THE SDSS-UKIDSS FUNDAMENTAL PLANE OF EARLY-TYPE GALAXIES

F. La Barbera,1 G. Busarello,1 P. Merluzzi,1 I. G. de la Rosa,2 G. Coppola,3 and C. P. Haines4

Received 2008 May 28; accepted 2008 July 22

ABSTRACT

We derive the fundamental plane (FP) relation for a sample of 1430 early-type galaxies in the optical (r band) and the near-infrared (K band), by combining SDSS and UKIDSS data. With such a large, homogeneous data set, we are able to assess the dependence of the FP on the wave band. Our analysis indicates that the FP of luminous early-type galaxies is essentially wave band-independent, with its coefficients increasing at most by 8% from the optical to the NIR. This finding fits well into a consistent picture in which the tilt of the FP is not driven by stellar populations but results from other effects, such as nonhomology. In this framework, the optical and NIR FPs require more massive galaxies to be slightly more metal-rich than less massive ones, and to have highly synchronized ages, with an age variation per decade in mass smaller than a few percent.

Subject headings: galaxies: evolution — galaxies: fundamental parameters

Online material: color figure, machine-readable table

1. INTRODUCTION

Early-type galaxies (ETGs) populate a two-dimensional surface in the space of parameters that reflect size (effective radius), density (mean surface brightness), and kinetic temperature (velocity dispersion; Djorgovski 1992). A key feature of the fundamental plane (FP; Dressler et al. 1987; Djorgovski & Davis 1987) is its deviation (“tilt”) from the virial theorem, which may be interpreted as a variation of the M/L ratio along the sequence of ETGs and/or the breaking of homology assumption, i.e., the fact that, for all galaxies, the observed parameters have the same power-law dependence on the corresponding physical quantities (namely, the central velocity dispersion on kinetic energy, the effective radius on “gravitational” radius, and the effective surface brightness on the overall light profile; see, e.g., Djorgovski & Santiago 1993). Despite all the observational efforts, the origin of the tilt is still under debate. The change of the M/L ratio can be explained by a change in either the stellar population (e.g., Prugniel & Simien 1996) or dark matter content with galaxy mass (Ciotti et al. 1996). Both structural and dynamical nonhomology have also been invoked as physical explanations of the observed tilt (see, e.g., Hjorth & Madsen 1995; Capelato et al. 1995; Graham & Colless 1997; Busarello et al. 1997). Recently, Trujillo et al. (2004, hereafter TBB04) showed that the tilt is mostly driven by dynamical and structural nonhomology, while stellar populations account for only a small fraction of it. Bolton et al. (2007) argued that the tilt is more likely because of a variation of the dark matter content with mass, still favoring a picture in which stellar populations play a minor role. Since the contribution of different stellar populations to galaxy luminosity is expected to be wavelength-dependent while other effects (e.g., nonhomology) are not, the dependence of the FP on wavelength directly informs on how properties of the stellar populations change with mass, which is a crucial point to understand galaxy formation and evolution.

Previous studies of the wavelength dependence led to contradictory results. Pahre et al. (1998b) and Scodeggio et al. (1998) found the tilt to significantly decrease from optical to NIR wavelengths, interpreting this result as an increase of age and metallicity with mass. Mobasher et al. (1999) and Zibetti et al. (2002) found only a small decrease of the tilt with wavelength, with the FP still being significantly tilted in the NIR. However, Bernardi et al. (2003b), deriving the FP for ETGs observed in the Sloan Digital Sky Survey (SDSS), found evidence for the FP to be wavelength-independent from the g to the z bands. Several different effects can produce this puzzling picture. The FP in different wave bands has often been derived for small samples, with inhomogeneous measurements of galaxy parameters, different selection criteria (e.g., galaxy samples spanning different ranges in magnitude and/or velocity dispersion), and different fitting methods. The FP by Bernardi et al. (2003b) avoided all these problems by analyzing the same sample of galaxies at different wave bands, but it was limited to the short wavelength baseline provided by the SDSS. In the present work, for the first time, we derive the FP by using the same, large, homogeneous sample of ETGs over the wide wavelength baseline provided by the r- and K-band data of the SDSS and the UKIRT Infrared Deep Sky Survey (UKIDSS).

