LoCuSS: The slow quenching of star formation in cluster galaxies at z~0.2

Chris Haines (Universidad de Chile)

Eiichi Egami, Maria Pereira (Steward Observatory), Graham Smith, Felicia Ziparo (Birmingham), Alexis Finoguenov (Helsinki), Arif Babul (Victoria), Tim Rawle (ESAC), Nobuhiro Okabe (ASIAA)
How long are $\sim L^*$ spiral galaxies able to continue forming stars after they have been accreted into a massive galaxy cluster?

- Rapid quenching ($t_Q < 10^8 \text{ yr}$)
  - Violent processes:
    - e.g. mergers, extreme ram-pressure stripping events

- Slow quenching ($t_Q > 10^9 \text{ yr}$)
  - Gentle processes:
    - e.g. starvation, incremental ram-pressure stripping
LoCuSS: The Local Cluster Substructure Survey

- Survey of 30 X-ray luminous clusters at 0.15<z<0.30 from ROSAT All Sky Survey cluster catalogues ($M_{200} > 3 \times 10^{14} M_{\odot}$; Okabe et al. 2010)

- Spitzer 24μm maps over 25’x25’ (2-3$r_{200}$) => obscured star formation
  \[ SFR(M_{\odot} \text{yr}^{-1}) = 7.8 \times 10^{-10} L(24\mu\text{m},L_{\odot}) \]  (Rieke et al. 2009)

- Deep GALEX NUV data for 23/30 clusters => unobscured SF

- Chandra/XMM X-ray data => $\rho_{\text{ICM}}(r)$ and $r_{500}$ for each cluster
  \[ r_{200} \approx 1.50 \ r_{500} \]  (Sanderson & Ponman 2003)

  Identify X-ray AGN as point sources in Chandra data

- Wide field $J,K$ and optical imaging (stellar masses, photo-z)
ACReS: Arizona Cluster Redshift Survey

- **ACReS**: Long term survey program with Hectospec on the 6.5m MMT obtaining spectra over 1-deg field for each cluster, providing ~24,000 redshifts, including 10,950 cluster members (126-1083 per cluster)

- K-band selected, reaching $K^*(z)+2.0$ for each cluster => approximate stellar mass selection with $M_*>10^{10}M_\odot$

- Prioritize 24µm-detected sources to provide complete census of obscured star-formation down to $2 M_\odot$ yr$^{-1}$.

- 96.4% complete for cluster galaxies detected at 24µm

- 80% complete for overall cluster population to $K^*+1.5$

- Obtain coeval field galaxy sample by considering narrow redshift slices either side of each cluster for which survey is still complete
Star-forming galaxies lie within narrow range of sSFR. Can constrain $\langle sSFR \rangle$ versus environment at fixed mass.
Comparison of cluster and field sSFRs at fixed stellar mass

The sSFRs of star-forming galaxies in clusters ($r_{\text{proj}}<r_{200}$) are systematically 30% lower than star-forming field galaxies of the same stellar mass and redshift (8.7σ significance)

Field galaxies
Cluster ($<1.5r_{500}$)
$0.15<z<0.25$

Does this reduction in sSFRs extend beyond $r_{200}$ and into the cluster infall regions?

Haines et al. (2013), ApJ, 775, 126
Comparison of cluster infall region and field sSFRs

No, the sSFRs of star-forming galaxies in the infall regions of clusters are indistinguishable from those in the field.

The systematic reduction of sSFRs appears to be a cluster-specific phenomenon.

Haines et al. (2013), ApJ, 775, 126
The systematic reduction in sSFRs suggests that many if not most of the star-forming galaxies in clusters are observed in the process of being quenched.

This implies that the quenching is a long, slow process.

How can we estimate this quenching time-scale?
**LoCuSS:** The infall of galaxies onto clusters

- In a ΛCDM Universe, star-forming galaxies are continually being accreted onto clusters from the surrounding infall regions. Their specific-SFRs should be the same as coeval field galaxies.

**Diagram:**
- **ICM** $T \sim 10^8 K$
- Massive cluster $M_{200} \sim 10^{15} M_{\odot}$
- Time; $r/r_{200}$
LoCuSS: Rapid quenching of star formation

- If star-formation is quenched rapidly ($<10^8$ yr) when galaxies are accreted into clusters...
Locuss: Rapid quenching of star formation

- If star-formation is quenched rapidly (<$10^8$ yr) when galaxies are accreted into clusters, we will see few cluster galaxies in the process of being quenched, leaving the specific-SFR distribution almost unaltered.
**LoCuSS:** Slow quenching of star formation

- If instead the quenching occurs slowly over $>10^9$ yr time-scales, we should see *many* cluster galaxies *in the process of* being quenched, with *reduced* s-SFRs, *skewing* the overall s-SFR distribution downwards.
**LoCuSS:** The effect of a decrease in sensitivity

- The level of skewing and number of quenching galaxies depends on the depth of the SFR completeness limit relative to the SF main sequence. Both are reduced as the survey becomes shallower...

