Galaxy Systems in the Optical and Infrared

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Plan of the lectures:

I. Identification, global properties, and scaling relations
II. Structure and dynamics
III. Properties of the galaxy populations
Introduction
The most striking characteristics of the cluster galaxy population:

its morphology mix
Field
Morphology + Luminosity Segregation

segregation in projected phase-space

(B. +02)
Why do the galaxies care about the density of the environment?

Analyse the properties of cluster galaxy populations in relation to their environment as a function of redshift → mechanisms of galaxy evolution
The properties of cluster galaxies: morphologies
Regular trend of morphology change with density

(Dressler 80)

Fraction

S0

E

S+Irr

log(local density)
Regular trend of morphology change with density

(Postman & Geller 84)
Another example of morphology vs. density
Regular trend of morphology change with radius

(Whitmore+93)
- Morphology-Density Relation (MDR)
- Morphology-Radius Relation (MRR)
...but also:
- Morphology-Velocity Relation (MVR)
Morphology-Velocity Relation (MVR)

(Adami+98)
Another example of velocity vs. morphology
The MDR at $z \sim 1$: still there, but less S0, more S

(Postman+05)
The MRR at $z \sim 1$: still there, but less S0, more S

(Postman+05)
Brightest galaxies in two $z \approx 1$ clusters (Postman+05)
MDR not present in medium-z irregular clusters

(Dressler+ 97)
Most MDR evolution occurs at $z<0.5$

(Desai+07)
S0 form earlier in higher density regions

(Smith+05)
Less evolution for more massive galaxies

Redshifts:  
0.02  
0.33  
0.59  
0.83  

(Holden+07)
The properties of cluster galaxies: colors
The color-magnitude relation, CMR

(from Durham Univ. website)
CMR also for dwarf galaxies

V-band magnitude

(Hilker+03)
CMR also at high-z

z=1.6 confirmed overdensity

z - J color

J-band magnitude

(Kurk+08)
CMR zero-point vs. $z \Rightarrow z_f \geq 2$
CMR zero-point vs. $z \Rightarrow z_f \geq 2$

Solid: $z_f=3$
Dashed: $z_f=2$

(De Lucia+07)
CMR vs. R $\Rightarrow$ age gradient

zero-point scatter

(Wake+05)
CMR vs. local density ⇒ age gradient

(Pimbblet+06)
CMR faint-end forms at low-z

Red-galaxy luminosity functions for two cluster samples

(Stott+07)
CMR faint-end forms at low-z

Bright-to-faint red galaxies number ratio

(De Lucia+07)
CMR faint-end forms at low-z
...more rapidly in higher-M clusters

Bright-to-faint red galaxies number ratio

(Gilbank+08) redshift
CMR faint-end forms at low-z
...at the expense of blue galaxies

(LF Red gals)

(Gilbank+08)
CMR faint-end forms at low-z
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(Gilbank+08)
Blue galaxies $\rightarrow$ red galaxies with time $f_B \uparrow$ with $z$ ... the Butcher-Oemler effect
$f_{\text{ELG}} \uparrow$ with $z$ ... the spectroscopic B-O effect

Poggianti+ 06

fraction of emission-line galaxies

Cluster velocity dispersion

high-redshift

low-redshift
fIR-emitters $\uparrow$ with $z$ ... the IR B-O effect

IR emission contours & optical image

(Coia+ 05)
$f_{\text{IR-emitters}} \uparrow$ with $z$ ... the IR B-O effect

SFR per unit mass increases with redshift

(Geach+ 06)

$L_{\text{IR}} \leftrightarrow \text{SFR}$
Cluster galaxy color evolution occurs later

➔ for fainter galaxies
➔ in the lower density cluster regions
➔ for less massive clusters
Cluster galaxy *morphological* evolution occurs later

- for fainter galaxies
- in the *lower density* cluster regions
- for less *massive* clusters
CMR & MDR: the same phenomenon?

E0 – E7

S0

Sa – Sb – Sc

SBa – SBB – SBc

Irr
No MDR at fixed age ⇒ CMR more fundamental
CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

✔ evolution of galaxy mass function
Galaxy Mass Function becomes dominated by RED galaxies before becoming dominated by EARLY type galaxies (Bundy+06)
CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

- evolution of galaxy mass function
- passive, red cluster spirals
Normal S

Passive spectrum, blue disk

Passive spectrum red disk

(Moran+07)
CMR & MDR: the same phenomenon?

