Systematic Variations in Age and Metallicity Along the Early-Type Galaxy Sequence

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**Abstract.** The form of the early-type galaxy scaling relation (the Fundamental Plane or FP) is a direct indicator of the underlying physical origins for the galaxy sequence. Observed properties of the FP include: (1) the slope increases with wavelength; (2) the slope deviates from the virial expectation (assuming homology and constant $M/L$ at all wavelengths); (3) the intercept evolves passively with redshift; and (4) the slope decreases slowly with redshift. The first property implies that stellar populations contribute to the slope of the FP, the second and fourth properties exclude metallicity effects as the sole cause of the slope, and the third implies that the stellar content of the “average” early-type galaxy formed at high redshift. A composite model—including variations in age and metallicity, as well as a wavelength-independent effects such as homology breaking—is presented which can fit all four observed properties. This model implies that the most luminous early-type galaxies contain the oldest and most metal-rich stars, while the lowest luminosity galaxies formed the bulk of their stars as recently at $z_f \sim 1$.

1. Introduction

The discovery that elliptical galaxies follow small-scatter, bivariate correlations among their properties (Dressler *et al.* 1987; Djorgovski & Davis 1987)—which are now referred to as the Fundamental Plane (FP)—provided a powerful new tool to study this galaxy population. Not only do elliptical galaxies have only a small variation among their properties for any given luminosity, but those mean properties also vary smoothly and systematically from the faintest to the most luminous galaxies. For a recent review, see Pahre & Djorgovski (1997).

The bivariate FP correlations, and their monovariate projections (such as the color-magnitude relation [CMR] or the Faber-Jackson relation), provide the basic tool by which the evolution and origin of the elliptical galaxy population can be studied. First, the evolution of the surface brightness “intercept” of the...
FP in (see §4) is an indicator of the mean formation epoch for the stellar content of the “average” elliptical galaxy (Barrientos et al. 1996; Pahre et al. 1996; van Dokkum & Franx 1996; Kelson et al. 1997; Stanford et al. 1998). Second, the variation of the “slope” of the FP with wavelength (§3) and redshift (§4), as well as its deviation from the virial expectation under the assumptions of homology and constant $M/L$ (§2; Djorgovski & Davis 1987; Faber et al. 1987), are all direct evidence of systematic variations in the intrinsic physical properties (age, metallicity, IMF, dark matter content, velocity anisotropy, homology breaking) of ellipticals along the galaxy sequence. Third, the small scatter of the FP at any given luminosity implies that all relevant, intrinsic physical properties, whether or not they are varying along the galaxy sequence, possess only a small variation among all elliptical galaxies of a given luminosity.

The slope of the FP as a function of wavelength appears to be the key parameter for determining the physical origin of the elliptical galaxy sequence. As was first pointed out more a decade ago (Djorgovski & Davis 1987; Faber et al. 1987), the observed form of the FP deviates from the virial expectation (assuming homology and constant $M/L$ of $R_{\text{eff}} \propto \sigma_{0}^{2} / \langle \Sigma \rangle_{\text{eff}}^{-1}$ [under the assumptions of constant $M/L$ and homology among elliptical galaxies]). This effect was usually interpreted as due to a systematic breakdown in $M/L$ as a function of galaxy luminosity, which is, in turn, due to variations in stellar or dark matter content along the elliptical galaxy sequence. More recent studies have suggested that homology-breaking is occurring along the galaxy sequence (Burkert 1993; Caon et al. 1993; Capelato et al. 1995; Hjorth & Madsen 1995; Busarello et al. 1997; Graham & Colless 1997) which could produce part or all of the deviation of the observed FP from the virial expectation. The answer may be a combination of the two (§7; Pahre & Djorgovski 1997; Pahre et al. 1998a,b).

Many past studies used simplistic models (e.g., elliptical galaxies form only a metallicity sequence) to explain a limited number of observed properties [e.g., only the B-band FP, or only the $(U - V)_{0}$ CMR]. As will be shown in §6, such simplistic models are typically ruled out by considering other observed properties (enumerated in §5), therefore requiring a more detailed, composite model to explain all of the observations simultaneously.

### 2. The Near-Infrared Fundamental Plane

If there exists a stellar populations component to the physical origin of the FP (as evidenced by its deviations from the virial expectation), then the form of the FP should vary with wavelength due to the stellar populations effects on the mean surface brightness $\langle \mu \rangle_{\text{eff}}$ which enters the FP. Since $M/L_{K}$ is independent of metallicity (see the contribution by MARASTON in this volume), studies in the near-infrared can test the effects of metallicity on the slope of the FP. The near-infrared FP described here is the result of a large survey of nearby galaxies in the $K$-band using IR imaging detectors (Pahre 1998b). The near-infrared form of the FP is plotted in Figure 1, and is represented by an equation of the form,

$$R_{\text{eff}} \propto \sigma_{0}^{1.53\pm0.08}/\langle \mu \rangle_{\text{eff}}^{0.79\pm0.03}$$  \hspace{1cm} (1)
5 6 7

Figure 1. The near-infrared form of the FP from Pahre et al. (1998a). The slope of the FP therefore deviates from the virial expectation \( (R_{\text{eff}} \propto \sigma_0^2) \) even in the near-infrared. Further implications of this scaling relation will be discussed below.

