Structure, dynamics and stellar populations in early-type galaxies

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Galaxy Formation, Durham, 20 July 2011
The Fundamental Plane (FP) relates the dynamical and structural properties of early-type (i.e. bulge-dominated) galaxies.

Stellar population variations can cause scatter about the FP, obscuring these relations and limiting the use of the FP as a distance estimator.

Conversely, trends in the FP with stellar population can reveal clues linking the structural & stellar assembly histories of early-type galaxies.

We explore these issues with the 6dF Galaxy Survey, which measures FP and stellar population parameters for large NIR-selected samples.

We determine the variations in stellar populations in FP space, and examine: (i) the implications for the merger histories of galaxies; (ii) whether SP trends drive FP variations with galaxy morphology & cluster richness; & (iii) prospects for improving FP distance estimates.
The 6dF Galaxy Survey – a brief introduction

- NIR-selected using 2MASS down to $K = 12.65$
- $z$-survey: 137000 spectra and 125000 redshifts
- $v$-survey: 10000 FP peculiar velocities; also ages, metallicities and $\frac{\alpha}{Fe}$ for 7000 galaxies
- 17000 deg$^2$ ($\delta<0^\circ, |b|>10^\circ$) to $<cz>\approx 16500$ km/s
- Fibre aperture = 6.7 arcsec $\approx 7$ kpc at $<cz>$
The 6dFGS View of the Local Universe

The 6dF Galaxy Survey covers the entire southern hemisphere to within 10 degrees of the Galactic plane. The map below shows the sky in Galactic coordinates with (l,b) = (300,0) at the centre.

- Shapley supercluster (0.048+)
- Centaurus cluster (0.02)
- Ophiuchus cluster (0.028)
- Norma wall (0.016)
- Pavo-Indus supercluster (0.015)
- Sculptor supercluster (0.054)
- Horologium supercluster (0.067)
- Columba cluster (0.034)
- Hydra cluster (0.01)
- Virgo southern extension (16 Mpc)
- Fornax cluster (20 Mpc)

Graphic: H. Jones (AAO), T. Jarrett (IPAC/Caltech).
Galactic Plane image courtesy of 2MASS.

Beutler et al., 6dFGS: Baryon Acoustic Oscillations & the Local Hubble Constant, astro-ph/1106.3366
The 6dF Galaxy Survey: The Fundamental Plane of Early-Type Galaxies

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Stellar Population Trends Across and Through the 6dFGS Fundamental Plane

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Fit the Fundamental Plane as 3D Gaussian distribution using maximum likelihood.

Study variations in the NIR Fundamental Plane with wavelength, morphology and group/cluster richness.
Principal axes of the 3D Gaussian Fundamental Plane with respect to the observed parameters

\[ r \equiv \log R_e, \ s \equiv \log \sigma, \ i \equiv \log \langle I \rangle_e \]

\(-v_1\) is \(\sim\) mass-to-light ratio:
\[
\log(M/L) = (r+2s) - (i+2r) = -r + 2s - i
\]

\(cf.\quad -v_1 = 1.13r - 1.72s - I\)

\(-v_2\) is \(\sim\) luminosity density:
\[
\log(L/R^3) = (i+2r) - (3r) = i - r
\]

\(cf.\quad -v_2 = i - 0.89r\)

\(-v_3\) is not special physically

<table>
<thead>
<tr>
<th>Axis of 3D Gaussian</th>
<th>(r)</th>
<th>(s)</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_1) short axis = through</td>
<td>0.494</td>
<td>-0.752</td>
<td>0.437</td>
</tr>
<tr>
<td>(v_2) long axis = along</td>
<td>0.663</td>
<td>0.000</td>
<td>-0.749</td>
</tr>
<tr>
<td>(v_3) medium axis = across</td>
<td>0.563</td>
<td>0.659</td>
<td>0.498</td>
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</table>
A 3D Gaussian distribution is found, empirically, to be an excellent fit to the observed bright end ($\sigma > 100$ km/s) of the NIR Fundamental Plane.
ML method recovers mock FP accurately and precisely.
The J-band Fundamental Plane for 8901 early-type galaxies

FP: \( r = a s + b i + c \)