The layout of the paper is as follows. In § 2 we describe the selection of the sample, while § 3 details how we obtain the r- and K-band structural parameters and the central velocity dispersions. Section 4 deals with the comparison of the r- and K-band FPs. In § 5 we show how the optical and NIR FPs constrain the variation of stellar population parameters along the galaxy sequence. The discussion follows in § 6. Throughout the paper, we adopt the cosmology $H_0 = 75\ \text{km}\ \text{s}^{-1}\ \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. SAMPLE SELECTION

We select a sample of ETGs, with available K-band photometry from the second data release of UKIDSS, and r-band photometry and central velocity dispersions from the fifth data release (DR5) of SDSS. First, a complete volume-limited catalog of galaxies is defined, consisting of all 105,036 objects in DR5 with an r-band absolute magnitude $M_r < -20$, and a spectroscopic redshift in the range 0.05–0.095. Absolute magnitudes are obtained from the SDSS r-band Petrosian magnitudes, k-corrected to redshift 0.1 by using the kcorrect v4_1_4 software (Blanton et al.}
3. FUNDAMENTAL PLANE PARAMETERS

The photometric parameters entering the FP, namely, the effective radius $r_e$ and the mean surface brightness within that radius $\langle \mu \rangle_e$, are derived using 2DPHOT (La Barbera et al. 2008). The $r$- and $K$-band images are processed by adopting the same 2DPHOT options, allowing homogeneous structural parameters to be derived between both bands. For each galaxy, a local PSF model is computed by simultaneously fitting the four closest stars to that galaxy on the image. Structural parameters, i.e., the effective parameters and the Sersic index $n$ (shape parameter), are then derived by modeling the galaxy images with two-dimensional seeing-convolved Sersic models. Effective radii are converted to physical units by using the angular diameter distance corresponding to the DR5 spectroscopic redshift, $z$, of each galaxy. Mean surface brightnesses are dereddened using the extinction maps of Schlegel et al. (1998), are corrected for cosmological dimming by subtracting the term $7.5 \log(1+z)$, and are $k$-corrected to redshift 0.1 with the kcorrect v4.1.4 software (Blanton et al. 2003). In order to estimate the accuracy on structural parameters, we use 160 of the 1430 galaxies having repeated observations in different UKIDSS frames. We find that the averaged differences between measurements of structural parameters are fully consistent with zero, amounting to $-0.01 \pm 0.01$, $-0.037 \pm 0.04$, and $0.005 \pm 0.01$ for $r_e$, $\langle \mu \rangle_e$, and $\log n$, respectively. The rms values of these differences amount to $32\%$ in $r_e$, $0.6$ mag arcsec$^{-2}$ in $\langle \mu \rangle_e$, and $25\%$ in $n$. Note that the scatter in $\log r_e$ is fully consistent with the typical accuracy of the measurement of the half-light radii (Kelson et al. 2000). The quantity $\log r_e - 0.3 \langle \mu \rangle_e$, which is the relevant photometric parameter entering the FP, has an uncertainty of only $7\%$, as expected due to the correlation of measurement errors of the effective parameters. The comparison of $r$- and $K$-band structural parameters for the present sample is fully consistent with what is found in our previous studies (e.g., La Barbera et al. 2004). In particular, the mean ratio between $r$- and $K$-band radii is $-0.11 \pm 0.01$ dex; i.e., on average, effective radii decrease by $\sim 25\%$ from the optical to the NIR. This value is consistent with that of $\sim 20\%$ found by Pahe et al. (1998a) and is in agreement with the existence of negative color gradients in early-type galaxies. Sersic indices are fully consistent between optical and NIR. The average ratio of $r$- to $K$-band $n$-values amounts to $-0.007 \pm 0.009$ dex. Central velocity dispersions are retrieved from DR5 and are corrected as in Bernardi et al. (2003b) to a relative aperture of $r_e/8$, following Jørgensen et al. (1995). As shown by Bernardi (2007) for $\sigma_v < 150$ km s$^{-1}$, the DR5 velocity dispersions are slightly overestimated. This small bias increases up to $12\%$ at $\sigma_v \sim 100$ km s$^{-1}$. We remove this effect by applying the correction curve shown in Figure 4 of Bernardi (2007; see the gray line in the upper left panel).$^6$ The $r$- and $K$-band effective parameters, as well as the corrected DR5 velocity dispersions, are given in Table 1 for all 1430 galaxies analyzed in the present study. Columns in the table provide the following quantities. Columns (1) and (2) report right ascension (R.A.) and declination (decl.) in units of degrees. Columns (3) and (4) provide the logarithm of the effective radius (in units of kiloparsecs) and the effective mean surface brightness (in units of mag arcsec$^{-2}$) in the $r$ band. Columns (5) and (6) list the same quantities as columns (3) and (4) but for the $K$ band. Column (7) reports the corrected DR5 velocity dispersions.

4. THE SDSS AND UKIDSS FUNDAMENTAL PLANES

We adopt the usual representation of the FP, $\log r_e = a \log \sigma_v + b \langle \mu \rangle_e + c$, where $a$ and $b$ are the “slopes” and $c$ is the offset. These coefficients were derived by minimizing the sum of the absolute residuals around the plane. This method has the advantage of being less affected by outliers (e.g., Jørgensen et al. 1996). We adopted two fitting procedures, minimizing the residuals either in $\log \sigma_v$ or in the orthogonal direction to the plane. The first method is virtually independent of selection effects in the plane of photometric parameters, while the orthogonal fit, adopted in most previous works, treats all the variables symmetrically (see La Barbera et al. 2000).

The FP coefficients were corrected for selection effects through Monte Carlo simulations. First, we generated galaxy magnitudes according to the $r$-band luminosity function of ETGs (Bernardi et al. 2003a). For each magnitude, we derived $\log r_e$ and $\langle \mu \rangle_e$ from the luminosity-size relation of Shen et al. (2003). Values of $\log \sigma_v$ were assigned by using the equation of the FP, assuming given values of $a$, $b$, and $c$, and a given scatter in $\log \sigma_v$. All these quantities were chosen to match the observed FP. Note that when deriving the simulated FP we applied the same cuts in magnitude and $\log \sigma_v$ as we did for the real sample. The corrections for selection effects on $a$, $b$, and $c$ were estimated by not applying the cuts in magnitude and $\log \sigma_v$ to the simulated FP. These corrections amount to $+0.01\%$, $+8\%$, and $+5\%$ for the $\log \sigma_v$ fit, and $+35\%$, $+7\%$, and $+17\%$ for the orthogonal fit. As expected (e.g., La Barbera et al. 2000), the magnitude cut underestimates the coefficient $a$ of the orthogonal fit, while for the $\log \sigma_v$ fit the effect is negligible. The above corrections depend mainly on the

---

$^5$ See the list of requirements in the Algorithms section of the SDSS-DR5 Web site, at http://www.sdss.org/dr5/algorithms/veldisp.html.

$^6$ The SDSS-DR6 velocity dispersions are not affected by this bias, but they are available for only $85\%$ of our sample. However, we verified that restricting the analysis to the sample with DR6 velocity dispersions changes the FP coefficients by less than $2\%$. 

