Brightest Cluster Galaxies

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Outline

• Galaxy Clusters
• Brightest Cluster Galaxies (BCGs)
• The growth of BCGs below $z \sim 1.5$
• BCGs beyond $z \sim 1.5$
Acknowledgments

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Galaxy Clusters

- Dominated by early-type galaxies
- Recognizable examples up to $z \sim 2$ (~10 billion years ago)
- Span a wide range of masses - $10^{13} - 10^{15}$ solar masses
- Grow significantly over that time
- Increase in star formation in the core beyond $z \sim 1.6$

RDCS J1252.9-2927 $z=1.24$
Growth of Galaxy Clusters

Start with a cluster of $10^{14}$ solar masses at $z \sim 2$
How does it grow?

Fitting formulae taken from Fakhouri et al. 2010
Dynamical Friction

\[ t_f = \frac{2.34}{\ln \lambda} \frac{\sigma_M^2}{\sigma_S^3} r_i \]
Growth of Galaxy Clusters

At later times it takes longer for galaxies to reach the core.
BCGs

Distinct from the general population due their privileged position

Consistent set of properties

• extended light profiles
• alpha element enhanced
• slightly younger ages
• more likely to host radio loud AGN
• slow rotators (?)
• ...

Their distinct properties and the ease at which they can be identified in both observations and simulations up to $z \sim 1.5$ makes them an attractive object to study
The growth of BCGs

DeLucia et al. 2008
The growth of BCGs
A new sample

- 10 BCGs from SpARCS (0.85 < z < 1.34)
  - Discovered as over-densities in IRAC images
  - 50-100 spectroscopic members each

- 2 BCGs from 2 newly confirmed z=1.6 SpARCS clusters

- 15 BCGs from CNOC1 z~0.3

- 130 from the literature (0.03 < z < 1.46)

Janette Suherli - 2011
SpARCS

- Spitzer Adaptation of the Red-sequence Cluster Survey

- Deep-wide z’-band survey combined with Spitzer SWIRE 50 deg$^2$ survey

- Clusters are selected based on z’-[3.6] color (gives photo-z)*

- 200 new cluster candidates $z > 1$ with estimated $M > 1 \times 10^{14} \, M_{\odot}$

Wilson et al. (2009), Muzzin et al. (2009), Demarco et al. (2010)

Large sample of $z > 1$ clusters
Spectroscopic follow-up

The Gemini CLuster Astrophysics Spectroscopic Survey “GCLASS”

- Spectroscopic survey of 10 rich clusters at $z \sim 1$ ($0.87 < z < 1.34$) with Gemini/GMOS
- ~210 hr (25 night) multi-semester project with Gemini/GMOS (completed 2011B)

Observational goal: Spectroscopy of 50 members in each cluster

- Low-res: $R=450 = 17\text{Å} = 400\text{km/s}$
- 4 to 6 masks per cluster (46 total)
- 3.6μm selected sample of galaxies
- Nod & Shuffle mode with microslits
Near-IR images

Obtained using WIRCAM, ISPI and HAWKI
Magnitude vs. Redshift

- Stott et al. (2008)
- Stott et al. (2010)
- This work

- BC03 SSP $z_f = 2$ $Z = 0.02$
- BC03 SSP $z_f = 5$ $Z = 0.05$
- BC03 $\tau = 0.9$ $z_f = 5$ 40/60
- BC03 DeLucia $Z = 0.05$
- M05 SSP $z_f = 4$ $Z = 0.04$
Estimating the mass

![Graph showing the relationship between lookback time and redshift, with different models and observations represented.]

- Stott et al. (2008)
- Stott et al. (2010)
- This work

Models:
1. BC03 SSP $z_f = 2$ $Z = 0.02$
2. BC03 SSP $z_f = 5$ $Z = 0.05$
3. BC03 $\tau = 0.9$ $z_f = 5$ 40/60
4. BC03 DeLucia $Z = 0.05$
5. M05 SSP $z_f = 4$ $Z = 0.04$
BCGs mass evolution
BCG mass and halo mass

Cluster mass ($M_\text{c}$) vs. BCG stellar mass ($M_\odot$) at $0.3 < z < 0.8$.

- **Best fit**
- **Constrained fit**

Data points are color-coded by redshift:
- Blue: $z \leq 0.3$
- Green: $0.3 < z \leq 0.8$
- Red: $z > 0.8$
Accounting for the correlation

Growth by a factor of \(~1.8\) between \(z\sim1\) and \(z\sim0.2\)

![Graph showing growth by a factor of ~1.8 between z~1 and z~0.2](chart.png)
What causes the growth?

1. Star Formation from accreted material
2. Mergers (major and/or minor)
BCGs and their bright friends

Companions are the 2nd to 4th brightest cluster galaxies
Will they merge?

- Average separation of 20 kpc
- The pairs are centred in their potential wells - they only sense the mass inside their orbits
- The relative velocities between the companions and the BCGs are around a few 100 km/s
- These galaxies will merge within 0.6 Gyr
- One pair shows evidence of a merging occurring
The expected number of companions

Uncertainties are large
Excess of bright companions
Growth over ten billion years

Is there a levelling off in the growth over the past few billion years?
A more detailed look

Figure 3.5: Hubble Diagram of the BCGs analysed within this study, as well as BCGs analysed in previous studies.