CMR more fundamental

CMR evolution proceeds faster:

✔ evolution of galaxy mass function
✔ passive, red cluster spirals
✔ early-S with = age of S0
Sa/b and S0 have equal age in highest-density regions

\[ \log \Sigma_{10}(h/\text{Mpc})^2 \]

\[ \text{age(C)/Gyr} \]
The properties of cluster galaxies: masses
Early-type galaxies lie on a Fundamental Plane

ETG FP relates their central $\sigma_v$
surf. brightness effective radius

FP $\Rightarrow$ $z_f \geq 2$

(Moran+07)
Deviation from FP expressed as M/L difference

Lower M/L for less massive ETG ⇒ younger age

(Moran+07)
Deviation from FP expressed as M/L difference

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Also:

field ETG younger than cluster ETG

(di Serego+06)
Deviation from FP expressed as M/L difference

Lower M/L for less massive ETG ⇒ younger age

Also:

cluster S0 younger than cluster E

(Barr+06)
FP analysis supports conclusions from CMR and MDR analyses
The properties of cluster galaxies: luminosities
Cluster LF $\neq$ field LF?

(Driver+04)
Cluster LF $\neq$ field LF?

Fill.pdf: group
Open circles: field

'magnitude $M^*$

Slope

Morphological type

(Martínez+02)
Cluster LF: shallower slope at small radii

(Popesso+06)
Cluster LF: shallower slope at small radii
...a.k.a. “luminosity segregation”

(Pracy+04)
Luminosity segregation:
brighter galaxies closer to $R=0$

Spatial distributions of bright and faint galaxies

(Capelato+80)
Another example of luminosity vs. density
Brighter galaxies closer to cluster center but also closer to $\langle V \rangle_{\text{cluster}}$
Brighter galaxies closer to cluster center but also closer to $\langle V \rangle_{\text{cluster}}$

Luminosity segregation: Ellipticals, not S0

(Adami+98)
Brightest Cluster Galaxies:
sizes > field galaxies
with = luminosities
BCG intimately related to their cluster

Central location

Alignenent

$L_{BCG} \leftrightarrow M_{\text{cluster}}$

solid line: BCG
dashed line: 2$^{\text{nd}}$ brightest

(Ramella 07)
BCG intimately related to their cluster

Central location

Alignment

$L_{\text{BCG}} \leftrightarrow M_{\text{cluster}}$
BCG color \( \Rightarrow z_f \geq 2 \)

...but BCG stellar mass increased since \( z \sim 1 \) in low-M clusters

(Brough+02)
BCG in lower-M clusters keep growing as their host clusters grow

Fraction of total cluster light in the BCG anti-correlated with cluster mass

(Lin & Mohr 04)
Lum(BCG)/Lum(2\textsuperscript{nd} brightest) ↑

in more regular (more evolved?) clusters

(Ramella+07)
BCG ↔ companions merger expected in \( \sim 0.1 \) Gyr

\( z = 0.39 \)
cluster
optical
surface-brightness contours

\( 10'' = 37 \) kpc

(Rines+07)
Intra-Cluster Light related to BCG

Similar colors

Aligned

Clusters with brighter BCG also have higher ICL surface brightness

ICL light ~ 5-25% total light
Intra-Cluster Light related to BCG

Similar colors
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ICL light ~ 5-25% total light
The properties of cluster galaxies:

nuclear activity
AGN fraction:
no (?) dependence on local density
but strong dependence on $\sigma_v$
Physical processes
Processes capable of affecting cluster (and group) galaxy properties:

- dynamical friction
- galaxy-galaxy collisions $\rightarrow$ tidal effects & mergers
- tidal forces induced by cluster $d\phi/dr$ $\rightarrow$ tidal truncation
- ram-pressure stripping

**Starvation** can result from any of the $\clubsuit$ processes as the galaxy gas is expelled or consumed.
Dynamical friction timescale

\[ t_{df} \propto \frac{v_g^3}{m_g \rho} \]
Galaxy-galaxy collision timescale

\[ t_c \propto \frac{1}{\nu r^2 v_g} \]
Rapid collisions $\rightarrow$ 'harassment'  

$\Rightarrow$ Morphological evolution

(Moore+96)
Collisions $\rightarrow$ gas expelled by tidal forces

(Durbala+08)
Slow collisions $\rightarrow$ mergers

Merger timescale

Leading to tidal gas loss and morphological evolution

(Barnes 92)
Galaxy orbiting cluster suffers tidal truncation outside $r_t$:

$$r_t \approx r_c \frac{\sigma_g}{2 \sigma_v}$$

$$r_c \approx 2 \, r_{\text{pericenter}}$$

BCG at $r=0$ not truncated, symmetric external forces
Ram-pressure from IC gas strips the galaxy gas from the galaxy halo.

\[ \rho_{IC} v_g^2 > \alpha \frac{G m_g(R) \rho_{gas}(R)}{R} \]

from the galaxy halo

\[ \rho_{IC} v_g^2 > 2\pi G \Sigma_\star \Sigma_{gas} \]

from the galaxy disk
Tidal or ram compression of galactic gas → central starburst

(Byrd & Valtonen 90)
Different processes are efficient in different environments

(Moran+07)
Evolutionary scenarios
'Nature' vs. 'nurture'?