---

LA BARBERA ET AL. 914 Vol. 689
scatter around the FP, and, because of the very similar dispersions of the \(r\)- and \(K\)-band FPs (see below), were applied to both the \(r\)- and the \(K\)-band coefficients. We note that the above procedure assumes that our sample of early-type galaxies is magnitude-complete. However, because of the matching of the initial volume-complete SDSS catalog with the UKIDSS database, which reduces the sample size from 33,628 to 1430 ETGs, the above assumption might not necessarily hold. To address this point, we retrieved effective parameters and velocity dispersions for the whole sample of the large sample size, the accuracy of our \(K\)-band coefficients is significantly higher (by 50\%) than in previous studies. Considering how stellar population parameters vary with mass (e.g., dark matter content). The quantity \(\sigma_0\) describing the variation of wavelength-independent properties differs by only 2\% for the log \(\sigma_0\) fit, which is virtually unaffected by selection effects. The value of \(b\) (~0.308) is independent of the wave band as well as the scatter of the FP, which presents a tiny difference (<2\%) for the log \(\sigma_0\) fit (see also Pahre et al. 1998b). The \(r\)-band value of \(a\) is fully consistent with the value of \(a = 1.49 \pm 0.05\) found by Bernardi et al. (2003b), while it is larger than that of \(a = 1.24 \pm 0.07\) found by Jørgensen et al. (1996). For the \(K\) band, the log \(\sigma_0\) coefficient is consistent with the value of \(a = 1.53 \pm 0.08\) found by Pahre et al. (1998b), while it is larger than that of \(a = 1.38 \pm 0.1\) found by Zibetti et al. (2002). We note that, because of the large sample size, the accuracy of our \(K\)-band coefficients is significantly higher (by 50\%) than in previous studies. The invariance of the FP with wave band is in agreement with Cappellari et al. (2006), who found for 25 ETGs from the SAURON project the \(M/L\) versus \(L\) relation to have the same slope in both the \(I\) and \(K\) bands.

5. CONSTRAINTS ON THE STELLAR POPULATIONS

The tilt of the FP can be parameterized as a power-law relation between \(M/L\) and \(M\). We assume that the stellar mass-to-light ratio of galaxies, \(M_*/L\), is a power law: \(M_*/L \propto M^{\gamma}\). This agrees with what was found in previous studies for bright ETGs (see TBB04). The \(M/L\) versus \(M\) relation can then be written as \(M/L \propto M^{\beta + \gamma}\) (see also Prugniel & Simien 1996). The quantity \(\beta\) is related to the ratio of stellar to total mass as \(M_*/M \propto M^{-\beta}\), describing the variation of wavelength-independent properties with mass (e.g., dark matter content). The quantity \(\beta^*\) depends on how stellar population parameters vary with mass. Considering

| R.A.          | Decl.    | \(\log R_{e,r}\) | \(\langle \mu \rangle_{e,r}\) | \(\log R_{e,K}\) | \(\langle \mu \rangle_{e,K}\) | \(\log \sigma_0\) |
|--------------|----------|-----------------|----------------|----------------|----------------|----------------|
| 145.34432    | −0.01692 | 0.860           | 21.602         | 0.527           | 17.046         | 2.282          |
| 147.24805    | −0.03572 | 0.834           | 21.346         | 0.680           | 17.437         | 2.228          |
| 146.81199    | −0.19005 | 0.459           | 19.968         | 0.349           | 16.319         | 2.217          |
| 146.09369    | −0.79309 | 0.985           | 21.521         | 0.475           | 16.216         | 2.259          |
| 146.46892    | −0.09284 | 1.622           | 23.236         | 1.090           | 18.009         | 2.317          |
| 146.19333    | −0.03887 | 0.625           | 20.555         | 0.445           | 16.439         | 2.226          |
| 145.68114    | −0.86722 | 0.701           | 21.576         | 0.721           | 17.350         | 2.196          |
| 145.70894    | −0.74768 | 0.134           | 18.936         | 0.088           | 15.655         | 2.112          |
| 145.48725    | −0.80963 | 0.965           | 21.993         | 1.065           | 19.167         | 2.180          |
| 145.42694    | 0.04954  | 0.470           | 19.852         | 0.018           | 14.473         | 2.367          |
| 145.44549    | −0.12268 | 0.381           | 19.576         | 0.166           | 15.351         | 2.353          |
| 145.34160    | −0.57727 | 0.087           | 18.124         | −0.152          | 13.574         | 2.355          |
| 145.19382    | 0.16887  | 0.192           | 18.862         | 0.137           | 15.669         | 1.930          |
| 146.28017    | −0.40695 | 0.033           | 17.760         | −0.129          | 13.996         | 2.288          |
| 147.30829    | 0.15116  | 0.830           | 21.046         | 0.454           | 16.295         | 2.287          |
| 146.72794    | −0.55688 | 0.262           | 19.223         | 0.178           | 15.409         | 2.316          |
| 148.85664    | −0.05916 | 0.978           | 21.643         | 1.160           | 19.055         | 2.226          |
| 147.79347    | 0.12326  | 0.614           | 20.337         | 0.227           | 15.566         | 2.187          |
| 147.74868    | 0.11584  | 0.480           | 20.362         | 0.125           | 15.682         | 2.233          |
| 148.58499    | −0.94207 | 1.180           | 22.575         | 0.703           | 17.637         | 2.199          |
| 149.12382    | −0.39828 | 0.365           | 19.682         | −0.037          | 14.726         | 2.324          |
| 149.11298    | −0.34883 | 0.685           | 20.638         | 0.593           | 16.954         | 2.270          |
| 149.18631    | −0.31181 | 1.291           | 23.217         | 0.823           | 18.064         | 2.101          |
| 148.84251    | −0.04411 | 0.469           | 20.031         | 0.387           | 16.276         | 2.202          |
| 149.11264    | −0.47563 | 0.572           | 20.065         | 0.471           | 16.069         | 2.398          |
| 149.17153    | −0.41298 | 0.359           | 19.539         | 0.266           | 15.894         | 2.260          |

