Observational Properties of Galaxy Clusters: Formation and Evolution

Outline

Part 1: Observational techniques
- Observational definition, observable physical properties
- Methods for cluster searches
- Cluster surveys: results, future prospects

Part 2: Clusters as Cosmological tools
- Evolution of the cluster abundance
- Independent constraints on cosmology from clusters
- Distribution and metallicity of baryons in distant clusters

Part 3: The Galaxy Content of Distant Clusters
- Multi-wavelength observations of distant clusters
- Galaxy populations and Environmental effects
- Formation and Evolution of cluster galaxies

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Observational Probes of Cluster Formation & Evolution

Cluster Mass (DM)
- Mass Function (e.g. from X-ray) ⇔ N-body simulations, Extended PS
- Mass Distribution (inner cores from Lensing) ⇔ CDM simulations

Intra-Cluster Medium (ICM)
- Cluster Scaling Relations (L_x-T, M-T, Entropy, f_{gas})
- Gas Metallicity
  ⇔ hydro cosmo simulations + SAMs + chemical evolution

Galaxies/Stellar Mass Assembly
- Spectrophotometry, line diagnostics
- Red Sequence of Early types: normalization, scatter, slope
- Luminosity Function of cluster galaxies
- M/L (fundamental plane), Stellar Mass Function
  ⇔ stellar synthesis + semi-analytical models (SAM) + hydro simulations
Towards understanding the formation and evolution of baryonic matter

Some key questions:

a) when and how most of the stellar mass was assembled in cluster galaxies? is this process different in lower density environments (e.g. the field)?

b) when did the first clusters form? i.e. when most of the mass in its dark and baryonic components (gas & gals) were assembled and thermalized in the cluster potential well

c) when and how was the gas pre-heated and polluted with metals?

Key requirements:

1) probe the largest look-back times (i.e. \( z > \sim 1 \)) in order to approach the formation epoch

2) study the physical properties of both the gas and the galaxy populations \( \Rightarrow \) multi-wavelength observations (X-ray + UV→IR)

3) (ideally) measure masses (for both member galaxies and clusters) over a large \( z \) range

4) model the cold and hot phase of cosmic structure in a self-consistent way...
Large look-back times ⇒ stronger leverage on models (fractional age differences among galaxies are greater, $\Delta T/T \uparrow$ with $z$)

- Color Sequence Evolution: stellar population models for a 2 Gyr burst and $z_F = 4,3,2$

- Evolution of M/L of cluster early-types: observations and models (van Dokkum et al. 02)

$$\Delta \ln(M/L_B) \propto (1.0 \pm 0.2) z = f(\tau, \text{IMF}, Z)$$

derived from the Fundamental Plane:

$$\log r_e = \alpha \log \sigma + \beta \log <I_e> + \gamma$$
Diagnostic Tools mentioned here

- Spectral Energy Distribution over large $\lambda$-range (i.e. colors)
- Spectral features
- CMD (red-sequence)
- Luminosity functions
- (Fundamental Plane)
How do we model galaxy colors, SEDs, spectra, M/L evolution, etc.?

Stellar population synthesis

Models based on the evolution of the single stars contained in the population (using library of observed stellar spectra and stellar evolution theory) for a given IMF

Evolution of a Simple Stellar Population (SSP) Bruzual&Charlot (2003,..)
Composite Stellar Population (CSP) models

\[ \Psi(t, \tau) = \frac{t}{\tau^2} e^{-\frac{t}{\tau}} \]

(R.Gobat, PhDThesis 08)
SED fitting with composite stellar population models (e.g. \( \tau \) models, of a given metallicity and reddening), yields the luminosity weighted age and stellar mass of the galaxy.

\[\text{How reliable are photometric masses?}\]
Measuring stellar masses
Comparing Dynamical & Photometric Masses at z~1

Rettura et al. (2006)

