Evolution of Early-Type Galaxies in Distant Clusters: The Fundamental Plane using HST Imaging and Keck Spectroscopy\textsuperscript{1,2}

Daniel D. Kelson

\textit{University of California Observatories / Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064}

Pieter G. van Dokkum, Marijn Franx

\textit{Kapteyn Astronomical Institute, P.O. Box 800, NL-9700 AV, Groningen, The Netherlands}

Garth D. Illingworth

\textit{University of California Observatories / Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064}

\textit{and}

Daniel Fabricant

\textit{Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02318}

\textbf{ABSTRACT}

We present new results on the Fundamental Plane of galaxies in two rich clusters, Cl1358+62 at \(z = 0.33\) and MS2053–04 at \(z = 0.58\), based on Keck and HST observations. Our new data triple the sample of galaxies with measured Fundamental Plane parameters at intermediate redshift. The early-type galaxies in these clusters define very clear Fundamental Plane relations, confirming an earlier result for Cl0024+16 at \(z = 0.39\). This large sample allows us to estimate the scatter reliably. We find it to be low, at 0.067 dex in \(\log r_e\), or 17\% in \(r_e\), similar to that observed in comparable low redshift clusters. This suggests that the structure of the older galaxies has changed little since \(z = 0.58\).

The \(M/L_V\) ratios of early-type galaxies clearly evolve with redshift; the evolution is consistent with \(\Delta \log M/L_V \sim -0.3z\). The \(M/L_V\) ratios of two E+A galaxies in Cl1358+62 are also lower by a factor of \(\sim 3\), consistent with the hypothesis that they underwent a starburst 1 Gyr previously. We conclude that the Fundamental Plane can therefore be used as a sensitive diagnostic of the evolutionary history of galaxies. Our data, when compared to the predictions of simple stellar population models, imply

\textsuperscript{1}Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

\textsuperscript{2}Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5–26555.
that the oldest cluster galaxies formed at high redshift \((z > 2)\). We infer a different evolutionary history for the E+A galaxies, in which a large fraction of stars formed at \(z < 1\). Larger samples spanning a larger redshift range are needed to determine the influence of starbursts on the general cluster population.

*Subject headings:* galaxies: clusters: general, galaxies: clusters: individual (Cl1358+62, MS2053–04), galaxies: evolution, galaxies: fundamental parameters, galaxies: kinematics and dynamics
1. Introduction

Evidence for evolution in galaxies at intermediate redshifts has been found in a number of pioneering studies, both in clusters (e.g., Butcher & Oemler 1978, 1984; Dressler & Gunn 1983, Couch & Sharpey 1987) and in the field (e.g., Kron 1980, Broadhurst, Ellis & Shanks 1988). Large spectroscopic surveys with 4 m class telescopes, coupled with HST images, have begun to clarify the nature of this evolution. The CFRS redshift survey of $\sim 10^5$ field galaxies (Le Fêvre et al. 1995; Lilly et al. 1995) is one such example. Here we pursue a complementary approach involving the detailed structural and kinematic study of smaller samples of individual galaxies using HST images and higher resolution spectroscopy with the Keck telescope. With these data, we can exploit the power of the Tully-Fisher relation for spirals (e.g., Vogt et al. 1996) and the Fundamental Plane relation for early-type (E/S0) galaxies (see Franx 1993).

The Fundamental Plane (Djorgovski & Davis 1987; Dressler et al. 1987) is particularly valuable due to its low intrinsic scatter (Jørgensen, Franx and Kjærgaard 1993). For the Coma cluster, the Fundamental Plane relation,

$$r_e \propto \sigma^{1.24} I_e^{-0.82},$$

(1)

where $r_e$ is the effective radius, $I_e$ is the surface brightness at that effective radius in the visible, and $\sigma$ is the central velocity dispersion, has a scatter of only 17% rms (Jørgensen, Franx and Kjærgaard 1996 [JFK96]). This low scatter implies that the following well-defined relation exists for early-type galaxies (Faber et al. 1987):

$$M/L_V \propto r_e^{0.22} \sigma^{0.49} M^{0.24} r_e^{-0.02}.$$  

(2)

Thus, the Fundamental Plane is valuable because it explicitly incorporates galaxy masses. Franx (1995) and van Dokkum and Franx (1996 [vDF]) have demonstrated the value of this relation for studying evolution in early-type galaxies at intermediate redshift. The latter authors showed that the Fundamental Plane in the rich cluster Cl0024+16 is well defined, and consistent with simple evolutionary models, but the observed sample was very small.