Note.—Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
only the effects of age and metallicity, for each wave band we can write

$$\frac{\delta(\log M/L)}{\delta(\log t)} = \frac{\delta^r}{1 - \beta} = c_1 \frac{\delta(\log t)}{\delta(\log M_r)} + c_2 \frac{\delta(\log Z)}{\delta(\log M_r)},$$

(1)

where the quantities $\delta(\log t)$ and $\delta(\log Z)$ are the logarithmic differences of age and metallicity defined between more and less massive galaxies (per decade in stellar mass), while $c_1 = (\partial \log M_r/L)/(\partial \log t)$ and $c_2 = (\partial \log M_r/L)/(\partial \log Z)$ are the partial derivatives of $\log M_r/L$ (in a given band) with respect to $t$ and $Z$.

Writing equation (1) for $r$ and $K$ bands, we obtain two independent constraints on $\delta(\log t)$ and $\delta(\log Z)$. Then, expressing the values of $\beta^r$ and $\beta^K$ as a function of the corresponding coefficients of the FP, we can estimate $\delta(\log t)$ and $\delta(\log Z)$. We introduce the parameter $\beta = \beta_K/(\beta + \beta_K)$, which defines the fraction of the $K$-band slope of the $M/L$ versus $M$ relation (i.e., the fraction of the $K$-band tilt) due to stellar population effects. We note that $\beta$ can vary between 0 and 1. For $\beta > 0$, the $K$-band tilt is independent of stellar populations ($\beta^K = 0$), while for $\beta = 1$ the tilt is entirely explained by stellar population effects ($\beta = 0$). Under the assumption of homology, the slope of the $M/L$ versus $M$ relation can be written as $(2 - a)/(2 + a)$. With the above notation, the following relations hold:

$$\beta + \beta^r = [(1 - f)/f] \beta^K + \beta^r = (2 - a_r)/(2 + a_r),$$

$$\beta + \beta^K = \beta^K/f = (2 - a_K)/(2 + a_K).$$

(2)