30% scatter
Comparing photometric and lensing stellar masses using SDSS Lens ACS Survey (SLACS, http://www.slacs.org)

\( M^{\text{tot}}_{\text{len+dyn}}(\leq R_{\text{Ein}}) \)

\( M^{\ast}_{\text{len+dyn}}(\leq R_{\text{Ein}}) \) vs \( M^{\ast}_{\text{phot}}(\leq R_{\text{Ein}}) \)

(Koopmans et al. 06)

(Grillo et al. 08)
Comparing photometric and lensing stellar masses

\[ M_{\text{len+dyn}}(\leq R_{\text{Ein}}) = 10^{2.3 \pm 1.7} \cdot M_{\text{phot}}(\leq R_{\text{Ein}})^{0.8 \pm 0.2} \]

(Grillo et al. 2008)
Morphology - Density relation
(Star Formation - Density relation)
(Galaxy colors/spectra - Density relation)

- Early-types are at high densities
- Late-type are at low-densities
- Morphology determined by local environment
- More recently one considers SF as opposed to morphology
- As a result colors and spectral energy distribution of galaxies depend on the environment

Dressler (1980)

Early-type galaxies
The colour-magnitude diagram in different environments

The distribution of galaxy colors is bimodal

Baldry et al. 2003
From SDSS data
The colour-magnitude diagram in different environments

Baldry et al. 2003
The Color-Magnitude relation in clusters

CMD in the Coma cluster (Terlevich A. et al. 99)
The Color-Magnitude relation in clusters

- The red sequence becomes extremely narrow (<0.05 mag) in the densest environments (clusters)

- Cluster galaxies (in contrast with the field) have a very well defined color-magnitude relation, which appears the same in all clusters (at least out to z<~1)

- Scatter (as small as 0.03 mag) sets strong constraints on age spread for the bulk of stars and challenges all semi-analytical models.

- The stars must be old to have such uniform colors, or formed in well coordinated single event: cluster galaxies are old passively evolved systems

- C-M slope&scatter set limits on degree of merging (number of galaxy mergers after the formation of its stars: reduces slope, increases scatter)

- The CM relations is likely a metallicity sequence, as opposed to an age sequence (given the lack of evolution of the slope and scatter)

- The higher is the redshift at which a tight CM relation is found the stronger the constraints on the age and formation syncronicity of the stellar populations
The Color-Magnitude relation in different environments

• The mean colors and scatter of the red (early-type) and blue (late-type) populations depends (mildly) on the environments

• The relative abundance of the populations is a strong function of the environment

• Blue galaxies move quickly into the red population as their environment changes

• Physical mechanisms which could make galaxy properties depend on the environment:
  - Ram pressure stripping (due to dense ICM, high velocities -> clusters)
  - Collisions (slow/fast)/harassment (cumulative effect of repeated encounters): preferred place “group environment”
  - “Strangulation”: removal of the gas halo, i.e. no more fuel supply

• Galaxy transformation time scale must be rapid otherwise the valley between the red and blue peak would be filled

• Modern semi-analytic models use “feedback” (exchange of gas/energy between SF disk and halo) to reproduce the color bimodality
A) Intermediate redshift clusters:

- Deep (2/3 band) imaging of 8 clusters at 0.8 < z < 1.4
  - five at z > 1: z = 1.11, 1.24, 1.26, 1.27, 1.39 (7/8 X-ray selected), covering a factor of 100 in mass
- Extensive ground-based data (spectroscopy and near-IR imaging)
- Spitzer/IRAC data for the rest frame near IR
- Chandra/XMM data (gas/DM masses, ICM thermodynamics, metallicity)

B) Sample of proto-clusters at z = 2–4

C) Deep observations of strong lensing clusters (→ Tom’s lectures)
The ACS intermediate redshift clusters slide show
The scatter (0.042±0.015 mag in i-z) and slope of the red sequence are very similar to low-z clusters (e.g. Coma)
Some cluster members in RDCS1252-29 with HST/ACS