Here we present new results for two additional clusters at intermediate redshifts. These new data triple the galaxy sample, and extend the observed redshift range to $z = 0.58$.

2. Observations and Data Reduction

The spectroscopic sample was selected on the basis of $R$-band magnitude. Blue galaxies were rejected to avoid field contamination, though the color restriction was chosen such that star-forming and post-starburst cluster members were not excluded.

Slit masks were designed to include as many bright galaxies as possible, though we only present data here for galaxies with HST imaging (see Figure [Plate 1]). In addition, two known “E+A” (Dressler & Gunn 1983) galaxies were added to the Cl1358 mask. These galaxies are not included in the general sample, but are discussed separately. Thus, ten galaxies in Cl1358, and five in MS2053, are analyzed in this paper.

2.1. Spectroscopy

The spectroscopic observations were made using multi-slit masks with the Low Resolution Imaging Spectrograph (LRIS) at the Keck telescope. We observed at a typical resolution of $\sigma_{inst} = 60-85$ km s$^{-1}$. The data reduction was very similar to the data reduction of vDF for Cl0024. The resulting spectra were very high S/N (typically 20-60 per resolution element). We show spectra of two galaxies in Figure [c,d].

We modeled the spectral resolution of the spectrograph in great detail, for the template stars as well as the galaxies. This is necessary to ensure that the template stars used for the determination of the velocity dispersions have the correct spectral resolution. This procedure is the most essential technical aspect of measuring velocity dispersions of galaxies at intermediate redshift.

Some galaxies showed peculiar features in their spectra. These features, either strong Balmer absorption lines, emission lines, residual sky lines, or atmospheric absorption bands, were given zero weight in the template fitting. We corrected the central velocity dispersions to an aperture of 3" at the distance of Coma, using the procedure of Jørgensen, Franx, & Kjærgaard (1995b). The corrections are small, 1.065 for Cl1358+62 and 1.066 for MS2053-04 ($q_0 = 0.05$). The resulting velocity dispersions and random errors are listed in Table 1.
2.2. Imaging

We used WFPC2 HST images to measure the structural parameters. Observations were taken in the filters F606W and F814W for Cl1358+62, and in F702W and F814W for MS2053–04. These data were processed in the usual way for cosmic rays and removal of the sky background. The field for Cl1358+62 was very large, \( \sim 8' \times 8' \) (Franx et al. 1997). For MS2053–04, only 1 central pointing was available. As a result we have more Fundamental Plane measurements for Cl1358+62.

We determined the photometric parameters in two different ways, following the procedures used by vDF. We first used Point-Spread Function images to fit convolved \( r^{1/4} \)-law profiles to the galaxy images. In addition, we deconvolved the images with the CLEAN procedure (Högbom 1974), and derived growth curves for the galaxies. The results from both methods were compared to estimate the errors. It is worth noting that the median differences in \( r_e \) and \( \mu_e \) were \( +7.4\% \) and \( -9.7\% \), but the combined parameter \( r_e I_e^{0.82} \) only differed by \( -1.2\% \) for Cl1358+62 and \( -1.4\% \) for MS2053–04. This is the combination of parameters that enters the Fundamental Plane, and as a result, our subsequent analysis is insensitive to the individual errors in \( r_e \) and \( I_e \). Because the Coma data were derived from growth curves, we proceeded to use the growth curve results in the following analysis. After calibration using Holtzman et al. (1995), the photometry was transformed to the redshifted \( V \)-band, for direct comparison to the Coma photometry. This is possible, because we have observations in multiple passbands close to the redshifted \( V \)-band. Colors were measured within an aperture of \( r < 3r_e \), and Galactic extinctions were derived from Burstein and Heiles (1982) and Cardelli, Clayton & Mathis (1989).

