The Evolution of Stellar Populations in Intermediate Redshift Clusters

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Abstract. The $M/L$ ratios and absorption line-strengths of distant cluster galaxies can be used to directly study their stellar populations, determine their redshift of formation, their scatter in ages, and any dependence of their ages on such internal properties such as velocity dispersion or mass. Comparing the zero-point the fundamental plane in the $z = 0.33$ cluster CL1358+62 to that in Coma, we conclude that the redshift of formation for the stars in massive cluster E/S0s was $z > 2$. The fundamental plane in CL1358+62 has the following form: 
$$r_e \propto \sigma^{1.31\pm0.13} \langle I \rangle_e^{-0.86\pm0.10}$$
indicating that the last epoch of star-formation has very little dependence on galaxy mass. The scatter in the CL1358+62 fundamental plane is also very low, equivalent to a scatter in ages of $\sim 15\%$. We have also analyzed the $M/L_V$ ratios of galaxies of type S0/a and later. These early-type spirals follow a different plane from the E and S0 galaxies, with a scatter that is twice as large as the scatter for the E/S0s. These residuals also correlate with the residuals from the color-magnitude relation. Preliminary analysis of the absorption line-strengths of the CL1358+62 early-types indicate that they are well-described by uniformly old, single-burst stellar populations with metallicity varying as a function of velocity dispersion.

1. Introduction

The fundamental plane (FP) is an empirical relation between galaxy half-light radius, $r_e$, surface brightness, $\langle I \rangle_e$, and central velocity dispersion, $\sigma$ for early-type galaxies. Locally,
$$r_e \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$$
in Gunn $r_g$ (Jørgensen et al. 1996). Under the assumption of homology, this implies $M/L_{r_g} \propto M^{1/4} r_e^{-0.02}$. The fundamental plane is very thin, with an $rms$
scatter of ±23% in Coma in $M/L_V$ ratio for a given galaxy mass, $M$ (Jørgensen et al. 1993). With its low scatter, the FP is a very powerful tool for measuring the evolution of galaxy $M/L$ ratios as a function of redshift, $M$, etc.

Because reasonable stellar populations evolve as $M/L_V \propto t^\kappa$ (Tinsley & Gunn 1976), evolution in the properties of the fundamental plane directly probe the star-formation histories of cluster galaxies. Measurements of the evolution of the FP zero-point, scatter, and slope can be used to constrain the mean epoch of star-formation, the spread in early-type galaxy ages; and the dependence of galaxy age on, e.g., $M$.

We exploit high resolution Keck spectroscopy for velocity dispersions and line strengths, and WFPC2 imaging for the structural parameters, colors, and morphologies. Details can be found in Kelson et al. (1999abc).

2. The Fundamental Plane of Early-Type Galaxies in CL1358+62

Figure 1. The left-hand panel shows the fundamental plane of E/S0s in CL1358+62. The early-type galaxies clearly form a tight relation. The intrinsic scatter is 14% in $r_e$. In the right-hand panel, the full sample of 53 galaxies is shown, including the early-type spirals.

The left-hand panel of Figure 1 shows the tight fundamental plane relation in the $z = 0.33$ cluster CL1358+62. The 30 E/S0s in this sample are fit by the following plane in Johnson $V$ (Kelson et al. 1999c):

$$
\log r_e \propto \sigma^{1.31 \pm 0.13} < I >^{-0.86 \pm 0.10}
$$

This sample has comparable depth to the FP samples of Coma, ensuring that the comparison of these FP exponents with those determined in nearby clusters is reasonably free from selection effects. We draw the following three conclusions:

- Mild evolution in the FP zero-point, of $\Delta M/L_V = -0.13 \pm 0.03$ ($q_0 = 0.1$), indicates a mean redshift of formation of $<z_f> \gtrsim 2$ for the stars in cluster E/S0s.

- The scatter in the color-magnitude relation and FP suggest a 1-$\sigma$ scatter in ages of 15%. For $q_0 = 0.05$ and $<z_f> = 2$, ±1-$\sigma$ is equivalent to $1.5 \leq z_f \leq 3.5$.

