average in high-SB galaxies (right panels) and increases on average in low-SB galaxies (left panels). In this respect, $[\text{Mg/Fe}]$ behaves similarly to stellar population age, showing the highest values in low-SB, older galaxies.

It is interesting that the low-SB slice of the FP (left panels) shows substantially more total variation in $[\text{Mg/Fe}]$ than the other panels. This trend is consistent through all three slices. Indeed, the high-$I_e$ slice (right panels) shows only a small range of $[\text{Mg/Fe}]$, while the low-$I_e$ slice (left panels) shows substantial variation. An equally valid way to state this (although perhaps harder to see clearly in Figure 10) would be to say that high-$\sigma$ galaxies (at the right side of each map) show substantial variation in $[\text{Mg/Fe}]$ between galaxies, but that the low-$\sigma$ galaxies (at the left side of each map) all have similarly low values of $[\text{Mg/Fe}]$.

Taken together, these maps of stellar population parameters along and through the FP show that age, $[\text{Fe/H}]$, $[\text{Mg/H}]$, and $[\text{Mg/Fe}]$ all vary strongly with $\sigma$, but that they also appear to vary with $\Delta \log I_e$ ($[\text{Mg/H}]$ varies only mildly, while the other three parameters vary substantially). None of them varies significantly with $R_e$. From these maps, it is clear that the spread around the $\sigma$ relations shown in Figure 4 is not just due to statistical errors but in fact is systematic behavior that is correlated with surface brightness differences. This furthermore implies that there are substantial correlations between stellar population properties at fixed $\sigma$. The next section looks explicitly at the correlations between residuals from the $\sigma$-driven relations of Figure 4 in order to understand the systematic co-variation of the various stellar population properties.

4.3. Residuals from the Stellar Population–$\sigma$ Relations

Stellar population residuals $\Delta(\log$ age), $\Delta[\text{Fe/H}], \Delta[\text{Mg/H}], \Delta[\text{Mg/Fe}]$ are defined with respect to the mean relations versus $\sigma$ by subtracting the linear fits shown in Figure 4 (dashed lines). Figure 11 shows various correlations between these residuals. Filled circles show the high-S/N data (corresponding to black points in Figure 4), while empty circles show the low-S/N data (gray points in Figure 4). Data points are color-coded by $\Delta \log I_e$, with blue representing the high-SB slice of the FP, green representing the midplane of the FP, and red showing the low-SB slice of the FP. As discussed in Section 3.2, the age–metallicity degeneracy results in correlated errors in the stellar population modeling process. Correlated errors arise because all absorption indices are sensitive to both age and metallicity, resulting in model grid lines that are not orthogonal in index-index space (see Figure 3).

The error ellipses in the lower left corners of Figure 11 indicate the slope of the correlated errors from the stellar population modeling, as determined by Monte Carlo simulations in Graves & Schiavon (2008, see Figure 3 of that work). The solid black and dashed gray error ellipses correspond to the median errors for high- and low-S/N data, respectively, based on the error estimates for the stellar population parameters determined by EZ Ages.

From Figure 11, it is clear that there are significant correlations between the residuals from the mean relations with $\sigma$. These correlations are strongly associated with $\Delta \log I_e$ and thus represent real variations in SFHs for galaxies with the same $\sigma$. Although the correlated residuals in panels (a–c) are in the same direction as the correlated errors from the stellar population modeling process, the residuals trends cannot be explained merely by the correlated errors, for two reasons. In all cases, the black error ellipses are far too small to account for the observed spread in residuals, so the degeneracies in the modeling process cannot produce the observed spread in the data. Even more conclusively, the residuals depend strongly on $\Delta \log I_e$. This cannot be explained by measurement errors in the absorption line strengths propagated through the correlated errors in the stellar population modeling because the sense of the measurement errors should be random, not dependent on $\Delta \log I_e$. Thus the known degeneracies of the modeling process cannot...
account for the observed correlation of residuals. The appendix further demonstrates that correlated systematic errors due to multiburst stellar population models also cannot be responsible for the observed trends.