Early-type spectra

Late-type spectra

AGN-2

BzK 5″
Color-(Stellar)Mass Diagram at z=1.24
Stellar Mass segregation in RDCS1252
HST/ACS observations of the Lynx clusters
(Mei et al. 2005b)

Lynx E (z=1.26)

Lynx W (z=1.27)
Lynx ($z = 1.26, 1.27$): C–M Relation with HST/ACS

(Mei et al. 2006b)

Again very small scatter: $\sigma = 0.03$ mag for both clusters
RDCS0910 (z = 1.105) C–M Relation with HST/ACS
(Mei et al. 2005a)

Small scatter: \( \sigma_{(E+S0)} = 0.06 \pm 0.02 \) mag
\( \sigma_{(E)} \approx \sigma_{(S0)} = 0.04 \) mag

E and SO seqs seem different
\( \Delta(E-S0) = 0.07 \pm 0.02 \) mag

Small scatter: \( \sigma_{(E+S0)} = 0.06 \pm 0.02 \) mag
\( \sigma_{(E)} \approx \sigma_{(S0)} = 0.04 \) mag
RDCS0910 ($z = 1.105$) C–M Relation with HST/ACS
(Mei et al. 2005a)
(no) Evolution of the CMD slope and scatter out to $z=1.3$

$\rightarrow$ The Cluster RS frozen over $\sim9$ Gyr, well within 0.1 mag!
σ=0.055±0.018 mag ➔ red sequence already as tight as Coma at lookback time of 9 Gyr (when T_u~4.5 Gyr), i.e. z_f~3-4.

Cluster red-sequence at z=1.4 from near-IR observations

XMM2235 CMDs (VLT+HAWKI)

• 7.5x2 arcmin across
• 0.3-0.4 arcsec seeing!
• Deep K=25.5 AB in 2 hrs
• J & Ks observations

Lidman et al 08
Spectro-photometric fitting method
(Gobat et al. 2008)

\[
\Psi(t) = \tau^{-2} e^{\frac{t}{\tau}} + A \delta(t - t_{\text{burst}})
\]

Grid: \{T, \tau, t_{\text{burst}}, A\}

Best fit params:
\{T, \tau, t_{\text{burst}}, A, M_{\text{Star}}\}
The modeling of the spectro-photometric data with BC models yield a distribution of SF-weighted ages of cluster ETGs and a formation redshift of $z_F \approx 4$, for both clusters. Their tight CMDs is expected to dissolve by $z \approx 2$.
Comparing physical properties of galaxies in high and low density environments

- A long-standing prediction of hierarchical models is that early-type galaxies in the field are younger and less massive than those in cluster cores, since galaxy formation is accelerated in dense environments...

- Studies at low redshifts, using FP (Bernardi et al. 06) or fossil record data (Thomas et al. 05) suggest that star formation in low density environments was delayed by 1-2 Gyr

- Important test: at higher redshifts this evolutionary clock delay should become more apparent..

Scenario for the averaged SF history of ETGs inferred from fossil record data: the higher the final mass, the sooner SF starts and the shorter SF lasts (Thomas 05)
Comparing physical properties of galaxies in high and low density environments

Cluster ETGs at $z=1.24$

All with $5 \times 10^{10} < M/M_\odot < 5 \times 10^{11}$

Field ETGs at $z \approx 1.24$ (GOODS)
Age-dating cluster and field ETGs

SFR-weighted age

\[ t_{SFR}(T,\tau) \equiv \frac{\int_0^T (T - t') \Psi(T - t',\tau) dt'}{\int_0^T \Psi(T - t',\tau) dt'} \]

Final formation time

\[ M(t_{\text{fin}}) \equiv 0.99 M(T) \]

difference of 0.5 Gyr in age and 1 Gyr in final formation epoch between cluster and field
Inferred SF History vs Environment and Mass
(the empirical evidence)

1. Similar mean colors, but (slightly) broader color distribution of field galaxies when compared to cluster galaxies in the same stellar mass bins.

