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THE FUNDAMENTAL PLANE IN RX J0142.0+2131: A GALAXY CLUSTER MERGER AT $z = 0.28$

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ABSTRACT

We present the fundamental plane (FP) in the $z = 0.28$ cluster of galaxies RX J0142.0+2131. There is no evidence for a difference in the slope of the FP when compared with the Coma Cluster, although the internal scatter is larger. On average, stellar populations in RX J0142.0+2131 have rest-frame *V*-band mass-to-light ratios (M/L_V) 0.29 ± 0.03 dex lower than in Coma. This is significantly lower than expected for a passively evolving cluster formed at $z_f = 2$. Lenticular galaxies have lower average M/L_V and a distribution of M/L_V with larger scatter than ellipticals. Lower mass-to-light ratios are not due to recent star formation: our previous spectroscopic observations of RX J0142.0+2131 E/S0 galaxies showed no evidence for significant star formation within the past ~4 Gyr. However, cluster members have enhanced α-element abundance ratios, which may act to decrease M/L_V. The increased scatter in the RX J0142.0+2131 FP reflects a large scatter in M/L_V implying that galaxies have undergone bursts of star formation over a range of epochs. The seven easternmost cluster galaxies, including the second brightest member, have M/L_V consistent with passive evolution and $z_f = 2$. We speculate that RX J0142.0+2131 is a cluster-cluster merger where the galaxies to the east are yet to fall into the main cluster body or have not experienced star formation as a result of the merger.

Subject headings: galaxies: clusters: individual (RX J0142.0+2131) — galaxies: evolution — galaxies: stellar content

1. INTRODUCTION

The fundamental plane (FP) of elliptical (E) and lenticular (S0) galaxies is a log-linear relation between effective radius, surface brightness, and velocity dispersion (e.g., Djorgovski & Davis 1987; Dressler et al. 1987; Jørgensen et al. 1996, hereafter JFK96). Its ubiquity in nearby clusters of galaxies has been noted by many investigators (e.g., Bender et al. 1992; JFK96; Colless et al. 2001). Coefficients in the observed FP differ from those predicted by the virial theorem, and this "tilt" implies that mass-to-light ratio (M/L) is not a constant for E/S0 galaxies but depends to some extent on galaxy properties (see Cappellari et al. 2006). The FP must confront studies showing that the growth of galaxies in clusters involves complex processes like galaxy mergers, cluster mergers, and active galactic nucleus activity (e.g., Fabian et al. 2000; Tran et al. 2005).

If E/S0 galaxies form in a short burst and their stellar populations subsequently evolve passively, one would expect a gradual decrease in M/L with cosmic epoch. This induces an offset in the FP as a function of redshift, with no change in slope. However, the tendency of star formation to occur over a longer period in lower mass galaxies (e.g., Juneau et al. 2005; Treu et al. 2005) would be manifest as a steepening of the empirical FP with redshift. Evidence for changes in the slope of the FP are seen in the latest studies of the FP at $z > 0.8$ (e.g., Holden et al. 2005; Jørgensen et al. 2006), but this has not been observed at $0.2 < z < 0.8$ (e.g., van Dokkum & Franx 1996; Kelson et al. 2000; Wuyts et al. 2004), most likely because these studies do not probe far enough down the mass function. The internal scatter of the FP reported at $0.2 < z < 0.8$ is consistent with that of the Coma Cluster (JFK96). Since scatter in the FP is a reflection of the variation in M/L, this is taken as evidence that cluster E/S0 galaxies at a given mass are coeval.

In this Letter we examine the FP in RX J0142.0+2131, a cluster of galaxies at $z = 0.28$ for differences in slope and internal scatter with respect to that of Coma. We use $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, and we convert previous work to these values where necessary. The look-back time to RX J0142.0+2131 in this cosmology is 3.2 Gyr.