<table>
<thead>
<tr>
<th>( N_g )</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( \bar{r} )</th>
<th>( \bar{s} )</th>
<th>( \bar{i} )</th>
<th>( \sigma_1 )</th>
<th>( \sigma_2 )</th>
<th>( \sigma_3 )</th>
<th>( \sigma_r )</th>
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</thead>
<tbody>
<tr>
<td>8,901</td>
<td>1.502</td>
<td>-0.877</td>
<td>-0.303</td>
<td>0.190</td>
<td>2.189</td>
<td>3.185</td>
<td>0.0517</td>
<td>0.3151</td>
<td>0.1686</td>
<td>0.13</td>
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</table>

slopes & offsets:

<table>
<thead>
<tr>
<th>da</th>
<th>db</th>
<th>dc</th>
<th>( d\bar{r} )</th>
<th>( d\bar{s} )</th>
<th>( d\bar{i} )</th>
<th>( d\sigma_1 )</th>
<th>( d\sigma_2 )</th>
<th>( d\sigma_3 )</th>
<th>( d\sigma_r )</th>
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</thead>
<tbody>
<tr>
<td>0.026</td>
<td>0.008</td>
<td>0.054</td>
<td>0.004</td>
<td>0.003</td>
<td>0.004</td>
<td>0.0009</td>
<td>0.0038</td>
<td>0.0029</td>
<td></td>
</tr>
</tbody>
</table>
Stellar Population Trends Across and Through the 6dFGS Fundamental Plane

Christopher M. Springob\textsuperscript{1}, Christina Magoulas\textsuperscript{2}, Rob Proctor\textsuperscript{3}, Matthew Colless\textsuperscript{1}, D. Heath Jones\textsuperscript{1,4}, Chiaki Kobayashi\textsuperscript{5}, Lachlan Campbell\textsuperscript{5,6}, John Lucey\textsuperscript{7}, & Jeremy R. Mould\textsuperscript{2,8}

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[1] Stellar population parameters (age, metallicity, [\(\alpha/\text{Fe}\)]) for 7,143 galaxies with FP parameters

[2] Derive directional derivatives of SP parameters in FP space; find variations with all of \(\sigma\), \(R_e\), \(I_e\) & \(\delta_{\text{FP}}\)

[3] SP parameters vary with \(v_1\) (through FP) and \(v_3\) (across FP), but not with \(v_2\) (along FP \(\sim L/R_e^3\))

[4] Relate this result to merger histories: lower luminosity densities \(\Rightarrow\) more mergers

[5] Can (some of) these trends be used to reduce the scatter in the FP?
Age-metallicity distribution for 7143 early-type galaxies
Pair-wise correlations between stellar population parameters and Fundamental Plane parameters

Correlations (in red) are consistent with well-known trends:

- All SP’s show clear trends with log $\sigma$
- Metallicity shows trends with log $R_e$
- There are weak or no trends with log $I_e$
Age trend in the Fundamental Plane
The variation in age is mainly through the FP (i.e. in $v_1$ direction)
[Z/H] trend in the Fundamental Plane

Variation in metallicity is mainly across the FP (i.e. in \( v_3 \) direction)
[α/Fe] trend in the Fundamental Plane

Variation of [α/Fe] runs both through and across the FP (i.e. in a combination of the \( v_1 \) and \( v_3 \) directions)
Directional derivatives of stellar population parameters w.r.t. the FP principal axes, the FP observables, and \( M, L \) and \( M/L \)

