Evolution of the most massive galaxies: a statistical study of SDSS LRGs

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Massive galaxies in the nearby universe

- Old stellar populations and low star formation rates
- The most massive galaxies are along the red sequence
- Spectra dominated by old stars

SDSS, Hogg et al 2004
Massive galaxies at high-z

- The most massive galaxies are also the oldest out to z~2 (10 Gyr ago)
- Colors possibly imply low star formation since shortly after creation

Whitaker et al 2010
Massive galaxies at $z=2$

- Continuous (and slow) mass growth from $z=2$ to $z=0$

van Dokkum et al. 2010
How do massive galaxies grow?

- Star formation rates are low at 0<z<1
  (e.g., Faber 73, Balogh+04, Worthey+92, Peletier 98, Jørgensen+99, Trager+00, , Kauffmann+03, Hogg+04, Thomas+05)

- Major mergers
  (e.g., van Dokkum+99, Patton+02, Tran +05, van Dokkum 05, Bell+06, Boylan-Kolchin+06, Naab+06, Bundy+06, Masjedi+06, Wake+06, McIntosh+08, Wake+08, Masjedi+08, Bundy+09)

- At least some growth due to minor mergers
  (e.g., Kormendy+89, Schweizer+92, van Dokkum 05, Naab+07,09, Bournaud+07, Stewart+08, Bezanson+09, Tal+09)
Minor mergers

• Consistent with simple analytic calculations

Bezanson et al. 2009
Observing (minor) mergers

• Direct observations of individual systems and their environments
  – Detailed information from photometry and spectra (accurate sizes, colors, neighbors, dynamical state)
  – Observationally expensive: high quality images and spectra are typically limited to small samples
    • HSC survey

• Alternative – statistical analysis
Statistical study of massive galaxies

- Well defined sample → LRGs
  - Properties of individual systems close to average properties
- Large sample → SDSS
  - Meaningful statistics
- Contamination → Important
Luminous Red Galaxies (SDSS)

- The reddest, most massive galaxies in SDSS \((10^{11}-10^{12} \, M_\odot)\)
- 90% are group centrals
- Selected in a narrow redshift bin

Wake et al. 2008
Luminous Red Galaxies (SDSS)

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[Graph showing redshift distribution of SDSS LRGs]
Massive galaxies at extremely large radii

EVIDENCE FOR MERGERS IN THE STELLAR HALOS OF LRGS
Mergers and stars

• Major mergers – stars from progenitors are well mixed in the resulting system
Mergers and stars

• Major mergers – stars from progenitors are well mixed in the resulting system

• Minor mergers – tidal stripping distributes accreted stars preferentially in outskirts
Stellar accretion via tidal stripping

• Energy balance:

\[ V^M_{\text{circ}} = V^m_{\text{esc}} \]

• “Typical” radius of accreted stars:

\[ R_a = \frac{M}{m} \frac{r_m}{2} \]
Color profile of individual ellipticals

- Steep color gradient at small radii
- Only a few galaxies with a measurement at $r > 15$ kpc
- Kormandy+09
Alternative - stacking

• Averaging a large number of galaxy images

• Improve noise properties by a factor of \( \sqrt{n} \)

• Lose all information from any single objects

→ LRGs – essentially a single parameter population of galaxies
Stacking

- 42,000 images
- 2.3 Msec integration time, equivalent to 40 hours on 10m class telescope
- Background removed using random stacks
Light Profiles

- PSF
- Reach r-band surface brightness of 31.5 mag arcsec$^{-2}$
- Well fitted with single Sersic parameter set out to 100 kpc
- Sizes typically underestimated by 10% and flux by 20%
Color profile

- Profile in inner $\sim 30$ kpc matches nearby galaxies
- Flattens out at $\sim 50$ kpc out to 100 kpc
- Consistent with minor mergers
Stellar accretion via tidal stripping