2.3. Errors

Errors have been determined directly from the spectroscopic, structural and photometric fits, as well as the photometric transformations. The random errors are listed in Table 1, and the typical random error bars are shown in Figure 3 (as thin error bars). We have considered possible sources of systematic errors and we have estimated their contribution (shown as thick error bars in Figure 3). We have several sources of systematic errors: (i) photometric transformations at \( \pm 0.05 \) mag, which is dominated by the uncertainties in the absolute zeropoint of the F814W passband; (ii) velocity dispersions, where our procedures may have relative errors of \( \pm 3\% \) with respect to similar measurements at low redshift (the absolute velocity dispersions may be in error systematically by up to \( \pm 5-7\% \)); (iii) structural parameters \( (r_e, \mu_e) \), where deviations from an \( r^{1/4} \)-law model could cause systematic errors on the level of \( \pm 1\% \) in the combined parameter \( r_e \mu_e^{0.82} \).

Another source of uncertainty is due to departures from homology (see, e.g., Capelato et al. 1995, Ciotti et al. 1996). Non-homology can affect our measurement of evolution through the aperture correction for the velocity dispersions. Jorgensen et al. (1995b) determined the aperture corrections empirically, by using long slit data on nearby galaxies. They found no strong effect out to an effective radius. Therefore, these aperture corrections are likely to be appropriate for most of our galaxies. However, for the smallest galaxies, this correction is more uncertain and may require future observations of velocity dispersion profiles to large radii in a broad sample of nearby galaxies (e.g., Corollo et al. 1995).

3. The Fundamental Plane in Cl1358+62 and MS2053–04

The Fundamental Plane for the clusters are shown in Figure 5 along with the FPs for Cl0024+16 (vDF) and Coma (JFK96). We use the coefficients for the FP determined by JFK96 from a large sample of 225 early-type galaxies in ten nearby clusters. The figure shows clearly that a well defined Fundamental Plane exists, despite the fact that the galaxies in the intermediate redshift clusters were chosen without morphological information. Furthermore, the sample is large enough to derive the scatter about the Coma Fundamental Plane. We find surprisingly low \( rms \) scatters in \( \log r_e \) of \( \pm 0.064 \), \( \pm 0.065 \), \( \pm 0.060 \), and \( \pm 0.072 \) for Coma, Cl1358+62, Cl0024+16, and MS2053–04, respectively. The galaxies also show a large offset from the Coma relation, due mainly to cosmological surface brightness dimming.

One interesting question is whether the coefficients of the FP are the same in higher redshift clusters, \( i.e. \), are the luminous and less luminous galaxies evolving at the same rate? However, the current sample is too small to provide a definitive answer. The weak
indication that the slope is flatter when the distant galaxies are taken together needs to be verified with larger samples before any conclusions should be made (see also vDF).

We determined the mean $M/L_V$ ratio for each cluster directly from the Fundamental Plane zero-point, adopting the slopes of the Fundamental Plane of JFK96 and $q_0 = 0.05$. The resulting evolution of $M/L_V$ ratio is shown in Figure 3. The errors are taken from §2.3 and have been added in quadrature. Weighting the individual galaxies by their random errors does not change the results significantly.

Clearly, the $M/L_V$ ratio is lower at higher redshift, consistent with evolution of the stellar populations. We have drawn simple, single-burst model predictions in the same plot, adopting formation redshifts $z_{\text{form}}$ of infinity, and $z_{\text{form}} = 1$. The current data are not consistent with the predictions for co-evolution populations which have formed recently. More data are needed to test whether more complex models with recent star formation can be accommodated (see, e.g., Franx and van Dokkum 1996 and Poggianti & Barbaro 1996).

