When Galaxy Clusters Collide: the impact of merger shocks on galaxy evolution

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In the Footsteps of Galaxies, 11 September 2015
Structure formation leads to shocks!

• Clusters grow through mergers
• Structure formation is a very violent process which leads to energy releases of up to $10^{64}$ erg (e.g. Hoeft et al. 2004)
• Some of the energy is released in the form of shocks
• Cosmological simulations predict $M=1-10$ shocks to be common in clusters and the filaments that connect them (e.g. Pfrommer et al. 2006)
Cluster radio relics

- Extended (Mpc-wide), diffuse patches of radio synchrotron emission
- Located at the outskirts of merging clusters
- No obvious optical counterpart
- Associated with the electrons in the ICM

Abell 3667

X-ray intensity in color, radio emission in white contours (Rottgering et al. 1997)
Why are relics important?

- The largest particle accelerators in the world!
- Select merging clusters
- Study effect of cluster merger on galaxies

The LHC is not impressed with radio relics! Maybe it's just jealous!
The 'Toothbrush' and 'Sausage' clusters

- $z \approx 0.2$
- Extremely massive ($> 10^{15} \, M_\odot$)
- X-ray luminous, disturbed morphology
- Merger in the plane of the sky $\rightarrow$ twin, outward traveling shock waves

Does the shock inhibit or trigger star formation?

- **Hα emission line**
  - Well calibrated
  - Sensitive
  - Compare with field and other clusters – same selection
  - Uniformly select large samples
  - Narrow-band technique – trace Hα at the redshift of the cluster

Sobral et al. 2009
Distribution of emitters

- 323 MHz radio intensity in gray
- Hα line emitters in red circles
- Many extended Hα emitters around the relic areas in the 'Sausage' cluster
- The 'Toothbrush' almost devoid of Hα emitters

Stroe et al. 2014a, 2015a
Hα luminosity function for the cluster volume

- 'Toothbrush' is consistent a blank field – same number of emitters, but slightly less luminous (=less star-forming)
- 'Sausage' emitters – higher normalization → many more luminous emitters than blank fields
Focusing on the 'Sausage' - evidence for supernovae

- Star forming galaxies in the hottest X-ray gas and/or in the cluster sub-cores (away from the shock fronts) show very low electron densities (<30 times lower than field galaxies)
- Significant contribution from supernovae
- Supernovae + AGN drive outflows (blueshifted and redshifted [SII]+NaD) → remove fuel for star-formation

Sobral, Stroe et al. 2015
Focusing on the 'Sausage' - increased metallicity

- Star forming galaxies in the cluster follow the local mass-metallicity relation
- Suggesting that these H\(\alpha\) emitters are using relatively metal rich gas to form new stars at all stellar masses
- Source of metal rich gas?
  - Accretion of high-metallicity ICM gas
  - Pre-enriched gas from supernovae in the past that was retained in the galaxies

Sobral, Stroe et al. 2015
Star formation on longer timescales in the 'Sausage'

- Use radio emission to trace super nova remnants
- Hα emission correlates with radio emission → star formation averaged over 10 Myr & 100 Myr
- A large fraction of cluster Hα emitters have radio → many more super novae in cluster galaxies compared to the field

Stroe et al. 2015b
HI to trace neutral gas content in the 'Sausage' field

- HI at the position of Hα emitters
- Use stacking:
  - Cluster line emitters
  - Field line emitters
- Cluster Hα emitters have just as much HI as their field counterparts
- HI gas should get stripped by cluster environment

<table>
<thead>
<tr>
<th></th>
<th>$M_{\text{HI}} (10^9 M_\odot)$</th>
<th>$M_\star (10^9 M_\odot)$</th>
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</thead>
<tbody>
<tr>
<td>Cluster Hα</td>
<td>2.50 ± 0.62</td>
<td>7.4 ± 0.5</td>
</tr>
<tr>
<td>Field Hα</td>
<td>1.86 ± 1.20</td>
<td>4.8 ± 0.8</td>
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</table>

Stroe et al. 2015b
Star-formation process?

- Cluster galaxies interact strongly with their environment
- **Shock fronts** have traveled more than 1 Mpc though the ICM → interacted with the cluster members?

**Shock induced star-formation?**

The gas in the galaxies is shocked!!
Shock induced star-formation?

- Roediger et al. (2014): after passage of a shock, star-formation starts in the galaxy for a few hundred million years
'Sausage' vs 'Toothbrush'

- Hα luminosity function and star-forming properties of the 'Sausage' and 'Toothbrush' are wildly different
Hα luminosity function – 'Sausage' vs 'Toothbrush'

- Hα luminosity properties of the 'Sausage' and 'Toothbrush' are wildly different

<table>
<thead>
<tr>
<th></th>
<th>'Sausage'</th>
<th>'Toothbrush'</th>
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<tbody>
<tr>
<td>Redshift</td>
<td>0.19</td>
<td>0.22</td>
</tr>
<tr>
<td>Temperature</td>
<td>7 keV</td>
<td>8 keV</td>
</tr>
<tr>
<td>Radio</td>
<td>2 relics</td>
<td>2 relics</td>
</tr>
<tr>
<td>Morphology</td>
<td>Elongated north-south</td>
<td>Elongated north-south</td>
</tr>
<tr>
<td>Orientation</td>
<td>In the plane of the sky</td>
<td>In the plane of the sky</td>
</tr>
<tr>
<td>Merger history</td>
<td>2 equal mass clusters</td>
<td>2 equal mass clusters + smaller sub-cluster</td>
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<td></td>
<td>(van Weeren et al. 2011; Jee, Stroe et al. 2014)</td>
<td>(Brüggen et al. 2011; Jee in prep.)</td>
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<tr>
<td>Core passage time</td>
<td>~1 Gyr</td>
<td>~2 Gyr</td>
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Star formation – 'Sausage' vs 'Toothbrush'

• Shock compression → excites star formation as the shock passes through a galaxy
• Observe the cluster when shock-induced star formation is still active
• We are viewing the 'Toothbrush' cluster at a more evolved 'time-slice' → galaxies evolved into ellipticals
• The 'Sausage' is full of massive galaxies → easier to hold onto their molecular gas during the cluster merger → numerous gas-rich galaxies for the shock to 'light-up'
• Even though clusters could go through episodes of vigorous star formation, the total stellar mass added is little
• Reversal of the normal trends
• Bursty star-formation → acceleration of evolution to passives
Take away message

Cluster shocks interact with the galaxies!

Thank you!
Questions?