2. Inspection of stacked spectra show small differences:

- **High masses**
  - Field
  - Cluster

- **Low masses**
  - Field
  - Cluster

Difference between field and cluster greater at lower masses: “downsizing”

See also FP studies (Treu et al. 05, van der Wel 05, van Dokkum et al. 07)
Inferred SF History vs Environment and Mass
(the empirical evidence)

Difference between field and cluster greater at lower masses: “downsizing”

See also FP studies (Treu et al. 05, van derWel 05, vanDokkum et al. 07)
Comparing cluster CMDs with semi-analytic models
(Menci et al. 08)

The tight RS at z>1 yield impressive constraints on gal formation models:
implies the presence of a process which moves galaxies into a narrow color distribution, acting on very short time-scales at the early epochs,

⇒ challenge for models which predict clusters to be the last structures to virialize (typically at z < 2).

• Using Menci et al. SAMs which include:
  – standard recipes for cooling and SF
  – feedback from SN and AGN
  – environment-dependent effects modulating SF (biased formation, merging/fly-byes, strangulation, AGN feedback)
  – Match most of the observables to date: LFs, MF at z<~3, color bimodal distribution in low and “high” density env. (less than group scale), AGN LF evolution via BH growth etc.)

• But do they reproduce the tight red sequences in the densest environments (rich clusters) out to z=1.3 ??
Field galaxies  
Cluster (M > 10^{14} M_\odot) galaxies

Menci et al. 08  
Evolution of CMDs scatter and normalization from models

(Menci et al. 08)

$C \equiv U - V$ rest frame (Vega)
The larger scatter in color, ages, stellar mass growth in field galaxies originates mostly from a more diverse mass assembly/merging history rather than a global shift in age values.

Models includes physical mechanisms which are able to explain the speed up of the transition from the blue cloud to the RS in high density environs.

The tight RSs at $z \approx 1.3$ in densest environs remain a challenge for models which cannot reproduce the faster time scale in SF/mass assembly in cluster galaxies.

Further acceleration of early mass assembly in clusters will require new physical mechanisms or better understanding of current ones.
K-band Luminosity Function of cluster galaxies out to $z>1$

- The K-band LF traces the stellar mass function of cluster galaxies (near IR light dominated by old evolved stars).

- In the near IR the effect of dust is mitigated and K-correction depends mildly from the galaxy type.

- At these large look-back times, the K-LF is a sensitive probe of the formation scenario (formation redshift and mass assembling history).

- Studies of LF evolution in Field vs Cluster can shed light on environmental dependence of galaxy evolution.
K-band LF vs redshift and environment

corrected for passive evolution by 1.4 mag

Strazzullo et al. 05
Evolution of $K^*$ out to $z=1.4$

(another probe of gal formation models)

(Kodama & Arimoto models)

Strazzullo et al. 06

Strazzullo et al. 06
K-band Luminosity Function of cluster galaxies out to $z>1$

- Compared to local clusters in the same rest-frame band ($z$):
  - Shape of the LF does not evolve significantly
  - $L^*$ brightens by $\Delta M_{L^*} = 1.4 \pm 0.3$ which consistent with $M/L$ evolution from FP studies (passive evolution)

- Massive ($M>10^{11}M_\odot$) early-types (bright end of the LF) were already in place at $z=1.2$ in cluster cores

- These observations might be a challenge for hierarchical models which predict $\alpha$ to steepen and $K^*$ to dim as massive gals break-up in their progenitors. Merging activity must be pushed to high redshifts.

- Shape of K-LFs remarkably similar to the field

- The inferred stellar mass function suggests that most of the stellar mass is already assembled in in massive galaxies by $z\approx1$, both in low and high density environments
Moving to the “Cluster Formation Epoch” ...