Massive cluster $M_{200} \sim 10^{15} M_{\odot}$

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**Diagram:**
- Logarithmic scale for s-SFR
- $r_{200}$ radius
- INFALLING GALAXIES
- SLOW QUENCHING
- SURVEY COMPLETENESS LIMIT
- Time; $r/r_{200}$
LoCuSS: Rapid quenching of star formation

- The fraction of star-forming cluster galaxies observed while being quenched, $f_Q$, increases roughly linearly with the quenching timescale $t_Q$.

\[ f_{\text{NQ}} \approx 85\% \quad r_{200} \quad f_Q \approx 15\% \]

- Time: $r/r_{200}$
Based on the observed reduction in sSFR, we estimate $f_Q = 60 \pm 10\%$.
To convert $f_Q$ into a quenching time-scale, we need to use cosmological simulations to follow how star-forming galaxies are accreted into clusters.
LoCuSS: Millennium simulation

- Need to place clusters in the cosmological context of continually accreting galaxies and groups from the surrounding large-scale structure
- The Millennium DM-only cosmological simulation covers $(500h^{-1}\text{Mpc})^3$ contains many massive clusters, while SAMs populate the DM halos with galaxies
- Database gives positions, masses, velocities of galaxies, halos at 63 snapshots

- Extract volumes around the 75 most massive clusters at $z=0$
- Follow the orbits of galaxies around each cluster halo to determine $z_{\text{acc}}(<r_{200}), \text{vel}(z)$
- Create “observations” of each cluster for a distant observer along z-axis, including all galaxies projected along the line-of-sight
- Stack all 75 systems (scaling by $r_{200}, \sigma$) to reduce impact of cluster-to-cluster scatter
Simulations: Redshift-space of cluster galaxies

Cluster galaxies lie within “trumpet”-shaped caustics
Most galaxies along the caustics are infalling. They are physically outside $r_{200}$ and have yet to encounter the cluster environment.
15.3% of “spectroscopic” cluster members within $r_{200}$ (1.5 $r_{500}$) have yet to be accreted (pass within $r_{200}$) by the epoch of observation ($z=0.21$).
15.3% of “spectroscopic” cluster members at $r_{\text{proj}} < 1.5r_{500}$ that are yet to be accreted

The 22.9% of “spectroscopic” cluster members at $r_{\text{proj}} < 1.5r_{500}$ that were most recently accreted into the cluster

Best-fit e-folding quenching time-scale $t_Q \sim 0.7-2.0$ Gyr

Haines et al. (2013), ApJ, 775, 126
Results: The observed SF-radius relation

The $f_{\text{SF}}$ increases steadily with radius out to $2 \, r_{200}$.

Star forming galaxies are found at all radii, even the very cores of clusters.
Results: The observed SF-radius relation

GALEX UV data provides a complementary selection of star-forming galaxies for 23 out of our 30 clusters.

Even out at 3 $r_{200}$, the $f_{\text{SF}}$ remains well below that seen in the coeval field population.
Results: Modelling the SF-radius relation

Simplest model: Assume infalling galaxies have the same $f_{\text{SF}}$ as our coeval field population, and are instantaneously quenched upon passing within $r_{200}$ for the first time.

Linear trend extending to 3 $r_{200}$ shaped by contribution from “back-splash” galaxies, is qualitatively similar but much steeper than observed relation.

Use Millennium simulation to predict SF-radius relation for the 75 most massive clusters.
Results: Modelling the SF-radius relation

Delayed quenching models:
The star formation in infalling SF galaxies is rapidly quenched, but only after a delay of $\Delta t$ Gyr after passing within $r_{200}$

A short delay of 0.7-2.2 Gyr is able to reproduce the $f_{\text{SF}}$ in the cluster cores, but no model can fit the shortfall of star-forming galaxies at large radii ($r_{\text{proj}} > 2 r_{200}$)
Pre-processing models:
To reproduce observations, the $f_{\text{SF}}$ of the galaxies arriving onto the cluster must be lower than that of the coeval field population.

Evidence for pre-processing in galaxy groups prior to their arrival into massive clusters?
Galaxies infalling into clusters are more likely to already be hosted in group-mass halos than coeval field galaxies of the same stellar mass, and being pre-processed.

Accretion bias: The halo mass function near clusters will be biased to higher masses than average.