3. The Slope of the FP Changes With Wavelength

Early work on the FP argued that the deviation of the slope of the FP from its virial expectation implied that the stellar \( M/L \) varied weakly, but systematically, as a function of galaxy mass or luminosity (Djorgovski & Davis 1987; Faber et al. 1987). Such stellar population effects—age, metallicity, or IMF—will have a distinctive signature in the broadband colors of the galaxies, hence the variations of the slope of the FP with wavelength ought to provide a constraint on those stellar populations effects.

Variations among the optical bandpasses, however, were clearly small and not substantially larger than the measurement uncertainties. For the FP of the form \( R_{\text{eff}} \propto \sigma_0^a \langle \Sigma \rangle^b_{\text{eff}} \), Lucey et al. (1991) found \((a, b) = (1.22 \pm 0.07, -0.83 \pm 0.06)\) in the \( V \)-band, Djorgovski & Davis (1987) found \((1.39 \pm 0.14, -0.90 \pm 0.09)\) in the \( r_G \)-band, Jørgensen et al. (1996) found \((1.24 \pm 0.07, -0.82 \pm 0.02)\) in the \( r \)-band, Scodéggio et al. (1997) found \((1.25 \pm 0.02, -0.80 \pm 0.03)\) in the \( I_C \)-band, and Pahre et al. (1998a) found \((1.53 \pm 0.08, -0.79 \pm 0.03)\) in the \( K \)-band. The wavelength dependence of the slope of the FP is small and not accurately constrained from these measurements. Clearly, an improved method to measure the change in the slope of the FP with wavelength is desired to quantify accurately the stellar populations contributions to the slope of the FP at all wavelengths.

The change in slope of the FP from the \( V \) to the \( K \)-band can be calculated by setting the SB coefficient to 0.32

\[
\begin{align*}
    r_{\text{eff}, V} &= a_V \log \sigma_0 + 0.32 \langle \mu_V \rangle_{\text{eff}} + \text{constant} \\
    r_{\text{eff}, K} &= a_K \log \sigma_0 + 0.32 \langle \mu_K \rangle_{\text{eff}} + \text{constant}
\end{align*}
\]
and then taking the difference

$$(\log \sigma_0 - (\log \sigma_0 - 0.32(\mu_K)_{\text{eff}})) - (\log \sigma_0 - (\log \sigma_0 - 0.32(\mu_V)_{\text{eff}})) = \Delta \log \sigma_0 + \text{constant},$$ (4)

where $\Delta \sigma = \sigma_K - \sigma_V$ is the change in the slope of the FP. Note that both sides of Equation 4 are distance-independent quantities; the analysis that follows therefore works both in clusters and the general field. If a particular galaxy sample suffers, say, from the resolved depth of a cluster, this approach will remove such distance-dependent effects on $\sigma_0$ from the analysis. Furthermore, this approach requires that a given galaxy have observations in both observed bandpasses, so there are no longer differences in the definition of two given galaxy samples—only those galaxies in common between the two datasets are used.

The generalized form of Equation 4 for various pairs of bandpasses are plotted in Figure 2 (from Pahre et al. 1998b), which demonstrates that the slope of the FP increases with wavelength for virtually every data comparison in the optical and infrared. The conclusion that the slope of the FP increases with wavelength is a strong indication that stellar populations variations contribute to the slope and hence help to define the early-type galaxy sequence.
4. The Evolution of the FP With Redshift

Since the FP represents the elliptical galaxy scaling relation with the smallest possible scatter, it is, by construction, the optimal tool to study the changes of the elliptical galaxy population with redshift. The color-magnitude relation has gained great popularity to study elliptical galaxy evolution, but the inclusion of the central velocity dispersion term of the FP allows for the estimation of dynamical mass. It is for this reason that the evolution of the FP is often referred to as the evolution of the mass-to-light ratio—although it is really only the evolution of galaxy luminosity at fixed mass.

