Fundamental Plane

Recall the virial theorem: for a system in equilibrium

\[ 2 \, kE + pE = 0 \]

For an elliptical galaxy, particularly one with no rotational support

k.e. \( \propto \sigma^2 \)  \text{ stellar velocity dispersion}

p.e. \( \propto \frac{GM}{r_e} \)

So \( \sigma^2 \propto \frac{GM}{r_e} \)

A. \( \sigma^2 = B \cdot \frac{GM}{r_e} \)

Now \( M = M/L \cdot L \)

surface brightness \( I_e = \frac{k_e}{\pi r_e^2} \)
So \[ A \beta^2 = B \cdot G \left( \frac{m_h \cdot \mu_r e^2 I_e}{r} \right) \]

\[ \log \beta^2 = \log(m_h) + \log r e + \log I_e + \text{const} \]

\[ \text{If } m_h \text{ is constant (old stellar population) then we would expect a relationship between } \]

\[ \log r e, \log \beta \text{ and } \log I_e (= \mu_e, \text{surface brightness}) \]

\[ \text{This is the fundamental plane.} \]

\[ \text{Q} \]

If two ellipticals are merging, would we expect such a relationship to hold?

\[ \text{Q} \]

If we observe a population of elliptical galaxies $z = 1$ (say in a massive cluster) would the fundamental plane equation still hold? Why or why not?
The fundamental planes for the clusters are shown in Figure 2 along with those for Cl 0024+16 (vDF) and Coma (JFK96). We use the coefficients for the fundamental plane determined by JFK96 from a large sample of 225 early-type galaxies in 10 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 ±0.064, ±0.065, ±0.060, and ±0.072 for Coma, Cl 1358+62, Cl 0024+16, and MS 2053−04, 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 fundamental plane 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 $M/Lr$ ratio for each cluster directly from the fundamental plane zero point, adopting the slopes of the fundamental plane of JFK96 and $q_e = 0.05$. The resulting evolution of $M/Lr$ 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 $M/Lr$ 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 $z_{form}$ of infinity and $z_{form} = 1$. The current data are not consistent with the predictions for coeval populations that have formed recently. More data are needed to test whether more complex models with recent star formation can be accommodated (see, e.g., Franx & van Dokkum 1996; Poggianti & Barbuy 1996).

4. DISCUSSION

We have measured structural parameters and central velocity dispersions for galaxies in two clusters at intermediate redshift, Cl 1358+62 at $z = 0.33$ and MS 2053−04 at $z = 0.58$. 

3. THE FUNDAMENTAL PLANE IN CI 1358+62 AND MS 2053−04

The fundamental planes for the clusters are shown in Figure 2 along with those for Cl 0024+16 (vDF) and Coma (JFK96). We use the coefficients for the fundamental plane determined by JFK96 from a large sample of 225 early-type galaxies in 10 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

Another source of uncertainty is due to departures from homology (see, e.g., Capelatto, de Carvalho, & Carlberg 1995; Ciotti, Lanzoni, & Renzini 1996). Nonhomology can affect our measurement of evolution through the aperture correction for the velocity dispersions. Jørgensen 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 (see, e.g., Corallo et al. 1995).

$r^{1/4}$-law model could cause systematic errors on the level of ±1% in the combined parameter $r_eM/Lr$. 

Notes from the authors:

The fundamental planes for the clusters are shown in Figure 2 along with those for Cl 0024+16 (vDF) and Coma (JFK96). We use the coefficients for the fundamental plane determined by JFK96 from a large sample of 225 early-type galaxies in 10 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...
Making ellipticals with mergers

Only quite recently have simulations become realistic enough to include gas (and feedback) in merger simulations.

- Comparison of mergers with stars only and with significant amounts of gas show different amounts of rotational support in remnants.

- "Felt" of fundamental plane (deviation from predictions of virial theorem) can be reproduced via gas-rich mergers.

- Elliptical galaxies made via gas-rich and gasfree mergers (dissipationless).
  Most massive Es made via dry (dissipationless) mergers. Less massive ones need gas in simulations to reproduce properties.
$V_{\text{maj}}/\sigma$ vs. ellipticity diagram for dissipational (40% gas) and dissipationless merger remnants. $V_{\text{maj}}$ is the maximum rotation speed measured in a slit along the major axis, $\sigma$ is the velocity dispersion averaged within half of an half-mass radius, and the ellipticity is measured at the half-mass isophote. Further details can be found in § 2.2. The solid line in both plots is that expected for an oblate isotropic rotator (Binney 1978). Overplotted are data from observed ellipticals from Davies et al. (1983), Bender (1988), Bender & Nieto (1990), and de Zeeuw et al. (2002).

---

**40% gas**

- ● Davies et al. (1983)
- * Bender (1988)
- + Bender & Nieto (1990)
- ▲ de Zeeuw (2002)

**dissipationless**

- ● Cox et al. (2006)