Figure 11(a) indicates that there is a strong anticorrelation between stellar population age and [Fe/H] at fixed σ, such that high-SB galaxies tend to be younger and more Fe-rich than their low-SB counterparts at the same σ. The total spread is at least a factor of two (0.3 dex) in both age and Fe abundance, with Δ[Fe/H] ∝ −0.7Δ(age). A similar anticorrelation was noted by Trager et al. (2000) and more recently by Smith et al. (2008), whose error estimates for individual galaxies were small enough to allow them to claim a genuine anticorrelation in the parameters. The clear dependence of age and [Fe/H] residuals on Δlog Ie shown in Figure 11(a) lays to rest any doubts that the anticorrelation could be due to errors alone, even though the slope of the anticorrelation is similar to the expected correlation of observational errors. In contrast to the clear dependence on Δlog Ie shown here, Trager et al. (2000) did not find any dependence of the age-[Fe/H] anticorrelation on Ie but in fact found that there was no improvement in statistical fits of age or [Fe/H] when Ie was included with σ as one of the fitting parameters. This is probably because they were fitting against absolute Ie rather than Δlog Ie at fixed σ and R_e (recall that Figure 6 shows only very weak dependence of stellar population parameters on absolute log Ie). There is a message here for multiparameter fits in general: to detect a relation versus a residual in a higher-dimensional space, it is necessary to fit against that residual explicitly; the variation may remain concealed when using the parent coordinate alone.

A similar anticorrelation between residuals in age and Mg abundance is apparent in Figure 11(b). Again, the anticorrelation is strongly dependent on Δlog Ie. The strength of the anticorrelation is weaker than the age-[Fe/H] trend at fixed σ (Δ[Mg/H] ∝ −0.4Δ(log age)). This is consistent with the fact that Figure 4 shows less spread in [Mg/H] at fixed σ than in [Fe/H]. In addition to the total abundance of Mg at fixed σ, there are also systematic variations in the abundance ratio [Mg/Fe]. Figure 11(c) shows that [Mg/Fe] is anticorrelated with [Fe/H] at fixed σ, so that Fe-poor galaxies are more Mg-enhanced than their Fe-rich counterparts. As with age, [Fe/H], and [Mg/H], residuals from the log [Mg/Fe] relation are correlated with Δlog Ie. Finally, Figure 11(d) shows that residuals in age are positively correlated with residuals in [Mg/Fe], such that older galaxies are more Mg-enhanced than younger galaxies at the same σ. The statistical errors in age and [Mg/Fe] are uncorrelated (i.e., the error ellipses in panel d are horizontal) because, although age errors in the stellar population modeling process affect individual abundance measurements, abundance ratio determinations are robust to modest age errors.

In summary, there are correlations between the residuals from all of the various stellar population parameter trends with σ. These depend on Δlog Ie such that high-SB galaxies have younger ages, higher [Fe/H], higher [Mg/H], and lower [Mg/Fe] than low-SB galaxies with the same σ and R_e. These trends are similar to those reported in Paper I, where more luminous galaxies (those with higher Δlog LV) were similarly younger, more Fe-rich, more Mg-rich, and with lower [Mg/Fe] with respect to less luminous galaxies at the same σ.

In this context, one can ask whether Δlog LV (from Paper I) or Δlog Ie (from this work) is the better discriminator of differing stellar populations at fixed σ. A “better” discriminator can be defined as the binning parameter which maximizes age and [Fe/H] differences at fixed σ (i.e., does the best job of separating galaxies with differing SFHs from one another). Figure 12 compares the discriminatory power of binning galaxies by Δlog Ie (as in this analysis) versus binning by Δlog LV (as in Paper I). In each analysis, galaxies were divided into “bright,” “medium,” and “faint” bins at fixed σ, based either on Δlog Ie or on Δlog LV. The “medium” brightness bins are not included
in Figure 12 because the “bright” and “faint” bins best illustrate the total spread in stellar population properties.