The field was pioneered by the velocity dispersion measurements at $z = 0.18$ of Franx (1993) and at $z = 0.39$ by van Dokkum & Franx (1996). Those observations at the MMT used very long exposure times to obtain the necessary S/N to measure the velocity dispersions. The advent of the Keck 10 m Telescope with its high-throughput spectrograph (Oke et al. 1995) allows for higher S/N spectra to be obtained in far less observing time, which means that real surveys of the properties of early-type galaxies at $0 < z < 1$ are possible. For example, the combined studies of van Dokkum & Franx (1996), Kelson et al. (1997), Ziegler & Bender (1997), and van Dokkum et al. (1998a) document only 36 galaxies at $z > 0.1$ that are suitable for studies of the FP. Our new survey with the Keck Telescope adds more than 100 galaxies at $0.1 < z < 0.6$ to create a large, homogeneous dataset for the evolutionary studies. The galaxies for each cluster were selected using two-color (three bandpass) and morphology (concentration index) criteria as described in Pahre (1998a).

The evolution of the SB intercept of the FP should probe the mean luminosity evolution of the “average” early-type galaxy, while the evolution of the slope of the FP should probe the relative evolution of the bright galaxies when compared to the faint galaxies. Only the evolution of the intercept has been discussed previously; the large galaxy sample described here allow the slope to
be constrained for the first time at these redshifts. The K-band FP for eight clusters at \(0.1 < z < 0.6\) are presented in Figure 3.

Several effects are evident. First, the galaxies at \(z > 0.1\) all lie to the right of the relation for the nearby galaxies, which is due to the cosmological SB dimming effect. A small amount of luminosity evolution is also present, which moves the data points a small amount back to the left in each panel. This is clear after the SB dimming effect is removed, and is plotted in Figure 4 [left]. Finally, the slope of the FP relation appears to become slightly flatter with redshift. This effect is quantified in Figure 4 [right], where the slope is measured to become smaller with redshift.

It is apparent from the luminosity evolution plot in Figure 4 that the “average” early-type galaxy is evolving passively as though its stars were formed at high redshift \(z_f \geq 3\). The evolution of the slope of the FP with redshift, however, argues that there is a variation in formation redshift along the early-type galaxy sequence: the brightest early-type galaxies formed their stars first at \(z_f \geq 5\), while the faintest early-type galaxies formed their stars later—as late as \(z_f \sim 1\). The model lines overplotted in Figure 4 [RHS] are the predictions based on the comprehensive models based on the nearby galaxies (see §7); two different normalizations are given (either to all the local galaxies, or to the Coma cluster alone; for details see Pahre 1998a), which provides the information as the the age spreads allowed by the evolution of the slope of the FP.

Several other lines of evidence may also show this effect. van Dokkum et al. (1998b) showed that the color-magnitude relation for S0 galaxies in a cluster at \(z \sim 0.3\) are typically bluer than the E galaxies. Kuntschner & Davies (1998) used line indices to show that the S0 galaxies in the Fornax cluster have a range of ages, while the elliptical galaxies show very little variation in age. Both of these results could be highlighting the same population that is causing the evolution of the FP slope with redshift seen here, since S0 galaxies are typically less luminous than E galaxies. Finally, the color-magnitude relation observations at \(0.3 < z < 0.9\) in Stanford et al. (1998) used large apertures to measure the galaxy colors; if there is a correlation between the size of the
populations gradient and the galaxy luminosity, as is suggested by González &
Gorgas (1995; see also the contribution by GONZÁLEZ to this volume), then
this effect would cause the slope of the corrected color-magnitude relation to
evolve with redshift, as appears to have been found in an independent analysis
(see contribution by KODAMA in this volume).

5. Constraints on the Origin of the Early-Type Galaxy Sequence

In the course of this meeting, there were many arguments presented as to the
physical origins of the elliptical galaxy sequence. There are a number of observed
properties of elliptical galaxies which should be explained by any proposed model
for the origin of the galaxy sequence:
1. the slope of the FP increases with wavelength;
2. the intercept of the FP and CMR evolve with redshift in an apparently
   passive manner;
3. the slope of the $K$-band FP deviates from the virial expectation (assuming
   constant $M/L$ and homology);
4. the slope of the FP flattens with redshift;
5. the slope of the CMR increases with redshift;
6. the residuals of the elliptical galaxy correlations do not show clear trends
   with age or metallicity; and
7. the velocity distributions of elliptical galaxies appear to deviate from a
   homologous scaling family.
To these can be added a general property of galaxies in clusters:
8. the fraction of blue galaxies in clusters increases with redshift (Butcher-
   Oemler effect).

6. Simple Models for the Origin of the FP

Metallicity Sequence. Most researchers working in this field would probably
wager that elliptical galaxies form a metallicity sequence, with the most lumi-
nous galaxies also being the most metal-rich. This would naturally explain the
change in the slope of the FP with wavelength in §3. Even though a metallicity
sequence seems to match the evolution of the color-magnitude relation (see the
contribution by KODAMA in this volume), it cannot explain the $K$-band FP:
such a metallicity sequence model must also invoke either homology breaking or
systematic variations in dark matter content or its distribution. The metallicity
sequence also fails to explain the evolution of the slope of the FP with redshift,
and provides no explanation for the Butcher-Oemler galaxies at intermediate
redshifts or their present-day counterparts.

