Galaxy cluster physics from the thermal / non-thermal connection

Kaustuv Basu  (AlfA, Bonn)

with Martin Sommer (Bonn), Jens Erler (Bonn), Franco Vazza (Hamburg) a.o.
Galaxy cluster physics (+ cosmology) from the thermal / non-thermal connection

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with Martin Sommer (Bonn), Jens Erler (Bonn), Franco Vazza (Hamburg) a.o.
By “thermal” I will mostly talk about the Sunyaev-Zel’dovich (SZ) effect

By “connection” I will try to emphasize the interdependence on selection, observation and modeling.
An SZ tale of Two Phenomena

**Radio Relics:**
- SZ contamination in GHz-frequency relic observations
- First measured SZ shocks in radio relics: Coma & El Gordo
- SZ/X-ray/synchrotron joint modeling — tool for cluster astrophysics


**Radio Halos:**
- Radio–SZ scaling relation for giant radio halos
- Radio halo statistics from SZ & X-ray selection in an unbiased way
- Follow-up observations of Planck clusters: high RH fraction corroborated
- Galaxy cluster merger rate — new tool for cosmology

The Sunyaev-Zel’dovich (SZ) effect

**Integrated signal:**

\[ \Delta S_v = \int \Delta I_v \, d\Omega \propto \int n_e T_e \, dV \propto f_{\text{gas}} M_{\text{tot}} T_e \]

**Line-of-sight signal:**

\[ \frac{\Delta T}{T_{\text{CMB}}} = g(x) \int n_e(l) \frac{k_B T_e(l)}{m_e c^2} \, dl \]
Radio Relics $\Rightarrow$ Shocks

An example:
Abell 3667 ($z = 0.05$)

X-ray analysis
Finoguenov et al. (2010)
Sarazin et al. (2016)

Radio data:
Roettgering et al. (1997)

Theoretical works:
(To cite a few) Miniati et al. (2001); Hoeft & Brueggen (2007); Nuzza et al. (2012); Skillman et al. (2013); Vazza et al. (2014)

\[ r = 2.3^{+0.7}_{-0.4} \]
A gradual spectral steepening is observed above ~2 GHz, which cannot be explained from the standard DSA model.

Stroe et al. (2015, 2016)
AMI (16 GHz) and CARMA (30 GHz) data
Spectral Steepening Explained (?)

RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

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² Department of Physics, UNIST, Iksan 53010, Korea; ryu@unist.ac.kr

Turbulent Cosmic-Ray Reacceleration and the Curved Radio Spectrum of the Radio Relic in the Sausage Cluster

Yutaka FUJITA¹, Hiroki AKAMATSU,² and Shigeo S. KIMURA³

Magnetic Field Evolution in Giant Radio Relics using the example of CIZA J2242.8+5301

J. M. F. Donnert¹,²,³*, A. Stroe⁴,¹†, G. Brunetti², D. Hoang¹, H. Roettgering¹
¹ Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
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The widest frequency radio relic spectra: observations from 150 MHz to 30 GHz

Andra Stroe,¹*† Timothy Shimwell,¹ Clare Rumsey,² Reinout van Weeren,³ Maja Kierdorf,⁴ Julius Donnert,¹ Thomas W. Jones,⁵ Huub J. A. Röttgering,¹ Matthias Hoefst.⁶ Carmen Rodríguez-Gonzálvez,⁷ Jeremy J. Harwood⁸
Spectral Steepening Explained

RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

Observation at 15 GHz

$S_v \ (\text{mJy/arcmin}^2)$

0 200 400 600 800 1000 1200
0.6
0.4
0.2
0.0
-0.2
-0.4

kpc

synchrotron
SZ
sync. + SZ

Andra Stroe, 1,1‡ Timothy Shimwell, 1 Clare Rumsey, 2 Reinout van Weeren, 3 Maja Kierdorf, 4 Julius Donnert, 1 Thomas W. Jones, 5 Huub J. A. Röttgering, 1 Matthias Hoeft, 6 Carmen Rodríguez-Gonzálvez, 7 Jeremy J. Harwood 8
Spectral Steepening Explained

OCCAM'S RAZOR?