- "Typical" radius of accreted stars:

\[
R_a = \frac{M}{m} \frac{r_m}{2}
\]

\[
R_a \approx 60 \left( \frac{M}{m} \frac{r}{10 \, \text{kpc}} \right) \left( \frac{r}{6 \, \text{kpc}} \right) \, \text{kpc}
\]
Stellar accretion via tidal stripping

• “Typical” radius of accreted stars:

\[ R_a = \frac{M}{m} \frac{r_m}{2} \approx 60 \left( \frac{M}{m} \right)^{10} \left( \frac{r}{6 \text{kpc}} \right) \text{kpc} \]
Observations of satellite galaxies around SDSS LRGs

THE ENVIRONMENTS OF LUMINOUS RED GALAXIES
Environment

• Important for understanding mergers - which galaxies do massive galaxies merge with?

• Estimates of a typical mass ratio
• Describes the mass that surrounds (and affects) the studied galaxy

• Difficult and expensive

→ Statistical analysis of many (LRG) environments
SDSS and BOSS LRGs

- Two redshift bins: $z \sim 0.34$ and $z \sim 0.65$
- Number-density matched
Photometry

- Detect all objects in 500 kpc apertures around each LRG
- Low detection threshold
- Repeat in randomly selected positions within the same SDSS imaging fields
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- Also in random fields
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- Also in random fields
- Subtract one from the other
The luminosity function of satellite galaxies

- Measure luminosity distribution in LRG fields
- Also in random fields
- Subtract one from the other
- Poor fit by just a Schechter function – use two-parameter fits
Deep stripe 82 images

- Using deep Stripe 82 data we constrained Schechter slope, detection threshold
Gap properties

- Width measurement:

\[ \int_{L_2}^{\infty} \Phi(L) d \log L = 1 \]

\[ \Delta M = 2.5 \log \left( \frac{L_2}{L_{cen}} \right) \approx 1.3 \text{mag} \]

at both redshifts

- LRG peak consistent with passive luminosity evolution
Selection and the gap

- Gap can be reproduced by randomly sampling a Schechter distribution.
- Underlying luminosity distribution may not be unique.
The mass growth of LRGs through mergers

- The gap width implies a typical mass ratio of 1:4 between the central galaxy and its most massive satellite
- Mergers of higher mass ratio within the environment unlikely
The radial distribution of satellite galaxies around LRGs

DARK AND LUMINOUS MATTER: WHAT SATELLITE GALAXIES TELL US
Where do LRGs live

• Luminous matter is only part of the story
• Really need total mass – mostly dark matter

• Cluster/group observations of dark matter are difficult
  – X-ray, lensing, clustering

• Alternative – satellite galaxies as tracers of mass
  – Already have that!
Method
Method

- B-spline model
- Subtracted image
- LRG and Surrounding sources
Completeness

- Radial, 4th order B-spline model fitting (Bolton+06)
- Improved source detection well inside of 10 kpc
Radial binning

- Combine measurements from 28,000 fields
- Radial distribution of sources in LRG and random apertures
Radial profile of satellite galaxies

- Foreground and background subtracted profile → satellite galaxies
- Profile confidently traced in the range $7 < r / \text{kpc} < 700$
- Power-law model fit
NFW model fit

• Overall well fitted by NFW
NFW model fit

- Overall well fitted by NFW
- Very good fit at large radii
- Significant excess at very small radii
Stellar light profile

Taken from a stack of >40k LRG images at same redshift

(Tal & van Dokkum 2011)
Luminous and dark mass profile
Small radii excess

- Fit to NFW+Sersic is excellent on all scales
- Consistent with Dark/baryonic mass ratio of ~80 – consistent with weak lensing measurements

![Graph showing number of satellites per LRG vs. radius (kpc), with completeness and radii labeled. The graph includes a fit to the data and other profiles.](image-url)
Summary

• Detailed analyses using statistical tools
  – Deep stacks
  – Satellite properties and distribution
• Evolution overall consistent with growth through minor mergers
• LRGs are unique – super massive for their halos
• Next (HSC survey?)
  – Satellite galaxy properties
  – Range of central galaxy masses, colors etc.