The top panels of Figure 12 show histograms of the residuals from the age–σ and [Fe/H]–σ relations based on the Δ log I_e used in this analysis. Sorting galaxies by Δ log I_e does an excellent job of separating out galaxies with differing SFHs: the galaxies with the high-SB (black histograms) have the youngest mean ages and the highest [Fe/H], while those with the low-SB (gray histograms) have the oldest mean ages and lower [Fe/H]. The separation between the two populations is very clear. If Δ log L_V is used to bin galaxies at fixed σ (lower panels), the results are generally similar. However, the differences between high and low peaks are larger in both cases with Δ log I_e than with Δ log L_V. This is as expected since Δ log I_e is a “pure” stellar population measure whereas Δ log L_V also contains information from Δ log R_e (at fixed σ). As illustrated in Figures 7–10, Δ log R_e is irrelevant to stellar population parameters, and thus its presence in Δ log L_V serves only to dilute the information in that quantity. To conclude, if one is searching for the best way to identify the youngest (or most Fe-rich) galaxies at a given σ, Δ log I_e is a better discriminant than Δ log L_V. There may be cases where radii are not measurable or not available for individual galaxies, particularly in high redshift surveys, in which case Δ log L_V still provides reasonable discriminatory power.

The stellar population maps discussed in Section 4.2 showed very little variation in stellar population properties as a function of R_e at fixed σ. A direct comparison of stellar population residuals and their dependence on R_e is shown in Figure 13. Here, stellar population residuals are shown as a function of Δ log R_e, where Δ log R_e is defined as the difference between the median log R_e for each bin and the median log R_e for all galaxies in the same σ range. The weak dependence of R_e on σ has therefore been removed, highlighting the effect of R_e alone. It is clear that the stellar population residuals are unrelated to galaxy size at fixed σ.

This is an interesting and perhaps surprising result. The total M_{dyn} scales as σ^2 R_e. Thus, if the fundamental galaxy property driving stellar population variations were galaxy mass, we would expect residuals from σ trends to correlate with R_e as well as with σ. If this were the case, the contours of age, [Fe/H], [Mg/H], and [Mg/Fe] in Figures 7–10 would follow the dashed lines of M_{dyn}. Instead, lines of constant population properties run nearly vertically in those figures, and the residuals shown here in Figure 13 are completely independent of R_e. This suggests that it is in fact σ and not total mass that is fundamentally related to the galaxy SFH. The emerging generation of cosmological models, including predictions for stellar velocity dispersions, may be able to shed light on the different evolutionary histories of galaxies with the same total M_{dyn} but different values of σ (and vice versa).

Taken together, these results indicate that σ is the primary structural parameter controlling stellar population variations, and therefore the primary predictor of a galaxy’s past SFH. Indeed, σ appears to be more fundamental than total mass, because residuals from the mean trends between σ and the various stellar population properties do not correlate with R_e. At fixed σ, there are additional, genuine correlations between stellar population parameters which seem to depend strongly on Δ log I_e such that high-SB galaxies are younger, more Fe-rich, and more Mg-rich, but with less enhanced [Mg/Fe] than typical galaxies at the same σ. Conversely, low-SB galaxies at the same σ are older, Fe-poor, Mg-poor, and show significantly enhanced [Mg/Fe]. These correlations provide strong constraints on cosmological models of galaxy formation and are an important tool for understanding past SFHs of early-type galaxies. The implications for galaxy SFHs will be discussed in detail in Paper III.

4.4. Can the Observed Variation in Stellar Populations be Caused by Measurement Errors in the FP Parameters?

We have argued that, because the thickness of the FP in I_e is strongly correlated with stellar population variations, that the thickness of the plane must be real, rather than merely scatter due to observational errors. But before accepting this, it is worth checking that the observed stellar population trends cannot be caused by observational errors in the FP parameters. It is obvious that, if the thickness of the FP in the I_e dimension is due to errors in I_e itself, we should not see any trends with I_e. What about thickness in I_e that is due to errors in R_e and/or σ that “scatter” galaxies into a different I_e bin?

The slope of the FP indicates that higher σ galaxies tend to have higher I_e, thus galaxies with observed high I_e should be galaxies that have “scattered” in from high σ (i.e., galaxies for which σ has been underestimated). However, the galaxies scattered in from higher σ would have older ages and higher [Mg/Fe], which is opposite to the observed trend with Δ log I_e. It is therefore not possible that errors in σ could produce the observed trends in I_e and stellar population properties. In the case of R_e, I_e is calculated as I_e = L/2π R_e^2 so overestimating R_e will result in underestimating I_e. However, we have shown that stellar populations do not depend on R_e and thus errors in measuring R_e cannot explain the observed stellar population variations as a function of I_e. This leads to the conclusion that the thickness of the FP in I_e is intrinsic to the galaxy population, rather than an artifact of measurement error, and therefore that the observed stellar population variation with Δ log I_e is likewise real.
We have identified a sample of ∼16,000 early-type galaxies from the SDSS spectroscopic Main Galaxy Sample to study simulations, along with a study of how various properties of the mergers affect the FP parameters of the resulting merger remnant galaxies. They find that the final $R_e$ of the merger remnant depends strongly on the orientation of the initial galaxy orbits and the total angular momentum of the premerger system. Different initial orientations produce a factor of two variation in the resulting $R_e$ of the merger remnant for re-simulations of collisions between identical progenitor galaxies. The stellar populations of a galaxy should be independent of galaxy orbit angular momentum and orientation before a merger; therefore dissipationless mergers will tend to decouple the remnant $R_e$ from any original relation between galaxy size and SFH, should one exist.

Subsequent dissipationless merging of early-type galaxies will also tend to further scatter galaxies in $R_e$, while having only a small effect on $\sigma$ and presumably having no effect on the stellar population of the galaxy. Simulations of dissipationless mergers between equal-mass systems by Boylan-Kolchin et al. (2005) result in remnants with $R_e$ around 70% (0.23 dex) higher than the pre-merger systems, while the $\sigma$ of the remnant differs by < 20% (0.06 dex) from the premerger system. Thus equal-mass dissipationless merging modifies $R_e$ without create major changes in $\sigma$ or the stellar populations of galaxies, thereby scrambling any pre-existing correlations.

These merger simulations suggest that any initial correlation between galaxy size and SFH will be erased through extensive merging. Gas-rich dissipational mergers will produce remnants whose radii depend strongly on the orbital orientations of the progenitors, scrambling any initial size-dependence. Variable quantities of subsequent gas-poor dissipationless mergers, which change $R_e$, but have only minor effects on $\sigma$ and no effect on the stellar population, will further serve to erase any original stellar population dependence on $R_e$.

6. CONCLUSIONS

We have identified a sample of ∼16,000 early-type galaxies from the SDSS spectroscopic Main Galaxy Sample to study...
SFHs in FP space. Bins of similar galaxies are defined along the FP in $\log \sigma$ and $\log R_e$, and through the thickness of the FP in $\Delta \log I_e$. Spectra of the galaxies in each bin are co-added to produce a set of high S/N mean spectra that span the FP. The mean spectra are compared with the stellar population models of Schiavon (2007) using the automated IDL code EZ_Ages (Graves & Schiavon 2008), which determines the mean luminosity-weighted age, abundances $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and the abundance ratio $[\text{Mg}/\text{Fe}]$ for each stacked spectrum. This allows us to study the variations of stellar populations throughout FP space.

The SFHs of early-type galaxies are found to form a two-parameter family. Interestingly, these two parameters correlate with $\sigma$ and with $\Delta \log I_e$ but not with $R_e$. In other words, the two-parameter family of SFHs vary across one dimension of the FP and through the thickness of the FP, but do not seem to vary with the second dimension across the FP. A detailed summary of our results follows.

1. Stellar population age, $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ all increase with increasing galaxy age. This implies a close relationship between $\sigma$ and the SFH of a galaxy. Age and $[\text{Fe}/\text{H}]$ show substantial spreads at fixed $\sigma$, while $[\text{Mg}/\text{Fe}]$ and $[\text{Mg}/\text{H}]$ vary less. The relation between $\sigma$ and $[\text{Mg}/\text{H}]$ is particularly strong and tight, showing very little spread at high $\sigma$ and only modest spread at low $\sigma$.

2. Stellar population properties are independent of galaxy size, $R_e$. This suggests that $\sigma$ is a better predictor of the SFH of a galaxy than total mass since dynamical mass scales as $M_{\text{dyn}} \propto \sigma^2 R_e$. This can be understood in the context of merger-driven galaxy formation, where $R_e$ is strongly affected by the initial orbital conditions of the merging galaxies and may be subsequently further altered by dissipationless merging (which does not affect the stellar population).

3. At fixed $\sigma$ and $R_e$, stellar populations vary substantially with surface brightness residuals from the FP, parameterized by $\Delta \log I_e$. This has a number of implications. Firstly, the thickness of the FP is real rather than merely due to measurement error. Furthermore, the thickness of the FP represents an age sequence, such that galaxies with higher surface brightness than the midplane of the FP have younger ages, while galaxies with lower surface brightness than the midplane have older ages. This result is in agreement with the work of Forbes et al. (1998), Terlevich & Forbes (2002), and Treu et al. (2005b).

4. In addition to age variations through the thickness of the FP, there are corresponding variations in all other stellar population properties studied here. The variations in age, $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ at fixed $\sigma$ are correlated with another such that the galaxies with higher surface brightness than the FP midplane are younger, significantly more Fe-rich, only slightly more Mg-rich, and have lower $[\text{Mg}/\text{Fe}]$ than their counterparts on the FP. Similarly, galaxies with lower surface brightness than the FP midplane are older, less Fe-rich, slightly less Mg-rich, and have substantially enhanced $[\text{Mg}/\text{Fe}]$ relative to their counterparts on the FP. The general age–metallicity anticorrelation is consistent with previous work by Trager et al. (2000) and Smith et al. (2008). Although these covariances are in the directions of the correlated errors in stellar population modeling, neither the statistical errors nor the known systematic errors in the modeling process can explain the variations, strongly suggesting that they are real effects.

5. The variations with $\Delta \log I_e$ at fixed $\sigma$ and $R_e$ demonstrated in this analysis are consistent with the results of Paper I, which showed similar stellar population variations with $\Delta \log L_V$ at fixed $\sigma$. However, the FP residual $\Delta \log I_e$ does a somewhat better job of distinguishing young Fe-rich populations from old Fe-poor populations at the same $\sigma$ and is thus preferable to $\Delta \log L_V$ for studying variations in the SFHs of early-type galaxies.

This work demonstrates that the stellar populations of early-type galaxy form a two-parameter family. This two-parameter family maps onto a cross-section through the FP. Paper III in this series will explicitly quantify this mapping, as well as translating the derived stellar population parameters into model SFHs.

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**APPENDIX**

**FROSTING MODELS**

Section 4.3 showed that correlated statistical errors cannot account for the co-variation of stellar population properties with $\Delta \log I_e$ at fixed $\sigma$. The younger ages observed for high-SB galaxies are genuine variations, in agreement with the results of Forbes et al. (1998). However, the stellar population models used in this work are single-burst models. Because young stars are luminous and contribute disproportionately to integrated galaxy light and Balmer absorption line strengths, a small population of young stars can skew the “mean” age to younger values than a true, mass-weighted mean age. The effect is largest when the age difference between subpopulations is large compared to the mean stellar age, so that the youngest age measurements in our data are likely to be somewhat too young. Determinations of age and $[\text{Fe}/\text{H}]$ from absorption indices are anticorrelated, so a young component would not only skew the mean age to younger values but should also skew the measured $[\text{Fe}/\text{H}]$ to higher values. Because $[\text{Mg}/\text{Fe}]$ is an abundance ratio, it is relatively insensitive to the correlated errors in age and $[\text{Fe}/\text{H}]$ (see Figure 3 of Graves & Schiavon 2008). The abundance $[\text{Mg}/\text{H}]$ is calculated as $[\text{Fe}/\text{H}] + [\text{Mg}/\text{Fe}]$, so errors in $[\text{Fe}/\text{H}]$ will translate directly into comparable errors in $[\text{Mg}/\text{H}]$. 