4. Discussion

We have measured structural parameters and central velocity dispersions for galaxies in two clusters at intermediate redshift, Cl1358+62 at $z = 0.33$ and MS2053–04 at $z = 0.58$. The Fundamental Plane relations in the intermediate redshift clusters are very similar to that found in Coma. This observation demonstrates that mature early-type galaxies existed in these clusters at $z \approx 0.6$; their primary epochs of star formation must have occurred at much higher redshifts.

The sample is also large enough to measure the scatter in the Fundamental Plane relation reliably. We find it to be low: ±0.067 in $\log r_e$, or ±17% in $M/L_V$. This suggests that the populations are very homogeneous, and that the age differences between the galaxies are not very large (Ciotti, Lanzoni, & Renzini 1996).

The mean $M/L_V$ ratio of the galaxies was clearly lower several Gyr ago, consistent with passively evolving stellar populations. This evolution depends on the formation redshift(s) of the population, the IMF(s), and cosmological model (e.g., Franx 1995). We show model predictions for formation redshifts of $z = 1$ and $z = \infty$ in Figure 3 (Tinsley & Gunn 1976) using $q_0 = 0.05$. The new data are fully consistent with a high formation redshift, $z_{\text{form}} > 2$, strengthening the conclusion of vDF. This result is a lower limit; the constraints are even stronger if $q_0 = 0.5$.

This interpretation, however, is complicated by the fact that mergers, interactions, starbursts, and other processes may continue to transform late-type galaxies into early-type galaxies: the early-type galaxies we observe at high redshift may only be a subset of the early-type galaxies we observe at low redshift. In this case, the early-type galaxies observed at high redshift (if they remained undisturbed until the present) should be compared to the oldest early-type galaxies locally. In some sense, these high redshift early-type galaxies have been compared to a mean low redshift counterpart, probably not as old as the comparison requires. Thus, the formation redshift estimated from the $M/L$ evolution can be biased upwards (see, e.g., Franx and van Dokkum 1996).

We included two Cl1358+62 “E+A” galaxies in our sample to test whether these galaxies are progenitors of early-type galaxies in low redshift clusters. They are shown in Figure 2 by the “x” symbols. We can use the Coma Fundamental Plane to measure the $M/L_V$ ratios of these “E+A” galaxies, assuming that their structural properties are similar to nearby early-type systems. This assumption may not necessarily be correct, as the Franx (1993) analysis of an E+A in Abell 665 ($z = 0.18$) shows that it is essentially bulgeless; it is not clear whether it will become an S0 or remain a spiral system.

With this caveat in mind, we show the mean $M/L_V$ offset for the two E+A galaxies in Figure 3 as an “x.” This $M/L_V$ is consistent with a “formation” redshift of $z_f \approx 0.5$, a $V$-band luminosity weighted mean of the formation redshifts of the subcomponents. This is consistent with the hypothesis that the E+As have undergone a burst of star formation 1-2 Gyr before they have been observed (Dressler and Gunn 1983). We conclude that a fraction of nearby cluster early-type galaxies has undergone secondary bursts of star formation at $z < 1$.

At this point, more work is needed to assess the relevance of the E+A galaxies to the evolution of early-type galaxies and we will study the E+As in these clusters in greater detail elsewhere. Observations of

4 These galaxies have spectra which can be interpreted as a superposition of an old population (the “E” for early type), and a young population with the spectrum of an A star (Dressler and Gunn 1983).
higher redshift clusters will be needed to test whether star formation and starbursts were even more prevalent at earlier times, as suggested by Lubin (1996) and Rakos & Schombert (1995). Our sample can also be compared to surveys of nearby field galaxies, in which the data of González (1993) and Faber et al. (1995) suggest that a large age spread (\(\sim 2-18\) Gyr) exists. Thus, a large fraction of these experienced bursts of star formation at \(z < 1\). Our data suggest that it might be hard, but not impossible, to model the evolutionary history of the cluster galaxies in the same way as the field galaxies.