For different values of $f$ and using the values of $a$ in Table 2, we computed $\beta^r$ and $\beta^K$ from equation (2), and then, inverting equation (1) for both bands, we derived $\delta(\log t)$ and $\delta(\log Z)$. The values of $c_1$ and $c_2$ were estimated using simple stellar population models, with solar metallicity and an age of 12 Gyr, using both the Bruzual & Charlot (2003, hereafter BRC03) and the updated Vazdekis et al. (1996, hereafter V96) models. We adopted a Scalo initial mass function (IMF) and a Salpeter IMF for the BRC03 and V96 models, respectively. Figure 2 shows $\delta(\log Z)$ versus $\delta(\log t)$ obtained for $f = 0$ and $f = 1$, as well as the mean values of $\delta(\log t)$ and $\delta(\log Z)$ as a function of $f$. The scatter seen in the plot reflects the uncertainties listed in Table 2 for the $a_i$ and $d_K$ coefficients. The figure shows that if the NIR tilt of the FP is not caused by stellar population effects ($f = 0$), more massive galaxies have to be more metal-rich than less massive ones [$\delta(\log Z) > 0$], with galaxy ages being remarkably homogeneous ($\delta(t)/t \sim 1\%$). As $f$ increases, we see that $\delta(\log Z)$ decreases, while $\delta(\log t)$ becomes larger. Specifically, for $f \sim 1$, more massive galaxies are much older ($\delta(t)/t \sim 50\%$) and less metal-rich than low-mass systems.

6. DISCUSSION

This work presents the wave band dependence of the FP by comparing the optical and NIR FPs for a large sample of galaxies, with homogeneous measurements of structural parameters.

---

6. DISCUSSION

This work presents the wave band dependence of the FP by comparing the optical and NIR FPs for a large sample of galaxies, with homogeneous measurements of structural parameters.

---

6. DISCUSSION

This work presents the wave band dependence of the FP by comparing the optical and NIR FPs for a large sample of galaxies, with homogeneous measurements of structural parameters.
and velocity dispersions. This is allowed, for the first time, thanks to the availability of both SDSS r-band photometry and spectroscopy and UKIDSS K-band photometry for the same sample of ETGs. Such a data set, together with the use of the same fitting procedure in both bands, makes our study virtually free from any methodological effect on the wave band dependence of the FP. Our analysis shows that the FP does not change significantly from the optical to the NIR, bringing interesting questions about the nature of the sequence of ETGs.

In § 5 we have shown how the r- and K-band FPs constrain the variation of the stellar population properties (age and metallicity) with stellar mass, and how such a constraint is strongly dependent on the fraction, f, of the FP tilt resulting from stellar population effects. Previous studies of the color-magnitude (CM) relation and of line-strength indices of ETGs might help us to solve this dependency, by deriving the proper value for f. Kodama et al. (1998) showed that the limited redshift evolution of the CM relation indicates that (1) all the (luminous) ETGs are equally old and (2) more massive galaxies are more metal-rich, with a metallicity change of δ(log Z) ~ 0.22 dex per decade in stellar mass. This finding is qualitatively consistent with that of Thomas et al. (2005), who found absorption-line indices consistent with a metallicity change of δ(log Z) ~ 0.12 dex per mass decade. They also found evidence for an age gradient along the sequence of ETGs, with δ(log t) = +0.05 ± 0.07 (see their eq. [3]). Figure 2 compares these values of δ(log Z) with those derived by the optical-NIR FP. For the BRC03 (V96) model, the maximum value of δ(log Z), which is consistent with the FP, amounts to 0.06 (0.09) ± 0.04 (0.04) dex for f = 0. This value is 4 σ (3.7 σ) lower than that derived by the CM relation, while it is only 1.5 σ (0.8 σ) lower than that found by Thomas et al. (2005). As f increases, the FP requires the value of δ(log Z) to decrease, making the above differences even larger. Therefore, reconciling previous estimates of δ(log Z) with our results leads to a scenario where f = 0, which means that the FP tilt is not driven by stellar populations. We have to remark, however, that this interpretation is troublesome, since galaxy colors and line indices are always measured within a given fixed aperture, and the presence of internal population gradients in galaxies can significantly affect the inferred values of δ(log Z) and δ(log t) (e.g., Scodeggio 2001).

Further constraints come from previous works addressing the origin of the FP tilt itself. Performing a detailed dynamical analysis of 25 galaxies, Cappellari et al. (2006) derived M/L ratios consistent with those obtained from the virial theorem under the assumption of homology, concluding that structural and orbital nonhomology have a negligible role in the tilt of the FP (see also Zaritsky et al. 2008). In support of this view, they also showed that the variation of the dynamical M/L is correlated with the H/β line strength, thus ascribing most of the tilt to stellar population (age) effects. However, as the authors note, this result strictly applies to their measurement of the velocity dispersion as the average over an aperture of radius equal to r_e, a fact that alone might compensate part of the dynamical nonhomology. Moreover, most of the galaxies in their sample (68%) are fast rotators, while five of them (20%) have low velocity dispersion (σ = 60–85 km s^{-1}). As found by Zaritsky et al. (2006) and D’Onofrio et al. (2008), bright and faint spheroids have different FPs, with the tilt becoming larger for galaxies having low velocity dispersion. Hence, the different selection of our sample and that of Cappellari et al. (2006) prevents a straightforward comparison. Bolton et al. (2007) showed that by replacing mean surface brightness with mass density, the FP relation closely approaches the virial theorem expectation, implying that most of the tilt is caused by a variation of dark matter content with galaxy mass. However, the uncertainties on their FP coefficients and the possible biases introduced by the gravitational-lens selection do not definitively exclude the contribution of nonhomology to the FP tilt. Our result agrees with Bolton et al. (2007) regarding the minor role played by stellar populations on the tilt. TBB04, agreeing with Busarello et al. (1997) and Graham & Colless (1997), found that structural and dynamical nonhomology can account for more than two-thirds of the FP tilt, with the remaining part being explained by stellar population effects. In particular, restricting the analysis to the magnitude-complete subsample, they found that the contribution of stellar populations to the tilt becomes negligible. Note also that their FPs are derived from different sources, with significantly different coefficients in the optical and NIR wave bands.

To understand how our results may be affected by the assumption of homology, we followed an approach similar to that of TBB04, using spherical, isotropic, nonrotating, one-component models of ETGs following the Sersic law (see La Barbera et al. 2005). For each galaxy, we considered the model with the corresponding Sersic index in the r band and used that model to correct the central velocity dispersion to the quantity σ_r (defined as the square root of the total specific kinetic energy) and the effective radius to the gravitational radius r_e, and to calculate the mean surface brightness within the gravitational radius (μ_r). Applying the orthogonal fit, we obtain the following equation of the FP in the K band: log r_e ∝ (2.3 ± 0.2) log σ_r + (0.4 ± 0.02)(μ_r). Applying the orthogonal fit, we obtain the following equation of the FP in the K band: log r_e ∝ (2.3 ± 0.2) log σ_r + (0.4 ± 0.02)(μ_r). This result is consistently above the virial theorem expectation, implying that nonhomology may account for the entire tilt. To explore how this result would affect stellar population properties, we normalized the r- and K-band FP coefficients in such a way as to match the virial theorem expectation (a = 2.0 and b = 0.4) in the K band. Then we derived the corresponding values of δ(log Z) and δ(log t) (see § 5). As we can see in Figure 2, accounting for nonhomology leads to the same δ(log Z) and δ(log t) values as those derived under the assumption of homology if the tilt of the FP is not due to stellar populations (i.e., f = 0). As discussed above, this is consistent with what is expected from the color-magnitude relation and absorption-line indices of ETGs.

In summary, our analysis suggests a consistent picture in which (1) the tilt of the FP does not originate from stellar population effects but is due to other effects, such as nonhomology, and (2) the SDSS-UKIDSS FPs require more massive galaxies to be mildly more metal-rich than less massive systems, and to have extremely synchronized ages, with the age variation per mass decade being smaller than few percent.