Nature:
CMR and MDR in place at high-z
Bright ETG undergo only passive evolution

Nurture (?):
S0, fainter ETG, ETG in lower-density regions are younger, especially in low-M irregular clusters
Cluster LF ≠ field LF (BCG, ICL)
Use Ockham's razor:

no nurture if nature suffices
Use Ockham's razor:
no *nurture* if *nature* suffices

Hierarchical cosmological models *naturally* predict biased galaxy formation:

more *massive* galaxies form *earlier* in *denser*
environment (*earlier* collapse of density fluctuations)
hence they form their stars, run out of fuel,
and stop forming stars *earlier*
ABSTRACT

$z = 0.8$ and $z = 1.6$, and also that galaxy formation took place in “downsizing,” with more massive galaxies forming at higher redshift. The late galaxy formation accounts for the
Numerical simulations:

Galaxy mass

(Gas mass) / (total mass)

formation redshift

(Cen & Ostriker 93)
But *nurture* does play a role in hierarchical models: galaxies grow via mergers

Mergers → increase galaxy masses
destroy disks and spiral arms
reduce angular momentum
trigger starbursts (reduce gas content)
form central Black Holes and AGNs
(AGN feedback quench SF)

Mergers effective in high-density regions with low-$\sigma_v$ (at early-times or via dynamical friction)
Merger origin of ellipticals: flat metallicity and color gradients

(La Barbera+04)
Merger origin of AGN: host galaxy colors and morphologies

1-4 Gyr old starburst
Merger origin of AGN: fraction vs. $\sigma_v$ fitted by merger model

(Popesso & B. 06)
Mergers become inefficient at later times in galaxy clusters when $\sigma_v \uparrow$
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Mergers at later times can still operate in lower-$\sigma_v$ but relatively high-density regions, i.e. groups (subclusters) and filaments
Mergers suggested by starburst activity in galaxies of cluster-feeding filaments

(Fadda+08)

Cluster
\( <z> = 0.2 \)

Filaments

5 Mpc
Dynamical friction $\Rightarrow$
merger continues until late in central cluster region
BCG continues to grow up

(De Lucia & Blaizot 07)
Dynamical friction and mergers can explain luminosity segregation

(Springel+01)
Merger explains bright part of LF cluster vs. field ≠
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Mass of merger products < \( \sum \) (progenitor masses)

lost mass during mergers create ICL
Merger explains bright part of LF cluster vs. field ≠

Mass of merger products < \( \sum \) (progenitor masses)

\( \therefore \) lost mass during mergers create ICL

Faint-end LF maybe created from tidal dwarfs
(they cannot survive in the central cluster regions)
Hierarchical clustering CDM numerical simulation with: cooling, star formation, SN feedback, dynamical friction, mergers

⇒ MRR ~ OK

$S0$? not really

(Springel+01)
Producing S0:

low-luminosity S0 from fading spirals
Spiral gas removed via tidal effects, ram-pressure
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A thesis supported by the analyses of:

✔ Blue vs. Red LF evolution
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A thesis supported by the analyses of:

✓ Blue vs. Red LF evolution
✓ Existence of an intermediate galaxy class

passive S, HI-deficient S
Normal S

Passive spectrum, blue disk

Passive spectrum red disk

(Moran+07)
Producing S0:

low-luminosity S0 from fading spirals
Spiral gas removed via tidal effects, ram-pressure

A thesis supported by the analyses of:

✔ Blue vs. Red LF evolution
✔ Existence of an intermediate galaxy class
✔ Specific number of globular clusters
When age $\uparrow$ $S_N \equiv N_{GC} / \text{Lum} \uparrow$

(Barr+07)
Producing S0:

High-luminosity S0, fading spirals insufficient
Must increase bulge luminosity

Via minor mergers
and/or

tidally-induced central stabursts
Producing S0:

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Possible progenitors: E+A galaxies
Spectrum with strong Balmer lines fit by Elliptical-like + A stars (post-starburst) (Dressler+Gunn 83)
Recent creation of bright S0 can occur in low-\(\sigma_v\) subclusters

Observational evidence for a high fraction of S0 in subclusters

(B.+02)
Conclusions:

We are close to understand the physical meaning of the Hubble tuning fork!
Thank you for the attention!