New clusters from RELICS

Work by Sabine Bellstedt
Summary

- BCGs increase their stellar mass by a factor of about 2 between $z=1$ and today.
- At $z \sim 1$, most of this increase seems to occur through dry major mergers. While star formation is apparent in some BCGs at these redshifts, it is not the mechanism by which BCGs acquire most of their stellar mass.
- The growth rate may be slowing down.

What is happening at higher redshifts?
Pushing to higher redshifts

From Muzzin et al. 2013

Red Sequence Method

Stellar Bump Sequence
A Cluster at z=1.63

\[ \sigma = 700 \pm 190 \text{ km s}^{-1} \]
\[ M_{200} = (2.4 \pm 1.5) \times 10^{14} M_{\text{Sun}} \]
\[ M(z=0) \sim 2 \times 10^{15} M_{\text{Sun}} \]

Wilson et al. 2015, in prep

z'Y[3.6] color image. FOV is 3 x 3 arcmin (1.5 x 1.5 Mpc)
An increase IR bright BCGs at z~1.5

The IR colours suggest that most of the IR luminosity comes from star formation and not AGN

What causes this - gas rich mergers or cooling flows?
Star formation in cluster cores

Beyond $z \sim 1.4$, there are an ever increasing number of known clusters with star formation in the cluster cores:

- XMMXCS 2215 ($z=1.46$) Hilton et al. Hayashi et al.
- XDCP J0044.0–2033 ($z=1.58$) Fassbender et al.
- CIG J0218.3–05101 ($z=1.62$) Tran et al.
- SpARCS 1049+56 ($z=1.71$) Webb et al.
- MRC 1138–262 ($z=2.16$) Hatch et al.

Galaxies are able to reach the cluster core while still forming stars. In other words, there has not been time for them to become fully quenched.
A massive cluster at $z=1.71$

22 members; mass $\sim 3 \times 10^{14} \, M_{\odot}$

Webb et al. 2015
Strong MIPS source near to the BCG

SED fit using HST near-IR, Spitzer, Herschel and SCUBA2

1000 solar masses per year!

$\chi^2/\nu = 1.3$

$L_{\text{IR}} = 5.4 \times 10^{12} L_\odot$

$SFR = 936 M_\odot/yr$

$\chi^2/\nu = 0.4$

$L_{\text{IR}} = 6.6 \times 10^{12} L_\odot$

$SFR = 1142 M_\odot/yr$

Figure 5. Top: The two-color (F160W, F105W) HST image of the central region of SpARCS1049, showing the complex morphology of the core. Diffuse emission in a tidal-tail shaped structure is visible, and embedded along its length are multiple clumps. The crosses mark the centroid of the 24 µm emission. Bottom: The 3.6 µm image of the same region (greyscale) with MIPS flux contours overlaid (orange) to show the location of the 24 µm centroid and the mild extent of the source in the N/S direction.

Figure 6. The infrared spectral energy distribution from the combined C F I R A C / M I P S / I R S / S P I R E / S C U B A 2 measurements—where the rest-frame optical photometry corresponds to the BCG. The photometric points are shown in dark blue and the IRS spectrum in cyan. The blue arrows show the 3$\sigma$ limits of the PACS measurements. Overlaid (solid black line) is the infrared template SED for $z \sim 2$ ULIRGs developed by Kirkpatrick et al. (2012), with the scatter in this SED denoted by the grey shading. The magenta and red curves correspond to the best-fit SED from the (Chary & Elbaz 2001) template library, with and without the BCG optical data included. Both SEDs are scaled to best-fit the photometric points only; the fit shown includes the IRS spectrum which provides an infrared luminosity of $L_{\text{IR}} = 6.6 \times 10^{12} L_\odot$. The green dotted line shows a modified blackbody ($\beta = 1.7$) fit to the SPIRE and SCUBA2 photometry which provides yet another estimate of the infrared luminosity, that is independent of the assumed SED. The dust temperature is found to be $T = 44 \pm 5$ K and $L_{\text{IR}} \sim 4 \times 10^{12} L_\odot$, which is consistent with the full SED, but lower because it does not contain a hot dust component.
A dry+wet merger?

Webb et al. 2015

Why are these kind of mergers less common at lower redshifts?
Summary

- BCGs increase their stellar mass by a factor of about 2 between $z=1$ and today
- Some of this occurs through major mergers
- There are some suggestions that the growth slows down

- Increasing fraction of BCGs at $z\sim1.5$ with high IR luminosities
- Star formation is occurring in the cores of some rich clusters at $z=1.4$. Galaxies are able to reach the cluster core while still forming stars.
- Discovery of SpARCS 1049 at $z=1.71$, a possible dry+wet merger caught in the act
A caveat on photometry

In the literature, three techniques are commonly used

- Profile fitting (e.g. GALFIT)
- Apertures with a constant physical size
- Scaled apertures (e.g. MAG_AUTO in SExtractor)

All are biased.

Ideally, one would like to perform the measurement on real and simulated data.