Observation at 15 GHz

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Basu et al. (2016), A&A, 591

Thermal/non-thermal connection
A Non-negligible Effect

Simulated interferometric observation at 10 GHz

<table>
<thead>
<tr>
<th></th>
<th>3 GHz</th>
<th>5 GHz</th>
<th>10 GHz</th>
<th>15 GHz</th>
<th>20 GHz</th>
<th>30 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sausage relic</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>4%</td>
<td>11%</td>
<td>24%</td>
<td>58%</td>
</tr>
<tr>
<td>(M = 2.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M = 3.5)</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>3%</td>
<td>10%</td>
<td>21%</td>
<td>49%</td>
</tr>
<tr>
<td>(M = 4.5)</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>4%</td>
<td>12%</td>
<td>24%</td>
<td>52%</td>
</tr>
<tr>
<td>Toothbrush relic</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>3%</td>
<td>9%</td>
<td>18%</td>
<td>43%</td>
</tr>
<tr>
<td>(M = 3.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(M = 4.5)</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>3%</td>
<td>10%</td>
<td>20%</td>
<td>46%</td>
</tr>
<tr>
<td>El Gordo relic</td>
<td>&lt;1%</td>
<td>3%</td>
<td>23%</td>
<td>53%</td>
<td>81%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>(M = 2.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2256 relic</td>
<td>1%</td>
<td>3%</td>
<td>28%</td>
<td>66%</td>
<td>96%</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>(M = 2.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Basu et al. (2016), A&A, 591
**Make simplistic assumptions:**

1. The kinetic power of the shock:

\[ P_{\text{kin}} = n_u v_s^3 S/2 \quad (\text{where} \quad v_s = \mathcal{M} c_s) \]

2. A fraction of this kinetic power goes in proton acceleration:

\[ P_{\text{CPp}} = \eta(M) P_{\text{kin}} \]

3. Assume a fixed electron-to-proton ratio (\( \xi = 0.05 \)):

\[ P_{\text{CPe}} = \xi_{e/p} \eta(M) P_{\text{kin}} \]

---

Basu et al. (2016), A&A, 591
**Synchrotron/SZ Flux Ratio**

**Make simplistic assumptions:**

1. The kinetic power of the shock:
   \[ P_{\text{kin}} = n_u v_s^3 S/2 \quad (\text{where } v_s = \mathcal{M} c_s) \]

2. A fraction of this kinetic power goes in proton acceleration:
   \[ P_{CPp} = \eta(\mathcal{M}) P_{\text{kin}} \]

3. Assume a fixed electron-to-proton ratio (\(\xi = 0.05\)):
   \[ P_{CPe} = \xi_{e/p} \eta(\mathcal{M}) P_{\text{kin}} \]

\[ \frac{S_{\text{sync.}}}{S_{\text{SZ}}} \approx -9 \times 10^4 \left( \frac{\xi_{e/p}}{0.05} \right) \left( \frac{\mathcal{M}}{3} \right) \left( \frac{T_u}{1 \text{ keV}} \right)^{1/2} \left( \frac{W}{100 \text{ kpc}} \right)^{-1} \times (1 + z)^{-4+\delta/2} \]

\[ \times \left( \frac{B_{\text{relic}}^{1+\delta/2}}{B_{\text{CMB}}^2 + B_{\text{relic}}^2} \right) \left( \frac{\nu}{1.4 \text{ GHz}} \right)^{-(2+\delta/2)} \]

\[ B_{\text{relic}} \propto \left[ -\left( \frac{S_{\text{sync.}}}{S_{\text{SZ}}} \right) \frac{W_{\nu}^{2+\delta/2}}{\mathcal{M} \xi_{e/p} T_u^{1/2}} \right]^{2/(\delta-2)} \]

Basu et al. (2016), A&A, 591

**BUT, RELIC SHOCK IN SZ?**
Shocks in SZ (within $r_{500}$)

SZ shock in MACS J0744 (GBT/MUSTANG; Korngut et al. 2011)

$R \leq R_{500}$ shocks in the Coma cluster (Planck collaboration 2013)

SZ shock modeling enabled by X-ray priors
Coma’s Relic, with Planck

- $y$-jump fits a shock, with $M = 2.9^{+0.8}_{-0.6}$
- Using 2015 Planck data (and spherical geometry)
- $M = 2.2 \pm 0.3$

---

Kaustuv Basu (AlfA, Universität Bonn)

Galaxy Clusters @ Cambridge, 2016
The (SZ) Future is Now

Measuring SZ shocks with Planck is like measuring X-ray shocks with Uhuru... but now we can do better!

Projected pressure map
$M_{\text{vir}} \sim 2 \times 10^{14}$ merger

(Simulations by F. Vazza, 2012)

First ALMA – SZ results:
- RXC J1347.5 core
  (Kitayama et al. 2016)
- El Gordo relic shock
  (Basu et al. 2016)
A Relic-Shock with ALMA at $z \approx 0.9$

360 ks *Chandra* (PI: J. Hughes) + ATCA 2.1 GHz radio (Lindner et al. 2014)

ALMA data ~ 3h on-source
ALMA noise rms ~ 6 $\mu$Jy/3" beam

How ALMA sees a Shock

To avoid interferometric imaging biases, we fit our shock model directly to the visibility ("uv") data, using a Bayesian MCMC method.