- Filling the gap at 1.4<z<2.5: a critical epoch for the formation of baryonic structure
- ~<50% of the stellar mass is assembled
- The global SF rate and the BH mass accretion rate peak there
- The morphology-density relation and the red sequence emerge
- The morphological Hubble sequence emerges
- The first massive (~$10^{14}$ M$_\odot$) virialized structures form (?)
- Who are the progenitors of z>~1 ETGs? (zBZK, DRGs, sub-mm ULIRGs)

Next step...

Realm of “protoclusters”

WFC3/IR(+ACS)

Next generation cluster samples

XMMJ2215

MRC1138

XMMJ2235

ACS

ROSAT limit

look-back time (Gyrs)

redshift

massive cluster formation

10.5

10

2.4

2.2

2.0

1.8

1.6

1.4

1.2

1.0

0.8

0.6

0.4

0.2

0.0

Filling the gap at 1.4<z<2.5: a critical epoch for the formation of baryonic structure
Proto-clusters around high-z AGN

- At high-z (>~2), searches for galaxy overdensities have concentrated on narrow-band Ly-α imaging around powerful AGN (QSO, Radio Gals)

- There has long been evidence that powerful radio galaxies at high redshift (HzRGs, z > 2) are located in the center of (forming) clusters
  - The environment of 3CR radio gals is overdensed
  - Radio rotation measures suggests presence of overdensed magnetized medium

- A systematic study on ten luminous HzRGs at 2.2 < z < 5.2 with the VLT (Miley et al.) has showed clear evidence of the presence of “protocluster environment”:
  - Strong overdensities of Ly-α (and H_α) emitters
  - Velocity distribution shows presence of infall patterns (no virialization, T_{cross}~T_{U}) and mass overdensities (M=<ρ>V(1+δ_m)) of ~>10^{15} M_☉
  - Ubiquitous presence of extended (~100 kpc) Ly-α emission
  - Overdensities of red objects towards the radio galaxies, no presence of a well-defined red sequence though
  - Presence of non-thermal ICM from X-ray observations
MRC1138: a protocluster at $z = 2.2$

**HST-ACS image of the central RG**

- Ly-$\alpha$ emitters
- EROs
- ~3 Mpc (Kurk et al. 06)

33x23' = 270x190 kpc (Miley et al. 06)

(Kurk et al. 06)
A Nascent Red Sequence at $z \sim 2$

MRC1138-262 ($z=2.16$) (Zirm et al. 2008)
TN J1338-1942: a protocluster at $z = 4.1$

(Miley et al. 04)
• Clusters and their baryons (galaxy populations and X-ray gas) were already in an advanced evolutionary state by z=1.4 (passive evol over 9 Gyrs)

• The cluster red sequence remains basically frozen over 9 Gyrs of cosmic history (scatter well within 0.1 mag, obiquitously out to z<1.4) → serious challenge for current galaxy formation models

• Build-up of stellar mass of massive galaxies via SF/merging occurs very rapidly (as well as metal enrichment of the ICM); SF/merging is quenched soon thereafter by not-well understood feedback

• Also galaxy transformation is rapid (blue cloud → red sequence)

• Most of the stellar mass was assembled by z=1 both in clusters and in field, only (mostly) passive evolution ever since

• Properties of ETGs (ages, FP, stellar mass density) in cluster and field envs converge at high-masses, downsizing otherwise
THE END

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The Fundamental Plane of cluster galaxies out \( z=1.25 \)  

\[
\log r_e = \alpha \log \sigma + \beta \log <I_e> + \gamma 
\]

\[
\Delta \ln(M/L_B) \propto (1.0 \pm 0.2) z = f(\tau, \text{IMF}, Z) 
\]

\( \Rightarrow \quad z_f=3.4^{+0.5}_{-0.4} \)  

or \( t=3.0\pm0.3 \) Gyrs before observation  

\( (z_f=2.3\pm0.2 \) Gyrs including the progenitor bias)