<table>
<thead>
<tr>
<th>Stellar population parameter</th>
<th>( v_1 )</th>
<th>( v_2 )</th>
<th>( v_3 )</th>
<th>( r )</th>
<th>( s )</th>
<th>( i )</th>
<th>( m )</th>
<th>( l )</th>
<th>( m - l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nabla \mathcal{F} ) Age</td>
<td>-1.47</td>
<td>-0.04</td>
<td>0.08</td>
<td>-0.70</td>
<td>1.16</td>
<td>-0.57</td>
<td>0.32</td>
<td>-0.39</td>
<td>0.60</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.12</td>
<td>0.04</td>
<td>0.09</td>
<td>0.08</td>
<td>0.11</td>
<td>0.08</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>( \chi )</td>
<td>12.25</td>
<td>1.00</td>
<td>0.89</td>
<td>8.75</td>
<td>10.55</td>
<td>7.13</td>
<td>6.92</td>
<td>11.01</td>
<td>14.51</td>
</tr>
<tr>
<td>( \nabla \mathcal{F} ) [( Z/H )]</td>
<td>0.07</td>
<td>0.05</td>
<td>0.46</td>
<td>0.32</td>
<td>0.25</td>
<td>0.22</td>
<td>0.16</td>
<td>0.17</td>
<td>-0.01</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.13</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.10</td>
<td>0.06</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>( \chi )</td>
<td>0.54</td>
<td>1.67</td>
<td>11.50</td>
<td>4.57</td>
<td>2.50</td>
<td>3.67</td>
<td>3.87</td>
<td>5.65</td>
<td>0.18</td>
</tr>
<tr>
<td>( \nabla \mathcal{F} ) [( \alpha/Fe )]</td>
<td>-0.24</td>
<td>-0.01</td>
<td>0.16</td>
<td>-0.03</td>
<td>0.29</td>
<td>-0.02</td>
<td>0.11</td>
<td>-0.02</td>
<td>0.11</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>( \chi )</td>
<td>4.80</td>
<td>1.00</td>
<td>8.00</td>
<td>1.00</td>
<td>7.25</td>
<td>0.67</td>
<td>6.44</td>
<td>1.19</td>
<td>6.96</td>
</tr>
</tbody>
</table>

Significant trends (in **bold**) have \( \chi > 5 \) (i.e. are significant at >5-sigma): e.g. age with \( v_1 \), metallicity with \( v_3 \) and over-abundance with both \( v_1 \) and \( v_3 \). Can use the 3D directional derivatives to predict the 2D pair-wise correlations between the stellar population parameters and the FP parameters.
2D correlations between stellar population parameters and Fundamental Plane parameters

Predicted correlations based on directional partial derivatives (blue) are generally consistent with – but not identical to – the observed correlations (red).

The 2D correlations are projections of more complex 3D correlations.
No stellar population parameter has any significant trend with \( v_2 \), the long axis of the FP – i.e. no variation in stellar population with luminosity density.
FP relation for galaxies in Kobayashi (2004) simulation of galaxy merger histories

There is a trend in merger history along the FP, but no trend between merger history & scatter off the FP.

$v_2$ vs log$\sigma$ for elliptical galaxies in Kobayashi (2004) simulation

There is a clear trend of merger history with $v_2$ (luminosity density), but there is no readily apparent trend with $\sigma$. 
There is a clear trend in the r-offset of the FP with age; additionally, galaxies with ages <3Gyr have larger rms scatter in distance than older galaxies. So, in principle, we can reduce the scatter in the overall FP either by *selection* on age or by *compensating* for the variation with age of the FP.
There is a weaker trend in FP r-offset with metallicity; so in principle could further reduce overall FP scatter by compensating for the effects of \([Z/H]\).
Simulations show that these significant FP r-offsets are not explained by the stellar population differences between clusters & field (or E/S0’s & early-type spiral bulges).
Summary and conclusions

[1] Successfully fit distribution of $\sim10^4$ 6dFGS galaxies in Fundamental Plane space as a 3D Gaussian distribution using maximum likelihood.

[2] For $\sim7000$ of these galaxies, stellar population parameters (age, metallicity, $[\alpha/\text{Fe}]$) are measured from Lick absorption line indices.

[3] The 3D directional derivatives of the stellar population parameters in Fundamental Plane space show variations with all of $\sigma$, $R_e$, $I_e$ and $\delta_{\text{FP}}$.

[4] We recover the pair-wise 2D relations between stellar population & FP variables from these 3D trends, with some unexpected dependencies.

[5] Stellar population parameters vary with $v_1$ (through FP) and $v_3$ (across FP), but not $v_2$ (along FP $\sim$ luminosity density); suggests that the extent of the FP in $v_2$ is driven by merger histories not stellar populations.

[6] These SP trends can in principle be used to reduce the scatter in the FP.