We measure the mass function of halos hosting $\sim L^*$ galaxies in the infall regions of clusters (not including those galaxies already accreted into the cluster).
Results: The ongoing assembly of Abell 1763

$r_{200} \quad z=0.2320$
For the 23 clusters with XMM data, we identify 30 X-ray groups infalling into the clusters with SNR>4. Just 6 other 0.15<z<0.3 “field” groups seen. Lots of scope for pre-processing and cluster mass assembly.
The surface density of star-forming galaxies declines steadily with radius, falling ~15x from core to $2r_{200}$. 

All $M_K < -23.10$ gals

$(NUV - r)_{0.0} < 4.5$

SFRs > 2.0 M$_\odot$ yr$^{-1}$
The surface density of star-forming galaxies declines steadily with radius, falling ~15x from core to 2 r_{200}.

If infalling star-forming galaxies are instantly quenched upon accretion, we expect flat $\Sigma(r)$ profile for star-forming cluster galaxies. We can exclude such immediate quenching models.
The surface density of star-forming galaxies declines steadily with radius, falling \(~15\)x from core to \(2 \ r_{200}\). If infalling star-forming galaxies are \textit{instantly} quenched upon accretion, we expect flat \(\Sigma(r)\) profile for star-forming cluster galaxies. We can exclude such immediate quenching models. Star-forming galaxies must survive for 2-3 Gyr after accretion to build up the apparent “over-density” of star-forming galaxies in clusters.
Results: The phase-space distribution of SF galaxies

Star-forming galaxies have l-o-s velocity dispersions which are 10-35% higher than their passive counterparts at all cluster-centric radii.

The $\sigma_{\text{los}}(r)$ profile of star-forming galaxies shows a sharp peak at $r_{\text{proj}} \sim 0.3r_{500}$, consistent with model predictions including recently accreted galaxies.
Results: The phase-space distribution of SF galaxies

Attempt to match the distribution of SF galaxies in the caustic diagram, by model infalling cluster galaxy populations whose SF declines exponentially upon accretion.
Best fit by models with $t_Q = 1.96 \pm 0.27$ Gyr

Attempt to match the distribution of SF galaxies in the caustic diagram, by model infalling cluster galaxy populations whose SF declines exponentially upon accretion.
Results: Constraining $t_Q$ from z-space dist. of SF gals

Best fit by models with $t_Q = 1.96 \pm 0.27$ Gyr

Consistent with $t_Q = 1.14$ Gyr implied by 30% reduction in sSFRs of cluster galaxies within $r_{200}$
**Discussion: Relation of Gas Removal**

- Infalling star-forming L* galaxies are stripped on time-scales of 0.7-2.5 Gyr up to 0.5 M• despite the presence of gas in the cores.

- The hot diffuse gas halo of galaxies (Bigiel et al. 2008) is strong enough to prevent further gas accretion onto the galaxy, resulting in independent time-scales of 2-3 Gyr (Bigiel et al. 2008).

- Infalling spirals encounter gradually increasing ICM densities and ram pressures which incrementally strip gas from their disks from the outside-in as they travel from the cluster outskirts to the core.

- Effective time-scale for ram-pressure stripping is the ~0.5-1 Gyr time required for infalling spirals to travel from \( r_{200} \) to the cluster core.
Take-home points

• Star-formation in high-mass ($>10^{10}M_\odot$) spiral galaxies is slowly quenched on $\sim 2$ Gyr time-scales when they are accreted into massive clusters at low redshifts

• Consistent picture of slow quenching on 2 Gyr time-scales from:
  • (i) reduction in specific-SFRs of star-forming cluster galaxies,
  • (ii) radial surface density profile of star-forming galaxies and
  • (iii) distribution of star-forming galaxies within caustic diagram

• Caveat: $t_Q$ may vary with stellar mass, halo mass and redshift

• Pre-processing in infalling galaxy groups may halt star formation in galaxies prior to their arrival into clusters
The radial surface density profile $\Sigma(r)$ for cluster galaxies predicted by the Bower et al. SAM is too steep for $r_{\text{proj}} < 0.1 r_{500}$. The radial surface density profile $\Sigma(r)$ of cluster galaxies can be well fit by an NFW profile with $c_g = 3.0$. The $\Sigma(r)$ profile for cluster galaxies predicted by the Bower et al. SAM is too steep for $r_{\text{proj}} < 0.1 r_{500}$. The DM halos hosting galaxies are continually stripped over $\sim 5\text{Gyr}$ after accretion into clusters. SAMs introduce “orphan galaxies” who lack a DM sub-halo. Affects our model trends within 0.1 $r_{500}$. All $M_K < -23.10$ gals ($\text{NUV} - r_{0.0} < 4.5$, SFRs $> 2.0 \text{M}_\odot \text{yr}^{-1}$).
LoCuSS: A census of star-formation at 0.1<z<0.35

Haines et al. (2013), ApJ, 775, 126