Step function–like jump in the SZ decrement

Deconvolved ("dirty") image produces ripple–like pattern
How ALMA sees a Shock

Simulations with our actual ALMA noise
Contours show 95% credible regions

Mach number

upstream pressure (keV cm$^{-3}$)

mass 2e14; Mach 4
mass 2e14; Mach 2
mass 2e14; Mach 1

M$=\ 4$
M$=\ 2$
M$=\ 1$

The Multi-Wavelength View

- **2 GHz**
- **0.5–7 keV**
- **100 GHz**

A wide shock, revealed in the X-rays

Background photon level

Mach number in the relic cone:
\[ M = 2.9^{+7.8}_{-0.9} \]

Mach number in the other half:
\[ M = 2.3^{+3.0}_{-0.8} \]

Magnetic Field at $z \approx 0.9$

**DSA formula (Hoeft & Brueggen 2007), simplified:**

\[ S_{\nu}^{\rm syn} = (1 + z)^{1 - \delta/2} \frac{P_{\nu}^{\rm sync.}}{4\pi D_L^2} \]

\[ \approx 24 \text{ mJy} \left( \frac{M}{3} \right)^3 \left( \frac{\xi_e/p}{0.05} \right) \left( \frac{L}{1 \text{ Mpc}^2} \right) \left( \frac{B_{\text{relic}}^{1 + \delta/2}}{B_{\text{CMB}}^2 + B_{\text{relic}}^2} \right) \]

\[ \times \left( \frac{n_u}{10^{-4} \text{ cm}^{-3}} \right) \left( \frac{T_u}{1 \text{ keV}} \right)^{3/2} \left( \frac{D_L}{10^3 \text{ Mpc}} \right) \]

\[ \times (1 + z)^{1 - \delta/2} \left( \frac{\nu}{1.4 \text{ GHz}} \right)^{-\delta/2} \]

Basu et al. (2016)
Magnetic Field at $z \approx 0.9$

Relic width is related to the cooling time, i.e., the magnetic field:

\[ \mathcal{N}_{\text{relic}} \approx v_d \, t_{\text{sync}} \]

\[ t_{\text{sync}} = 3.2 \times 10^{10} \, \text{yr} \frac{B^{1/2}}{B^2 + B_{\text{CMB}}^2} \frac{1}{\sqrt{\nu (1 + z)}} \]
ALMA SZ data alone points to a weak shock: \( M = 1.4^{+1.2}_{-0.2} \)

X-ray brightness jump suggests stronger: \( M = 3.5^{+6.4}_{-1.3} \)

We use an X-ray pressure prior on the SZ modeling.

ALMA SZ with Chandra X-ray prior

To the more global ICM properties:

Radio Halo — SZ connection
Diffuse radio emission in clusters

Radio halos: $L_{1.4 \, \text{GHz}} \sim 10^{24-25} \text{ W/Hz}$
- Mpc scale diffuse sources near cluster centers
- Low surface brightness and generally not polarized
- Mostly steep spectrum ($\alpha \sim 1.2$)
- Morphology roughly similar to X-ray or SZ emission, no severe projection bias

Gallery taken from Feretti et al. (2012)

Yet another really bad misnomen!
The radio halo problem

Radio halos imply GeV energy electrons filling up cluster volume (~ Mpc$^3$). But CRe lifetimes are much shorter (~ $10^8$ years) than cluster dynamic timescales.

Some *in-situ* acceleration is necessary for the CRe

Original competing models for radio halo origin

More complex hybrid models

**Primary models** (or re-acceleration models):
electrons are accelerated in diffusive shocks via turbulence induced by cluster mergers, through inefficient Fermi–I process

**Secondary models** (or hadronic models):
e$^{-}$/e$^{+}$ are produced from collision between thermal ions and cosmic ray protons, the latter having significantly longer lifetimes

Radio halo in Bullet cluster (Liang et al. 2000)
“Observational benchmarks” for radio halos

There is a strong bi-modality

They are rare ~50 known halos

Cassano et al. (2010)

Brunetti et al. (2007)

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“Observational benchmarks” for radio halos

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Cassano et al. (2010)

WHAT'S THE SZ TAKE ON THESE?

what's the sz take on these?
The cluster SZ signal and radio halo power are correlated (as expected from known X-ray correlation).


The correlation becomes tighter (and roughly linear) when the SZ signal is scaled to within the radio halo radius.
Radio-SZ morphological connection

Radio-SZ morphological comparison can provide crucial test for the theory of radio halo origin

From very simplified theoretical estimates

Hadronic model with secondary creation of CR electrons:

\[ \epsilon_r \propto n_e \propto \frac{y}{T} \]

Primary models with turbulent re-acceleration of CR electrons:

\[ \epsilon_r \propto n_e T^{1.5} \propto y \sqrt{T} \]
We found from \textit{a posteriori} selection of radio halo clusters, taken from the Planck catalog, that the bi-modality is weak in the radio–SZ correlation.

