The Graveyard of Galaxy Evolution: Age-Dating the Red Sequence in Clusters

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Fine-Tuning Stellar Population Models,
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The Red Sequence and the Blue Cloud

✦ A bimodal galaxy population:
  ✦ “Blue Cloud” forming stars
  ✦ “Red Sequence” with no ongoing star-formation - the end-point of galaxy evolution

✦ Red sequence harbours ~50% of stellar mass at z=0; dominates rich clusters.

✦ A relic of early star-formation and chemical enrichment history.

**AIM:** To date the arrival of galaxies onto the red sequence, as a function of mass, environment, morphology, etc

Hogg et al. (2002)
NOAO Fundamental Plane Survey (NFPS)

- All-sky survey of the most X-ray luminous clusters in $z<0.067$ and with $|b| > 20$ deg.
- B+R imaging from mosaic cameras at KPNO 0.9m+4m, CTIO 4m, CFHT.
- Multi-fibre spectroscopy from Hydra at WIYN, CTIO 4m, for red-sequence to $R=17$.
- Spectroscopic sample: 5479 galaxies in 93 clusters.
- Redshifts, velocity dispersions (Smith et al. 2004).
- Age indicators (HdF, HgF, Hbeta); Z/H indicators (Fe5270, Fe5335 etc); $\alpha$/Fe indicators (Mgb, CN1)
Classical method uses “Diagnostic Plots” of Balmer vs metal lines.

Need to “invert” to recover population parameters

Absolute calibration of models (and data!) is uncertain

How to interpolate off-grid points?

How to deal with correlated errors in interpolated parameters?

How to make use of multiple indices?

**From Stellar Population models to Response Vectors**

Models from Thomas et al. (2003)

- $a/Fe = 0.0$
- $a/Fe = +0.3$

Diagram showing relationships between $H beta$, $a/Fe$, Age, $Z/H$, and Fe4531.
From Stellar Population models to Response Vectors

✦ Classical method uses “Diagnostic Plots” of Balmer vs metal lines.
✦ Need to “invert” to recover population parameters
✦ Absolute calibration of models (and data!) is uncertain
✦ How to interpolate off-grid points?
✦ How to deal with correlated errors in interpolated parameters?
✦ How to make use of multiple indices?
The Mass Scaling Relations

- Use velocity dispersion $\sigma$ as proxy for galaxy mass.
- Index-sigma relations, trace scaling of stellar population with mass,
  - e.g. classic Mgb - $\sigma$ relation
  - Mgb depends on Age, Z/H and $\alpha$/Fe (Thomas et al. 2003)
- So which of these parameters vary with mass to drive the relationship?

Log velocity dispersion ($\sim$mass)

Line-strength

NB: Compared to Thomas et al. (2005), NFPS covers $\sim$2x the range in $\sigma$, or $\sim$10x baseline in mass
Never attempt to measure Age (etc) for individual galaxies.

Need at least three indices to recover age, Z/H and a/Fe scalings.

Differential method: insensitive to absolute calibration of models and data.

Not over-sensitive to “off-grid” points (unlike multi-index $\chi^2$ methods).

Responses calculated over restricted parameter space as spanned by E/S0s.
With just three non-degenerate indices we can solve for the scaling relation slopes.

More robustly, use many partially-redundant indices to over-constrain the model.

In practice, use the “NFPS 12”: HdF, HgF, Hbeta, CN1, Fe4668, Mgb5177, Fe4531, Fe5270, Fe5335, Fe5406, Fe5709, Fe5782 (Nelan et al. 05, Smith et al. 06)
Mass Scaling Relations: Results

- Compared to $\sigma=300$ km/s, galaxies of $\sigma=100$ km/s have:
  - Younger “ages” (by factor $1.9 \pm 0.2$) (!!)
  - Lower total metallicity (by $0.25 \pm 0.04$ dex)
  - Less alpha-enriched (by $0.15 \pm 0.03$ dex) (star-formation timescale $\sim 8x$ longer)

- Errors derived from running fits with different choices of indices.
- Similar results from averaged-index grid-inversion
- Strong age-vs-mass relation $\text{Age} \propto \sigma^{0.6 \pm 0.1}$ (Nelan et al, revised to $X=0.7$ in Smith et al.)
- Low-mass (100 km/s) red-sequence galaxies have ages only $\sim 7$ Gyr, corresponding to $z \sim 1$. 