2. RX J0142.0+2131: PREVIOUS OBSERVATIONS

We presented high signal-to-noise ratio GMOS-N (Gemini Multi-Object Spectrograph at Gemini North) spectroscopy of 43 spectroscopic targets in the field of RX J0142.0+2131 in Barr et al. (2005, hereafter BDJBC05). Velocity dispersions and line indices for 30 cluster members were derived. We determined that scaling relations between metal indices and velocity dispersion, and the strengths of the 4000 Å break, are inconsistent with a scenario in which stellar populations form at $z_f \gtrsim 2$ and evolve passively to look like cluster galaxies at low redshift (i.e., without additional star formation and/or merging). Stellar populations in RX J0142.0+2131 have α-element abundance ratios ([α/Fe]) that are enhanced by, on average, 0.14 ± 0.03 over Coma galaxies. Luminosity-weighted mean ages for galaxies in RX J0142.0+2131 are similar to those in Coma, i.e., older than would be expected at $z = 0.28$. The cluster velocity dispersion is much larger than its X-ray luminosity or richness suggest. Despite this, no sign of substructure was found by testing the distribution of spectroscopically confirmed cluster members in (R.A., decl., z)-space.

3. DATA REDUCTION AND ANALYSIS

The data reduction and analysis method for the GMOS-N spectroscopy was presented in BDJBC05. In this Letter we restrict the surface photometry calculations to spectroscopically confirmed cluster members. We will present effective radii, mean surface brightnesses, and morphological classifications for a larger sample at a later date.

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RX J0142.0+2131 was observed with the *Hubble Space Telescope* Advanced Camera for Surveys (ACS) on UT 2003 November 1 and 2004 July 3. Two positions were imaged in the F775W band for 4420 s each. Reductions are performed with the PyRAF task MULTIDRIZZLE using the standard procedure. ACS surface photometry is analyzed using the two-dimensional fitting program GALFIT (Peng et al. 2002). We fit galaxies' luminosity profiles as $r^{1/4}$ profiles. Background or companion galaxies may influence the derived parameters, so these are fit simultaneously as Sérsic profiles (Sérsic 1968). We also classify galaxies by Hubble type using a method analogous to that of Smail et al. (1997). Magnitudes and surface brightnesses are corrected to rest-frame V using F775W magnitudes and GMOS colors in a similar way as that used in BDJBC05. A complete description of our data, reduction techniques, and analysis of potential systematics, as well as our method of deriving surface-brightness parameters from the GALFIT fitting program, will be presented in a future paper (K. Chiboucas et al. 2006, in preparation). Twenty-eight spectroscopically confirmed cluster members were covered by the two ACS fields. Of these, 11 are E, 12 are S0, and the remaining five are spirals, irregulars, mergers, or not classifiable.

We estimate the systematic and random errors in the values returned by GALFIT using Monte Carlo simulations. Artificial galaxies are generated with GALFIT and with the IRAF routine ARTDATA/MKOBJECTS. These objects cover the full range of parameter space in magnitude, r_e, axis ratio, and position angle of RX J0142.0+2131 sample. The Sérsic index is varied randomly between 2.5 and 5, and we adjust the diskiness/boxiness of each artificial galaxy. Noise is then added to the artificial galaxies that are placed randomly in the ACS images and recovered as $r^{1/4}$ profiles.

The results of the simulations indicate that $\log r_e$ derived for the $r^{1/4}$ profile is systematically greater than the simulated value by 0.06 dex. The quantity, $\log r_e + \beta \log \langle I \rangle_e$, which enters the FP and hereafter referred to as the fundamental plane parameter (FPP), is known to be much less sensitive to the imposition of the $r^{1/4}$-law fit (e.g., Lucey 1997). The derived FPP is systematically offset from its simulated value by -0.02, with a standard deviation of 0.03. The magnitude of the deviation is not a function of the FPP. We do not make corrections to the surface photometry but quantify the total uncertainty on the FPP as 0.05.

4. THE COMPARISON SAMPLE

Our comparison sample consists of 116 E/S0 galaxies in the Coma Cluster; velocity dispersions are from Jørgensen (1999). We use Gunn r surface photometry of E/S0 galaxies fit using an $r^{1/4}$ law from Jørgensen et al. (1995), as well as new B and R_c photometry obtained with the McDonald Observatory 0.8 m telescope. We transform from Gunn r to the rest-frame V using $r - R_c = 0.354$ (Jørgensen 1994), $V = R_c + 0.337(B - R_c) + 0.089$ derived for E/S0 galaxies using the Bruzual & Charlot (2003) models, a median Coma red-sequence color of $B - R_c = 1.485$, and $V_{\rm rest} = V - Q_V - 10 \log (1 + z)$, where the k-correction, $Q_V = 0.043$, is derived from the Bruzual & Charlot (2003) models. The surface brightness parameter in the V-band FP is $\log \langle I \rangle_e = -0.4(\langle \mu \rangle_e - 26.43)$.

We recalculate the FP for the Coma Cluster by minimizing the absolute residuals in $\log r_e$, $\log \sigma$, and $\log \langle I \rangle_e$ perpendicular to the plane, following JFK96. Three emission-line galaxies are excluded from the fit. We find

$$\log r_e = (1.29 \pm 0.07) \log \sigma - (0.83 \pm 0.03) \log \langle I \rangle_e - 0.28,$$

with an rms of 0.08 in $\log r_e$.

5. THE FUNDAMENTAL PLANE IN RX J0142.0+2131

We fit the FP to E/S0 galaxies in RX J0142.0+2131 in the same way as for the Coma Cluster. Emission-line galaxies identified in BDJBC05 are excluded. The FP is

$$\log r_e = (0.93 \pm 0.26) \log \sigma - (0.97 \pm 0.11) \log \langle I \rangle_e + 1.10,$$

with an rms of 0.10 in $\log r_e$.

Selection effects can be crucial when comparing two samples at varying epochs. As a test we recalculate the FP in Coma and RX J0142.0+2131 for the subsamples with $M_V < -19.7$ and $M > 10^{10.3}\ M_\odot$. There are no significant differences in the coefficients of $\log \sigma$ or $\log \langle I \rangle_e$, or rms between either the low- or high-redshift sample and its parent sample.

In order to assess the significance of any difference in slope between the Coma FP and that of RX J0142.0+2131, we make 500 random realizations of a high-z cluster. Twenty-three galaxies are taken from the Coma Cluster and scattered so that the rms in $\log r_e$ is equal to that in RX J0142.0+2131. We then fit the FP as described above. Values of the coefficients in the FP are consistent with Coma 89% of the time, and consistent with RX J0142.0+2131 55% of the time. We therefore conclude that there is no strong evidence for a difference in the slope of the FP for RX J0142.0+2131 when compared with Coma. The galaxies from RX J0142.0+2131 are plotted on the Coma Cluster FP in Figure 1.

Even with the imposition of the same mass cutoff at $M > 10^{10.3}\ M_\odot$, the internal scatter of the points from the FP remains higher for RX J0142.0+2131 than it is for Coma (it actually increases to 0.13 in $\log r_e$ for RX J0142.0+2131 as opposed to 0.08 in Coma). This phenomenon is not seen in previous studies of the FP in clusters at similar redshift (e.g., Kelson et al. 2000; Fritz et al. 2005). The scatter in the FP reflects the variation of M/L within stellar populations, and a high scatter could imply that there are two or more groups of galaxies with different mean values of M/L. In Figure 1 we separate galaxies according to E or S0 classification; the scatter for S0 galaxies is higher, 0.12 in $\log r_e$ compared with 0.10 for E galaxies. We also plot cluster members east of $01^{\rm h}42^{\rm m}06^{\rm s}$, including the second brightest member, as filled boxes; open boxes are galaxies in the main body of the cluster. The internal scatter is 0.05 and 0.12 in $\log r_e$ for the filled and open points, respectively.

Observables are converted to mass and M/L_V via $M = 5\sigma^2 r_e/G$ and $\log (M/L_V) = 2 \log \sigma - \log r_e - \log \langle I \rangle_e + \Gamma$, where $\Gamma = -0.73$ for σ in km s^{-1}, r_e in kpc, and $\langle I \rangle_e$ in $L_\odot$ pc^{-2}. Figure 2 shows $\log (M/L_V)$ versus $\log M$.

We determine the slope of the $\log (M/L_V)$ versus $\log M$ diagram for Coma and the complete RX J0142.0+2131 sample by minimizing absolute residuals perpendicular to the slope. The slopes are consistent, although the uncertainty for RX J0142.0+2131 is large. We therefore calculate the offset in M/L_V ratio for RX J0142.0+2131 by preserving the Coma slope and calculating the median offset of the RX J0142.0+2131

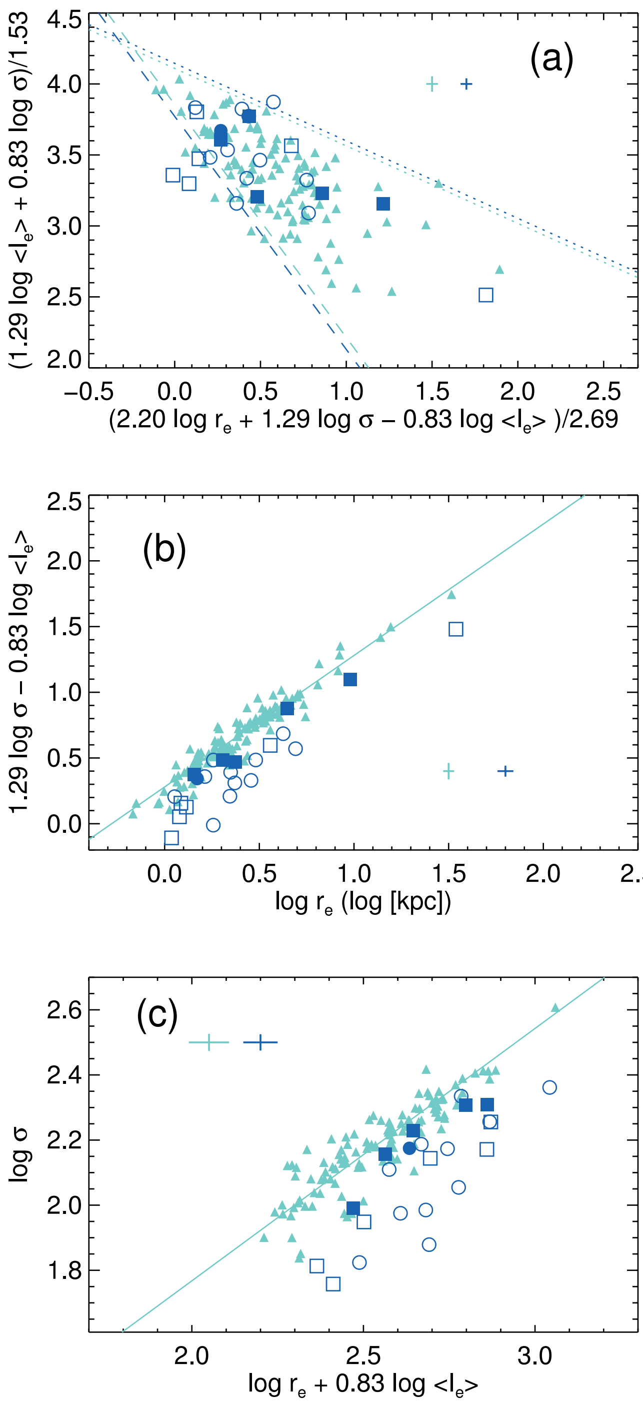

FIG. 1.—(*a*) FP for RX J0142.0+2131 and Coma seen face-on. Triangles are E/S0 galaxies in Coma, squares are E galaxies in RX J0142.0+2131, and circles are S0 galaxies in RX J0142.0+2131. Filled squares or circles are members of RX J0142.0+2131 east of $01^h42^m06^s$. Error bars show the median error for each sample. The dashed lines indicate the selection effect of the magnitude limits. Dotted lines denote the region not occupied by luminous ellipticals in Bender et al. (1992). (*b*) FP seen edge-on against the effective radius. (*c*) FP projected along one of its shortest edges. In panels *b* and *c*, the solid line is the best fit to the low-*z* sample minimizing absolute residuals (see text).

galaxies. This is -0.29 ± 0.03 dex in M/L_V for the whole sample. Lenticular galaxies have lower average M/L_V than ellipticals (0.06 dex), and their scatter in M/L_V is 0.18 dex as opposed to 0.14 dex. The offset predicted by the single-stellar population (SSP) models of Maraston (2005) with passive evolution and $z_{\rm form} = 2$ is -0.10, shown as the dot-dashed line

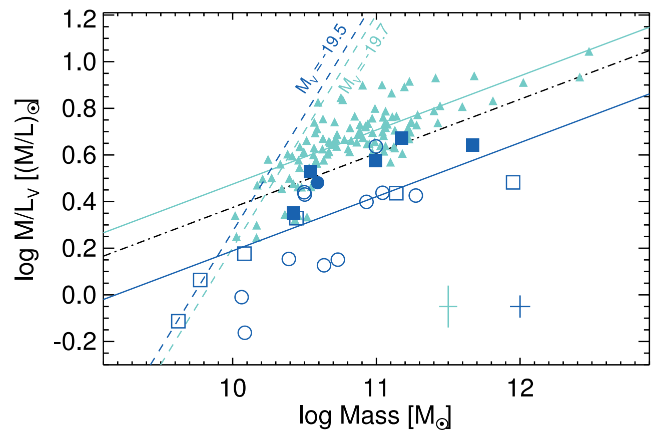

FIG. 2.—Mass-to-light ratios inferred for galaxies in RX J0142.0+2131 and Coma sample. Plotting symbols are the same as those in Fig. 1. Median error bars for each sample are shown. Dashed lines represent the completeness limits for each sample. The solid lines are the fits to the points (see text). The dot-dashed line shows the relation expected for galaxies formed at $z_f = 2$ and passively evolving to the Coma galaxies according to the models of Maraston (2005).

in Figure 2. If the differences in mass-to-light ratio are caused by different luminosity-weighted mean ages of stellar populations, then the Maraston models suggest that galaxies in RX J0142.0+2131 incurred a major star formation episode at $z = 0.85 \pm 0.1$, making them only ~4 Gyr old. This is highly unlikely given the spectroscopic evidence for old stellar populations presented in BDJBC05.

6. THE HISTORY OF E/S0 GALAXIES IN RX J0142.0+2131

The internal scatter of the RX J0142.0+2131 FP is larger than that of Coma. This suggests that galaxies in RX J0142.0+2131 have undergone bursts of star formation over a range in epochs. The fact that the S0 galaxies have lower M/L_V and larger scatter is consistent with results suggesting they form stars at lower redshift or are more recent additions to clusters (e.g., Treu et al. 2003; McIntosh et al. 2004).

The eastern galaxies have M/L_V consistent with passively evolving stellar populations formed at $z_{\rm form} \sim 2$, and their internal scatter is consistent with the Coma FP. They also have a lower fraction of S0 galaxies, one of six rather than 11 of 17. This can be explained if the western galaxies have undergone star formation at a more recent epoch than $z \sim 2$, while the eastern galaxies have yet to interact with the intracluster medium or have not undergone a burst of star formation during their incorporation into the cluster.