We appreciate the effort of all those in the HST program that made this unique Observatory work as well as it does. The assistance of those at STScI who helped with the acquisition of the HST data is gratefully acknowledged. We also appreciate the effort of those at the Keck, MMT and KPNO telescopes who developed and supported the facility and the instruments that made this program possible. Support from STScI grants GO05989.01-94A, GO05991.01-94A, and AR05798.01-94A is gratefully acknowledged.
REFERENCES

Broadhurst T. J., Ellis R. S., & Shanks T. 1988, MNRAS, 235, 827

Burstein D., & Heiles C. 1982, AJ, 87, 1165

Butcher H., & Oemler A. 1978, ApJ, 219, 18

Butcher H., & Oemler A. 1984, ApJ, 285, 426

Capelato, H. V., de Carvalho, R. R., & Carlberg, R. G. 1995, ApJ, 451, 525

Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245

Butcher H., & Oemler A. 1984, ApJ, 285, 426

Corollo, C. M., de Zeeuw, P. T., van der Marel, R. P., Danziger, I. J., & Qian, E. E. 1995, ApJ, 441, L25

Couch W. J., & Sharples R. M. 1987, MNRAS, 229, 423

Djorgovski S., & Davis M. 1987, ApJ, 313, 59

Dressler A., & Gunn J. E. 1983, ApJ, 270, 7

Dressler A., Lynden-Bell D., Burstein D., Davies R. L., Faber S. M., Terlevich R. J., & Wegner G. 1987, ApJ, 313, 42

Ellis R. S., Smail, I., Dressler, A., Couch, W.J., Oemler, A., Butcher, H., & Sharples, R.M. 1996, preprint

Faber S. M., Dressler A., Davies R. L., Burstein D., Lynden-Bell D., Terlevich R., & Wegner G. 1987, Faber S. M., ed., Nearly Normal Galaxies. Springer, New York, p. 175

Faber, S. M., Trager, S. C., González J. J., & Worthey, G. 1995, IAU Symp. 164, Stellar Populations (Dordrecht: Kluwer), 255

Franx M. 1993, PASP, 105, 1058

Franx M. 1995 IAU Symp. 164, Stellar Populations (Dordrecht: Kluwer), 269

Franx M., & van Dokkum, P. G. 1996, New Light on Galaxy Evolution, eds. Bender, R., & Davies, R. L., in press.

Franx M., et al. 1997, in preparation

González, J. J. 1993, Ph.D. Thesis, Univ. California, Santa Cruz

Högberg J. A. 1974, A&AS, 15, 417

Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065

Jørgensen I., Franx M., & Kjærgaard P. 1993, ApJ, 411, 34

Jørgensen I., Franx M., & Kjærgaard P. 1995a, MNRAS, 273, 1097

Jørgensen I., Franx M., & Kjærgaard P. 1995b, MNRAS, 276, 1341

Jørgensen I., Franx M., & Kjærgaard P. 1996, MNRAS, 280, 167 [JFK96]

Kron, R. 1980, ApJS, 43, 305

Le Fèvre, O., et al. 1995, ApJ, 461, 534

Lilly S. J., Tresse L., Hammer F., Crampton D., & Le Fèvre O. 1995, ApJ, 455, 50

Lubin, L. 1996, AJ, accepted for publication

Poggianti, B. M., & Barbaro, G. 1996, A&A, in press

Rakos, K. D., & Schombert, J. M. 1995, ApJ, 439, 47

Tinsley, B. M., & Gunn, J. E. 1976, ApJ, 203, 52

van Dokkum, P. G., & Franx M. 1996, MNRAS, 281, 985 [vDF]

Vogt, N. P., Forbes, D. A., Phillips, A. C., Gronwall, C., Faber, S. M., Illingworth, G. D., & Koo, D. C. 1996, ApJ, 465, L15

This 2-column preprint was prepared with the AAS LATEX macros v4.0.
Figure Captions

Fig. 1.— [Plate 1] (a) Montage of color images for the sample galaxies in Cl1358+62, using F606W and F814W; and in (b) MS2053–04 using F702W and F814W; (c) Spectrum of galaxy #256 in Cl1358+62; and (d) #197 in MS2053–04.