- No evolution in the FP slope is seen, indicating that the mean luminosity weighted ages of the stellar populations do not depend significantly on $\sigma$ or $M$:

$$
\log M/L|_{z=0.33} - \log M/L|_{z=0} \propto (0.01 \pm 0.23) \log \sigma - (0.16 \pm 0.16) \log r_e
$$
3. The Spiral Galaxies of CL1358+62

Our sample contains many galaxies of type S0/a through Sb. These early-type spirals are shown with the E/S0s in the right-hand panel of Figure 1. The spirals show large scatter about the FP and have systematically higher surface brightnesses for a given $\sigma$ and $r_e$. The scatter for the early-type spirals is twice as large as that for the E/S0s. For the spirals, the FP residuals correlate strongly with residual from the color-magnitude relation (see Kelson et al. 1999c).

Correcting the surface brightnesses of the spirals for their young stellar populations using their residuals from the color-magnitude relation, one obtains a new plane for the spirals which follows that of the E/S0s. We conclude that after several Gyr, these spirals, including the low-mass E+As, may evolve into present-day, low-mass S0s and appear in nearby FP samples.

4. Absorption Line Strengths of Early-Type Galaxies in CL1358+62

The CL1358+62 spectra are of sufficiently high $S/N$ that one can accurately measure absorption line strengths, and use stellar population synthesis models, such as those of Vazdekis et al. (1996), to constrain the systematic variation of the stellar populations along the FP and color-magnitude relations.

In Figure 2, we show that the sequence of E/S0 galaxies in CL1358+62 is defined by a tight correlation between C$_2$4668 Å and restframe $(B − V)$ color. The best-fit slope of the correlation is nearly identical to that predicted for a sequence of single-burst stellar population models of constant age, in which only metallicity varies. Even with these preliminary measurements, this conclusion is reinforced by the correlations of the metal-sensitive C$_2$4668Å index with the high-order Balmer lines. In the first panel of Figure 3, the C$_2$4668Å index is shown to systematically correlate with the H$\delta_A$ index in a manner which is also consistent with the line of constant age. The scatter in these two diagrams is consistent with the small scatter in ages that has been estimated using the FP and color-magnitude relations (Kelson et al. 1999c, van Dokkum et al. 1998).

The latter two panels show the correlations of C$_2$4668Å and H$\delta_A$ with central velocity dispersion, indicating that metallicity is strongly correlated with the depth of the galaxy potential. The solid lines are the best-fit slopes, with the $±1-\sigma$ uncertainties indicated by dotted lines. Using the Vazdekis et al. (1996) models, these correlations with velocity dispersion imply $M/L_V ∝ M^{0.14±0.02}$. 
Preliminary analysis using Monte Carlo simulations of real data (Kelson 1999) indicate that this correlation can produce an observed FP of the approximate form: \( r_e \propto \sigma^{1.3} \langle \langle I \rangle \rangle^{-0.8} \), though the precise shape depends on sample selection criteria, and the underlying distribution of bulge-to-disk ratios.

\[ \text{Figure 3. Using the E/S0 galaxies we show, in the left-most panel, the observed correlations of the metal-sensitive C_2 4668 Å Lick/IDS index with the H\delta_A index of Worthey & Ottavianni (1997). The two right-hand panels show these two indices plotted against central velocity dispersion for the same galaxies.} \]

5. Summary

We have found that the slope of the fundamental plane has remained constant with redshift. Together with the absorption line strengths and restframe colors, these data suggest that early-type galaxies in clusters have very uniform stellar population ages, and chemical abundances which are strongly determined by the depths of their potential wells, assuming that the stellar populations of cluster E/S0s can be adequately modeled by simple single-burst models. The implied correlation of metallicity with \( \sigma \) appears to be the physical basis behind both the color-magnitude relation and the fundamental plane, though further work is required to fully understand the nature of the selection biases and other systematic effects.

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