In BDJBC05 we found no evidence for recent star formation in any cluster of E/S0 galaxies and no spatial segregation of age-sensitive absorption-line diagnostics. Indeed, we found stellar populations with similar luminosity-weighted mean ages as those in the Coma Cluster. This is inconsistent with ages derived from our measured M/L_V via the Maraston models. A complication is introduced by [α/Fe], which we found to be enhanced by 0.14 ± 0.03 in RX J0142.0+2131 galaxies and could have a systematic effect on M/L_V. If this were the case, our data indicate that enhanced [α/Fe] decreases M/L_V. It has been suggested that an enhancement of α-elements will increase the blue luminosity of a stellar population (Salasnich et al. 2000; Thomas et al. 2003), and preliminary models from C. Maraston (2006, private communication) predict L_V is up to 20% higher for young galaxies with solar metallicity and [α/Fe] $= 0.3$. Qualitatively, the models and data therefore act in the same sense. We might expect

to see this effect as a correlation in residuals from the log (M/L_V)–log M and the [α/Fe]–log M relations. No correlation is seen in either Coma or RX J0142.0+2131 galaxies. However, the errors on [α/Fe] derived in BDJBC05 are relatively large ($\sim\frac{1}{5}$ of the dynamic range), and the effect of age, metallicity, and internal scatter on log (M/L_V) is not clear. A more thorough analysis using a larger data set will be required to decouple the effects of these quantities on the mass-to-light ratio.

We speculate that the systematically lower M/L_V in RX J0142.0+2131 is due to a cluster-cluster merger that must have occurred at $z > 0.85$. Rapid star formation episodes serve to increase [α/Fe] and so decrease M/L_V further. Individual galaxies interact with the cluster at different epochs, which introduces a large scatter in the FP. The imprint of such an interaction should still be clearly visible in the large-scale distribution of gas or galaxies. A more detailed picture can be painted with high-resolution X-ray imaging or multi-object spectroscopy of ∼100 s of galaxies in RX J0142.0+2131.

If it is challenging to explain the history of stellar populations in RX J0142.0+2131, then it is nearly impossible to imagine an evolutionary path from their position at $z = 0.28$ to the Coma Cluster. The [α/Fe] ratios can be decreased if there is a significant amount of merging between the bright E/S0 galaxies and galaxies that have formed their stars over longer periods. Such mergers would have to occur in the 3 Gyr available without any star formation to avoid decreasing the M/L_V further.

7. CONCLUSIONS

We have established the FP for E/S0 galaxies in RX J0142.0+2131. There is no evidence that the slope of this FP is different from that of the Coma Cluster. On average, M/L_V for galaxies in RX J0142.0+2131 is 0.28 ± 0.03 dex lower than that in the Coma Cluster.

The internal scatter of the FP in RX J0142.0+2131 is larger than that for Coma. This can also be visualized as a larger scatter in mass-to-light ratio for galaxies in RX J0142.0+2131. Lenticular galaxies have lower average M/L_V with a larger scatter than E galaxies. Spectroscopically confirmed members east of $01^h42^m06^s$, including the second brightest cluster galaxy, have M/L_V ratios consistent with passively evolving galaxies formed at $z_f \sim 2$ and an internal scatter consistent with the Coma FP.

The large scatter in the FP can be explained by spatially segregated galaxies with different average M/L_V, consistent with galaxies in RX J0142.0+2131 having undergone bursts of star formation over a range in epochs. This effect is not evident when looking at age-sensitive absorption line indices. However, galaxies in RX J0142.0+2131 have enhanced [α/Fe], which might serve to push any putative star formation episode to higher redshift. If this were the case, our data suggest that increased [α/Fe] acts to reduce M/L_V. Improved modeling of the effect of age and [α/Fe] on M/L_V is required before more accurate statements about star formation epochs can be made.

We speculate that the large scatter in galaxies' M/L_V is caused by a cluster-cluster merger. This scenario is consistent with the large cluster velocity dispersion and implies that gaseous or galactic substructure should be detectable with X-ray imaging or spectroscopy of hundreds of cluster galaxies.

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