Fig. 2.— The FP for the four clusters with the mean FP for Coma (JFK96) plotted on each panel. Note that the two E+As in Cl1358+62, shown as “x”s, lie to the left of the mean relation of the “old” Cl1358+62 early-type galaxies. The previous results of JFK96 and vDF are shown as open circles. The new data are shown as filled circles. Typical random (thin) and systematic (thick) errors are shown.

Fig. 3.— The mean $M/L_V$ offsets with redshift, for $q_0 = 0.05$. The area enclosed by solid lines corresponds to single burst models with $z_f = \infty$ and a range of IMFs. The region marked by dash lines corresponds to the equivalent $z_f = 1$ models. The previous results of JFK96 and vDF are shown as open circles. The new data are shown as filled circles. The “x” marks the $M/L_V$ offset derived from the two E+A galaxies in Cl1358+62. The errors were estimated by adding the random and systematic errors in quadrature.
Table 1
FUNDAMENTAL PLANE PARAMETERS

| ID | $I$ (mag) | $R - I$ (mag) | $\sigma$ (km s$^{-1}$) | $r_e$ (arcsec) | $\mu_{e,V}$ (mag arcsec$^{-2}$) |
|----|-----------|---------------|-------------------------|---------------|-------------------------------|
| 200 | 18.70     | 0.68          | 135 $\pm$ 11           | 0.913         | 22.50                         |
| 236 | 17.98     | 0.80          | 166 $\pm$ 11           | 0.541         | 21.93                         |
| 256 | 17.56     | 0.78          | 273 $\pm$ 7            | 1.024         | 21.81                         |
| 269 | 17.85     | 0.82          | 342 $\pm$ 10           | 0.826         | 21.55                         |
| 298 | 18.25     | 0.82          | 280 $\pm$ 8            | 0.448         | 20.77                         |
| 328 | 19.08     | 0.60          | 98 $\pm$ 7             | 0.712         | 22.24                         |
| 375 | 17.44     | 0.81          | 301 $\pm$ 11           | 3.910         | 23.83                         |
| 408 | 19.04     | 0.77          | 265 $\pm$ 17           | 0.287         | 20.74                         |
| 454 | 18.71     | 0.73          | 171 $\pm$ 6            | 0.780         | 22.23                         |
| 470 | 18.41     | 0.79          | 185 $\pm$ 6            | 0.738         | 22.23                         |
| 311 | 20.52     | 1.12          | 223 $\pm$ 25           | 0.402         | 22.53                         |
| 197 | 18.59     | 1.20          | 319 $\pm$ 18           | 2.182         | 23.99                         |
| 422 | 20.59     | 1.20          | 158 $\pm$ 22           | 0.413         | 22.57                         |
| 551 | 20.89     | 1.14          | 217 $\pm$ 19           | 0.157         | 20.93                         |
| 432 | 20.41     | 1.08          | 161 $\pm$ 20           | 0.483         | 22.82                         |

Note.— (1) Galaxy identification; (2) Integrated $I$ magnitude ($\pm 0.1$ mag); (3) $R - I$ color within a $3r_e$ aperture ($\pm 0.05$ mag); (4) Velocity dispersion with formal (random) errors; (5) Effective radius $r_e$ from clean/growth curve fit of $r^{1/4}$-law to HST images; (6) Surface brightness in rest frame $V$-band from that fit at $r_e$
1.24 \log \sigma - 0.82 \log \mu_e
This figure "figure1.jpg" is available in "jpg" format from:

http://arxiv.org/ps/astro-ph/9701115v2