The galaxy population of an X-ray luminous cluster at z~1: the HST/ACS colour-magnitude relation

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Outline

INTRO:
- Formation and evolution of early-type galaxies
- Tools to study ETGs
- State-of-the-art on studies of high-z clusters

XMMUJ1229, $z=0.975$ (J.S. Santos et al 2009 A&A)
Photometric, morphological & spectral properties of the cluster galaxies
- XMM1229 dataset
- X-ray analysis
- Colour-Magnitude Relation (CMR)
- Structural analysis: fitting SB models, visual morphological class.
- Spectral Energy Distribution (SED) fitting
- Brightest Cluster Galaxies (BCG)
- Conclusions
Formation & evolution of ETGs

• Scenarios of galaxy formation & evolution:
  1) Monolithic collapse model  
  Eggen, Lynden-Bell & Sandage 1962  
  Massive galaxies formed in a single event at high-z

  2) Hierarchical merging model  
  Toomre 1977  
  ETGs form and evolve through mergers

• Early-type galaxies (ETGs, ellipticals & S0s):
  - found in massive clusters, 60% of the stellar mass
    see review by Renzini 06
  - Passive, i.e., negligible ongoing star formation
  - Compact, bulge-dominated
    Surface brightness:
    de Vaucouleurs  \[ I(r) = I_0 \exp \left[ \left(\frac{r}{r_e}\right)^{1/4} \right] \]
    Sersic  \[ I(r) = I_0 \exp \left[ \left(\frac{r}{r_e}\right)^{1/n} - 1 \right] \]
Formation & evolution of ETGs

• Observational Thomas 05 & Theoretical De Lucia 06 studies show that SFH is mass dependent: massive galaxies have higher formation redshift @ $z \sim 5$

“downsizing” Cowie 1996

STUDY THE EVOLUTION OF ETGs:
1) Fossil record: low-z studies
2) Directly investigate high-z ETG population
Local CMR

CMR scaling relation

\[ \text{Baum 1959} \]

Coma cluster, \[ \text{Bower 1999} \]

Red-sequence of ETGs
small Scatter (~ 0.03 mag in Coma)

-> SFH of ETGs well synchronized

Slope metallicity effect

Zero point age indicator
Spectrophotometric tools

Modelling Spectral Energy Distribution (SED) of galaxies and spectra

- Simple stellar population synthesis models
- Composite stellar population models: star formation, \( \psi(t) = \frac{t}{\tau} e^{-t/\tau} \)
e.g. Bruzual & Charlot 2003, Maraston 2005

- Initial Mass Function
  \( \Phi(m) \propto m^{-2.35} \) Salpeter 1955
  top-heavy IMF Kroupa 01, Chabrier 03

Fitting the SEDs

- photometric data
- obtain stellar ages, masses

Combine stack spectra + photometry of ETGs
constrain star formation histories
State-of-the-art: high-z cluster studies

- ACS Intermediate Redshift Cluster survey, 8 clusters $0.8 < z < 1.2$ Blakeslee 03+06, Homeier 05, Holden 06, Mei 06+09
- RDCS1252 $z=1.23$ Demarco 07

CMR scatter very tight up to $z\sim 1.23$
State-of-the-art: high-z cluster studies

XMMUJ2235, $z=1.39$  
Lidman 08  
NIR CMR, Hawk-I@VLT

Build-up of RS: inside -> outside
State-of-the-art: high-z cluster studies

XMMXCS2215, $z=1.45$ Hilton 09

No evolution of the CMR slope
XMMUJ1229, $z=0.975$

(J.S. Santos et al 2009 A&A)

• XMM-Newton serendipitous discovery:
  XDCP survey Boehringer et al. 2005

• HST/ACS $i_{775}, z_{850}$ + VLT/FORS2 spectra
  Supernova Cosmology Project Dawson et al. 2009

• NTT/SOFI NIR J (40 min), Ks (1 hr)
Analysis

Investigate the properties of the cluster galaxy population

- Intracluster medium: $T$, $Z_{Fe}$, $L_X$

- Galaxy structural analysis: SB profile fitting, visual classification

- Colour-Magnitude Relation: slope, $zp$, scatter
- SED analysis: stellar ages, masses, SFH
- BCG(s) properties
X-ray analysis

• XMM-Newton
  Exp ~ 400 ksec ~ 1300 counts

• Spectral fit
  z = 0.975

$\frac{Z_{\text{Fe}}}{Z_{\text{sun}}}$ = 0.34 ± 0.14

T = 6.5 ± 0.7 keV

$L_{X[0.5-2.0]}$ = 3.3 $10^{44}$ erg/s
Redshift distribution

Target selection: R-Z colour

Priority 1: \((R-Z) > 1.8\) and \(z < 23\)

Priority 2: \(1.6 < (R-Z) < 1.8\) and \(z < 23\)

median \(z=0.975\)