But this is not enough: we need statistics from \textit{a priori} SZ selection.


Cassano et al. (2013)

PSZ data and X-ray selection
Relaxed, **cool-core clusters** are a minority, but they are over represented in X-ray flux limited samples. These systems generally do not host giant radio halos → producing a **strong** bi-modal distribution in X-rays.
PSZ1 & REFLEX+eBCS+MACS catalogs

PSZ1 clusters (Planck coll. 2013)

Before filtering

After filtering

For an unbiased comparison between SZ and X-ray selections, we first used the NVSS data (Sommer & Basu 2014)

<table>
<thead>
<tr>
<th>Sub-sample</th>
<th>Mass limit</th>
<th>Primary selection</th>
<th>Flagged due to bad data</th>
<th>Final sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSZ(V)</td>
<td>z-dependent</td>
<td>90</td>
<td>1</td>
<td>89</td>
</tr>
<tr>
<td>X(V)</td>
<td>z-dependent</td>
<td>86</td>
<td>1</td>
<td>85</td>
</tr>
<tr>
<td>PSZ(C)</td>
<td>$8 \times 10^{14} M_\odot$</td>
<td>79</td>
<td>0</td>
<td>79</td>
</tr>
<tr>
<td>X(C)</td>
<td>$8 \times 10^{14} M_\odot$</td>
<td>78</td>
<td>1</td>
<td>77</td>
</tr>
</tbody>
</table>


Flux comparison with Giovannini et al. (2009)
We fit a **regression model** that includes errors in both direction, intrinsic scatter, non-detections and a *dropout fraction* (i.e. zero population).

Most of our cluster radio halos from NVSS are non-detections. But we can find the $L_{1.4}-Y_{SZ}$ scaling and the “off state” fraction statistically.

We ran extensive null tests and simulations for potential systematic biases.
Results for SZ/X-ray selection

We fit simultaneously for an “on–correlation” population and a “zero” population for both SZ and X-ray sub-samples.

The “on–correlation” populations give consistent mass scaling, with large scatter.

**But the zero-populations are significantly different!**
Results for SZ/X-ray selection

We fit simultaneously for an "on-correlation" population and a "zero" population for both SZ and X-ray sub-samples. The "on-correlation" populations give consistent mass scaling, with large scatter. But the zero-populations are significantly different!

Planck–SZ(V)  
X-ray(V)

X-ray dropout 70 ± 10 %
SZ dropout 29 ± 12 %
Based on N-body hydro simulation results by Poole et al. (2007)
With deep radio data (and a uniform analysis), 18 out of 26 Planck selected clusters showing diffuse radio emission on ~1 Mpc scale.

⇒ 70% !!
Number of Radio Halos in the Sky

**Up by factor ~5 or more**

*(several 100-s RHs out to z=0.5 for $M_{500,c} > 4 \times 10^{14} M_{\odot}$ clusters)*

Current prediction for 1.4 GHz are conservative

But, we didn’t talk about mass and z-dependence

New surveys (e.g. ASKAP/EMU and MeerKAT/MIGHTEE might find these answers very soon!)

(Cassano et al. 2012)
Cosmology from the Merger Rate

The radio halo count can be connected to the cluster merger rate, but need assumptions on mass ratio threshold, radio halo lifetime, etc.

\[ M_{500} > 4 \times 10^{14} \, M_{\odot}; \text{Mass ratio} \geq 0.1; \, t_{RH} = 1.5 \, \text{Gyr} \]

\[ \frac{dN}{dt} = \frac{D}{dt} N_{PS}(M, t) \frac{\delta_c^2}{\sigma^2(M)D^2(t)}. \]

(Sasaki 1994)

Merger rate brings extra cosmological information, and can help to break the \( \sigma_8-\Omega_m \) degeneracy

in prep

Kaustuv Basu (AlfA, Universität Bonn)
Summary

**SZ connection for RADIO RELICS**

- Thermal SZ/X-ray and non-thermal synchrotron are modeled self-consistently
- Shocks that underlie radio relics have now been measured also in the SZ
- Radio observations are affected by SZ at cm-wavelengths (1-30 GHz)
- ALMA is opening the SZ-substructure window in cluster cores as well as outskirts
Summary

**SZ connection for RADIO RELICS**

- Thermal SZ/X-ray and non-thermal synchrotron are modeled self-consistently
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**SZ connection for RADIO HALOS**

- First demonstration of the radio-SZ correlation for radio halos
- Reduced “apparent bimodality” in SZ selection, but certainly radio-off clusters
- SZ and X-ray selection in the high-mass end show significant difference with radio
- The SZ selection part (~70% RHs) no confirmed with deep radio data