Figure 14. Comparing observed index variations with two-burst “frosting” stellar population models. The black grid shows solar-ratio single burst models from Schiavon (2007). The solid lines indicate lines of constant [Fe/H], while the dotted lines indicate lines of constant age, as labeled. The dark gray trajectory shows the effect of adding a 1.2 Gyr burst with [Fe/H] = −0.4 to an underlying 14.1 Gyr old population with the same [Fe/H]. The diamonds indicate the fraction of the galaxy light that would be contributed by the young population, starting from 0% at the bottom and increasing in increments of 5% to 45% at the top of the diagram. The light gray trajectory shows the effect of adding a 1.2 Gyr burst with four times larger Fe abundance ([Fe/H] = +0.2) to the underlying 14.1 Gyr population. “Xs” indicate the fraction of light contributed by the young Fe-rich population in increments of 5%. The indices measured in our stacked SDSS spectra are shown as colored points, with purple, blue, green, gold, orange, and red indicating the lowest through highest σ bins, respectively.

Figure 14 shows absorption line strength predictions for Hβ and Fe from stellar population models. The black grid shows a set of single-burst models from Schiavon (2007) with solar abundance ratios. The solid lines indicate lines of constant [Fe/H], while the dotted lines indicate lines of constant age, as labeled in the figure. In addition to the grid of single burst models, two different frosting models are shown. The dark gray line shows the effect of adding a burst with age 1.2 Gyr to an underlying stellar population with an age of 14.1 Gyr. Both the old and young population components have [Fe/H] = −0.4. Diamonds indicate the fraction of galaxy light contributed by the young burst, starting at the bottom at 0% and increasing in increments of 5% moving upward along the line. This line shows the trajectory in Hβ–(Fe) space produced by adding young bursts at the same [Fe/H] to an underlying old population. Though this model is computed for a burst, the direction traced by adding a range of younger stars would be the same or tilted even more strongly to the left. The light gray line with “X” symbols shows a similar frosting model, but here the young 1.2 Gyr burst is four times more Fe-rich than the underlying old population, with [Fe/H] = +0.2.

The colored points show the data from our stacked galaxy spectra. Different colors represent the different bins in σ, with purple indicating the lowest-σ bin and red indicating the highest-σ bin. At each value of σ, the three circles indicate the three bins in Δ log Ic, with the smallest circle showing the low-SB bin and the largest circle showing the high-SB bin. The bins have been averaged over Rg.

It is interesting that the slopes between the low-SB and midplane bins (small and medium circles) are substantially different from those between the midplane and high-SB bins (medium and large circles). Comparing first the low-SB and midplane bins, it is clear that the differences between low-SB and midplane galaxies cannot be explained at all by a small frosting of younger stars at the same [Fe/H]. The same-Fe frosting model (dark gray line with diamonds) is nearly orthogonal to the change in Hβ–(Fe) space between the low-SB and midplane bins. Even adding a frosting population with four times larger Fe abundance (light gray lines with exes) does not come close to explaining the ⟨Fe⟩ line strength differences between the low-SB and midplane galaxies. The low-SB galaxies must have genuinely lower values of [Fe/H] than the galaxies at the FP midplane, as well as having older ages.

Line strengths differences between the midplane galaxies and the high-SB galaxies are more similar to the Hβ–(Fe) trajectories expected for frosting models, particularly for low-σ galaxies. At high σ, neither the constant [Fe/H] nor the Fe-rich frosting models can account for the observed increases in (Fe) in the high-SB galaxies. For the lowest σ bin, the difference between the midplane and high-SB galaxies and the high-SB galaxies is consistent with a ~5% frosting of young stars at similar [Fe/H].

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