Cluster members = 27

(21 members in ACS FoV)
Velocity dispersion

\[ \sigma = 683 \text{ km/s} \]

Beers 1990 estimator

\((\Delta z=10^{-3})\)

Within the large scatter of \(T_x - \sigma\) relation

\(T_x - \sigma\) High-z clusters Rosati 2002

\(T_x - \sigma\) relation Wu 1999,
Visual classification of cluster members

ACS galaxy templates: Postman 2005
Structural analysis

Sersic model fitting with GIM2D Simard 2002

Spec gals
median Re = 5.5 pix
median n = 3.9
Colour-Magnitude Relation I

Standard method: PSF aperture correction from data

PSFs

$i_{775} = 0.085''$

$z_{850} = 0.095''$

Correction: 0.03 mag @ $r=0.25''$

$→$ colour aperture
Colour-Magnitude Relation I

Standard method: PSF deconvolved from data

Colour \( r = 0.25'' \)

spec members only:
- Robust linear fit
- CMD \( \sigma = 0.04 \) mag

photometric sample
- 31 galaxies in 3 \( \sigma \) region
- CMD \( \sigma = 0.05 \) mag
Colour-Magnitude Relation II

Different approach: use galaxy models GIM2D, PSF convolved with models

Colour $r = 0.25''$

CMR slope = -0.031, $ZP = 0.829$, $\sigma = 0.04$

(all) CMR slope = -0.022, $ZP = 0.814$, $\sigma = 0.05$
SED fitting

Stellar masses & ages of 16 spec members + 18 “red-sequence” gals

1) PSF matching
- Growth curves of stars in the science images
- Match $i_{775}$, $z_{850}$, $Ks$ data to J-band seeing
- Aperture photometry in fixed aperture $r=0.5”/1.2”$
- Extrapolate to 3” radius -> bulk of the flux

Image quality

$\text{i}_{775} = 0.085”$  
$\text{z}_{850} = 0.095”$  
$Ks = 0.69”$  
$J = 0.98”$

2) Fitting:
- 3-parameter fit (age $T$, $\tau$, mass)
Bruzual & Charlot 2003 models, delayed exponential SFR,

$$\psi (t) = \frac{t}{\tau} e^{(-t/\tau)} , \tau = [0.2-5.8] \text{ Gyr}$$

- Solar metallicty
- Salpeter IMF, cut off $[0.1-100] \text{ M}_\odot$
SED fitting

SED of one of the brightest galaxies
SED fitting: masses, ages

ETGs:

$M = 7 \times 10^{10}$ sun

SF weighted age = 4.3 Gyrs

(median values)

Spec members
Red-sequence sample
OII / late-types
Star formation history

Stacked spectrum of 8 passive galaxies with no H$_\delta$ absorption

$z_{\text{form}} = 3.0 \pm 0.5$

Age = $3.7^{+0.4}_{-0.5}$ Gyr
Brightest Cluster Galaxy(ies)

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<tr>
<th>ID</th>
<th>3507</th>
<th>3430</th>
<th>3025</th>
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<td>$Z_{850}(AB)$</td>
<td>21.47</td>
<td>21.06</td>
<td>21.05</td>
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<tr>
<td>Dist X-ctr (&quot;)</td>
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<td>5</td>
<td>78</td>
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<td>$M \left(10^{10} M_{\odot}\right)$</td>
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<td>23</td>
<td>20</td>
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<tr>
<td>Age (Gyr)</td>
<td>5.74</td>
<td>5.74</td>
<td>4.83</td>
</tr>
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Conclusions

• **X-ray properties** show that XMM1229 is a massive cluster (> L*)
  \[ T = 6.5 \text{ keV}, \frac{Z_{\text{Fe}}}{Z_{\text{sun}}} = 0.34 \]

• **\(i_{775} - z_{850}\) CMD:**
  1) Standard method, scatter = 0.04 mag -> construct “red-sequence” sample
  2) Model CMD, scatter = 0.04 (0.05) mag
  CMD parameters consistent with other works at high-z

• **Velocity dispersion:** \(\sigma = 683 \text{ km/s}\)

• **Galaxy morphology:** deficit of S0s?
  – Spec gals: high Sersic index \(n (~ 3.9)\) \(15/21\) EII, \(4/21\) S0s
  – “Red-sequence” gals: high Sersic index \(n (~ 3.7)\) \(22/31\) EII, \(9/31\) S0s

• **Old & massive galaxy population** mass: \(7.4 \times 10^{10} M_{\text{sun}}\) SFR age: 4.3 Gyr
• **3 bright galaxies** instead of one prominent BCG

ICM-galaxy population: high \(\frac{Z_{\text{Fe}}}{Z_{\text{sun}}} + \) old gals -> chemical enrichment ended