We thank R. R. de Carvalho, S. G. Djorgovski, M. Capaccioli, and A. Mercurio for the helpful comments and suggestions. We also acknowledge the referee for helpful suggestions. We also thank A. Vazdekis for providing us with the most recent version of his stellar population code. We have used data from the 2nd data release of the UKIDSS survey (Lawrence et al. 2007), which is described in detail in Warren et al. (2007). Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England.
REFERENCES

Bernardi, M. 2007, AJ, 133, 1954
Bernardi, M., et al. 2003a, AJ, 125, 1849
———. 2003b, AJ, 125, 1866
Blanton, M. R., et al. 2003, AJ, 125, 2276
Bolton, A. S., Burles, S., Treu, T., Koopmans, L. V. E., & Moustakas, L. A. 2007, ApJ, 665, L105
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000 (BRC03)
Busarello, G., et al. 1997, A&A, 320, 415
Capelato, H. V., de Carvalho, R. R., & Callegari, R. G. 1995, ApJ, 451, 525
Cappellari, M., et al. 2006, MNRAS, 366, 1126
Ciotti, L., Lanzoni, B., & Renzini, A. 1996, MNRAS, 282, 1
Djorgovski, S. 1992, in ASP Conf. Ser. 24, Cosmology and Large-Scale Structure in the Universe, ed. R. R. de Carvalho (San Francisco: ASP), 19
Djorgovski, S. G., & Davis, M. 1987, ApJ, 313, 59
Djorgovski, S. G., & Santiago, B. X. 1993, in ESO/EIPD Workshop on Structure, Dynamics, and Chemical Evolution of Early-Type Galaxies, ed. I. J. Danziger, W. W. Zelinger, & K. Kjar (Garching: ESO), 59
D’Onofrio, M., et al. 2008, ApJ, 685, 875
Dressler, A., et al. 1987, ApJ, 313, 42
Gómez, P. L., et al. 2003, ApJ, 584, 210
Graham, A., & Colless, M. 1997, MNRAS, 287, 221
Hjorth, J., & Madsen, J. 1995, ApJ, 445, 55
Jørgensen, I., Franx, M., & Kjaergaard, P. 1995, MNRAS, 276, 1341
———. 1996, MNRAS, 280, 167
Kelson, D. D., Illingworth, G. D., van Dokkum, P. G., & Franx, M. 2000, ApJ, 531, 137
Kodama, T., et al. 1998, A&A, 334, 99
La Barbera, F., Busarello, G., & Capaccioli, M. 2000, A&A, 362, 851
La Barbera, F., Merluzzi, P., Busarello, G., Massarotti, M., & Mercurio, A. 2004, A&A, 425, 797
La Barbera, F., et al. 2005, MNRAS, 358, 1116
———. 2008, PASP, 120, 681
Lawrence, A., et al. 2007, MNRAS, 379, 1599
Mobasher, B., et al. 1999, MNRAS, 304, 225
Pahre, M. A., de Carvalho, R. R., & Djorgovski, R. 1998a, AJ, 116, 1606
Pahre, M. A., Djorgovski, S. G., & de Carvalho, R. R. 1998b, AJ, 116, 1591
Prugniel, P., & Simien, F. 1996, A&A, 309, 749
Schlegel, D., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Scodeggio, M. 2001, AJ, 121, 2413
Scodeggio, M. M., et al. 1998, MNRAS, 301, 1001
Shen, S., Mo, H. J., White, S. D. M., Blanton, M. R., Kauffmann, G., Voges, W., Brinkmann, J., & Csabai, I. 2003, MNRAS, 343, 978
Sorrentino, G., Antonuccio-Delogu, V., & Rifatto, A. 2006, A&A, 460, 673
Thomas, D., et al. 2005, ApJ, 621, 673
Trujillo, I., Burkert, A., & Bell, E. 2004, ApJ, 600, L39 (TBB04)
Vazdekis, A., et al. 1996, ApJS, 106, 307 (V96)
Warren, S. J., et al. 2007, preprint (astro-ph/0703037)
Zaritsky, D., Gonzalez, A. H., & Zabludoff, A. I. 2006, ApJ, 638, 725
Zaritsky, D., Zabludoff, A. I., & Gonzalez, A. H. 2008, ApJ, 682, 68
Zibetti, S., et al. 2002, ApJ, 579, 261