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1Note that Kodama has reached a different conclusion from the present work for the origin of
evolution of the CMR slope in the data of Stanford et al., although it is not yet clear to what
extent composite models of age and metallicity are allowed by his analysis.

2(See the contribution by LOEWENSTEIN in this volume, which includes a discussion of the
scale-length changes for the dark matter distribution as a function of galaxy luminosity.)

7
Figure 5. Residuals from the $\kappa$-space form of the $K$-band FP [vertical axis] plotted against the residuals from the Mg$_2$–$\sigma_0$ relation [horizontal axis]. The residuals show no correlation in the directions of either age or metallicity, suggesting that there is no single origin for the scatter of the scaling relations.

**Systematic Homology Breaking.** It is currently popular to explore systematic homology breaking as the origin of the FP. This effect, however, is independent of wavelength, which contradicts the variation of the FP slope with wavelength shown in §3. Systematic homology-breaking along the elliptical galaxy sequence cannot by itself explain the origin of the FP at all wavelengths without also invoking systematic variations in stellar content along the FP.

**Conspiracy Theories.** One possibility is that variations in metallicity could offset those in age in order to keep the FP thin. A model of this kind was proposed by Worthey et al. (1995), who predicted that $M/L_K \approx$ constant. The deviation of the $K$-band FP from the virial expectation implies $M/L \propto M^{0.15 \pm 0.01}$, which contradicts this model.

**Scatter of the FP.** One explanation for the scatter of the FP is that it is due to small metallicity or age variations among elliptical galaxies at any given luminosity. Since $M/L_K$ is a function of age but not metallicity, and Mg$_2$ is primarily a function of metallicity but not age (Mould 1978), the residuals of the $K$-band FP and the Mg$_2$–$\sigma_0$ relation should provide a clean separation of age and metallicity effects on the scatter of the relations. These are plotted in Figure 5, and show no clear trend with either age or metallicity. The origin of the scatter of the FP is not so simply described: it probably has an origin in both age and metallicity, and possibly also in another effect (like dissipationless merging).

7. A Comprehensive Model for the Early-Type Galaxy Sequence

The deviation of the $K$-band FP from the virial expectation (Figure 1) implies that metallicity variations alone are insufficient to explain the origins of the FP;
age and/or a wavelength-independent effect (homology breaking or systematic variations in dark matter content) are also required. The variation of the slope of the FP with wavelength (Figure 2) implies that homology breaking or dark matter variations alone are insufficient to explain the origins of the FP—stellar populations are also required. The lack of a correlation among the residuals of the $K$-band FP and the $\text{Mg}_2-\sigma_0$ relation (Figure 5) implies that the scatter of the FP cannot be attributed to age or metallicity effects alone. A complete understanding of the physical origins of the FP will therefore require a detailed model: it must also simultaneously account for all of the elliptical galaxy correlations at all redshifts.

Such a model has been constructed by Pahre et al. (1998b), which provides four model parameters: (1) variation in age from one end of the elliptical galaxy sequence to the other; (2) variation in metallicity along the entire galaxy sequence; (3) a mean value for stellar populations gradients; and (4) a wavelength-independent effect such as non-homology. Simple stellar populations models (Bruzual & Charlot 1996, in preparation, as appeared in Leitherer et al. 1996; Vazdekis et al. 1996) are used to convert between observed and physical quantities. This is a decidedly empirical model that is meant to describe the global properties of elliptical galaxies in a complete manner, but not explain the origins of these effects in the galaxy formation process.

This model has a range of observational measurements that can be used as equations of constraint: (1) the slope of the $K$-band FP; (2) the variations in the slope of the FP with wavelength; (3) the slope of the $\text{Mg}_2-\sigma_0$ relation; (4) a mean value for color gradients in ellipticals; and (5) a measurement of the aperture effect on velocity dispersion. The effects of the stellar populations gradients on the observed parameters is fully accounted for in the model.

This analysis demonstrates that both age and metallicity are varying along the elliptical galaxy sequence, with the relative contributions of the two depending on the simple stellar populations model used—up to a factor of two in age and a factor of three in metallicity. The variations are in the sense that the most luminous galaxies are the oldest and the most metal-rich; the latter effect appears to contradict the conclusions of Trager (1997; see, however, the discussion in Pahre 1998a).

The result that age contributes to the slope of the FP suggests that the slope of the FP should evolve with redshift, since the lowest luminosity galaxies are the youngest and hence will evolve fastest with redshift. This prediction, based solely on the properties of the nearby galaxies, is plotted in Figure 4 against the observed evolution of the slope of the FP with redshift.

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