Nelan et al. (2005)
Strong age-vs-mass relation $\text{Age} \propto \sigma^X$ with $X=0.6\pm0.2$ (Nelan et al, revised to $X=0.7$ in Smith et al.)

Confirms previous hints from much smaller samples:
- Caldwell et al. (2003) : $X=0.8-1.2$
- Thomas et al. (2005) : $X \sim 0.8$
  (NOT $\sim 0.2$ as often quoted!)

...And supported by studies from SDSS (more galaxies, but narrower mass baseline):
- Bernardi et al. (2006) : $X=0.8-1.2$
- Clemens et al. (2006) : $X \sim 0.75$

Need a careful treatment of selection bias for flux-limited samples; most severe for samples dominated by $L<L^*$.  
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Comparison with other work

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{comparison.png}
\end{figure}
Emerging observational consensus for “red-sequence down-sizing” -- can hierarchical models reproduce this?

Recent semi-analytic models with AGN feedback (Croton et al., de Lucia et al., Bower et al., Cattaneo et al.) are more successful than older attempts.

Detailed behaviour differs among published models (fundamental, or due to different selection?)

Coming soon: detailed comparisons with Bower et al. versions, attempting to match NFPS selection cuts.
Interesting to compare to intermediate redshift observations...

Luminosity of red sequence “truncation” at $z=0.8$ (de Lucia et al. 2004) corresponds to sigma $\sim 150$ km/s at lookback time $\sim 6$ Gyr.

Mass scale of E+A galaxies follows the age-mass relation too, with an offset of $\sim 2$ Gyr

DEEP2 “Quenching mass” follows similar track.

Hopkins et al. link QSO luminosity function to low-z spheroids, indicating similar trend

Jorgensen et al. FP mass-dependent evolution in clusters; Treu et al. in field.

Adapted from Smith (2005)
Environmental Dependence of Red-Sequence Ages

- When and how is the red-sequence established? What is the role of the cluster environment?
- Model index-sigma relations with an extra term describing cluster-centric radius effects:
- Sample is ~3000 emission-free cluster members with \( R < R_{200} \), cDs excluded.
- Partial residual, isolating radial effect:
  \[ \delta = I - (a \log \sigma + c + d z/z_0) \]
- Significant detection of radius coefficient, \( b \), for many indices.
- e.g. \( M_{\text{gb}} \) decreases with large \( R \), after controlling for mass. (Previously detected in Coma by Guzman et al. 1992; Carter et al. 2002).
- Which parameter varies with radius to drive the index trends?

Model:
\[ I = a \log \sigma + b (R/R_{200}) + c \]

*Smith et al. (2006)*

![Graph showing index residual vs radius with binned residuals and linear fit](image)
Origin of the Index Residual vs Radius Relations

With three or more indices we can fit for the radial trend slopes...

Smith et al. (2006)
A model for cluster-centric trends

- **Results:** at $R_{200}$, galaxies are...
  - $16 \pm 4\%$ younger and
  - $10 \pm 2\%$ less alpha-enriched ($\sim 2x$ longer star-formation timescale)
  - similar in metallicity ($2 \pm 3\%$)
  - ...compared to galaxies of the same mass in the cluster core.

- Fit to trends of 12 indices (same set as used by Nelan et al. 2005)
- Model adequately describes the radial trends in all of the indices.
- Must have both Age and $a$/Fe variations (cf. Guzman et al. 1992; Carter et al. 2002).
- Hint that radial trends are stronger in the low-mass objects...

![Graph showing Predicted vs. Observed Slope with data points from Smith et al. (2006)]
- Cluster environment causes “suffocation” by stripping of gas halo (Larson & Tinsley 1980, etc.)
- Star formation truncated within 1-2 Gyr of infall into cluster.
- N-body: clusters not well-mixed even within $R_{200}$ (Gao et al.): $z_{\text{infall}} - R_{\text{cl}}$ correlation
- So expect some radial age gradient, at the 10-20% level out to $R_{200}$.
Summary


✦ Ties in with (some) observations at higher redshifts (E+A mass evolution, red sequence truncation, FP rotation...).

✦ Detailed comparisons to semi-analytic models underway.

✦ Clear evidence for cluster-centric trends in stellar populations, independent of particular synthesis models.

✦ Pattern of radial trends best reproduced if outer galaxies are younger and had longer star-formation time-scales, after controlling for mass (and morphology).

✦ New observations obtained with AAOmega vastly improve coverage at low-masses -- stay tuned....

For full details, see: