SZ observation of cluster \textit{(relic)} shocks

Kaustuv Basu \textit{(University of Bonn)}

In collaboration with: Martin Sommer, Jens Erler, Franco Vazza, Dominique Eckert, and many others
The Sunyaev-Zel’dovich effect

Inverse Compton scattering producing unique spectral distortion on the background CMB.

An ideal tool for finding and characterizing galaxy clusters.

Resolved source flux is redshift independent and scales linearly with the gas density!

Credit: Planck collaboration

Sims: Pfrommer et al.
Thermal SZ to measure shocks

Shocks create a pressure boost, which roughly scales as the **Mach number squared** (and unlike density compression, the pressure ratio does not saturate at $M \approx 4$)

On projection ($\int P \, dl = \text{Compton } y \text{ parameter}$) this looks like a step function and relatively easily detectable also in the cluster outskirts

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**Vazza et al. (2012)**

**Basu et al. (2016)**
The steepening spectrum of some relics

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
The steepening spectrum of some relics

RE-ACCELERATION MODEL FOR RADIO RELICS WITH SPECTRAL CURVATURE

Hyesung Kang\textsuperscript{1} and Dongsu Ryu\textsuperscript{2,3,4}

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

Yutaka Fujita\textsuperscript{1}, Hiroki Akamatsu\textsuperscript{2}, and Shigeo S. Kimura\textsuperscript{3}

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

J. M. F. Donnert\textsuperscript{1,2,3*}, A. Stroe\textsuperscript{4,1†}, G. Brunetti\textsuperscript{2}, D. Hoang\textsuperscript{1}, H. Roettgering\textsuperscript{1}

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The widest frequency radio relic spectra: observations from 150 MHz to 30 GHz

Andra Stroe,\textsuperscript{1*†} Timothy Shimwell,\textsuperscript{1} Clare Rumsey,\textsuperscript{2} Reinout van Weeren,\textsuperscript{3} Maja Kierdorf,\textsuperscript{4} Julius Donnert,\textsuperscript{1} Thomas W. Jones,\textsuperscript{5} Huub J. A. Röttgering,\textsuperscript{1} Matthias Hoeft\textsuperscript{6} Carmen Rodríguez-Gonzálvez,\textsuperscript{7} Jeremy J. Harwood\textsuperscript{8}
The steepening spectrum of some relics

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

- synchrotron
- SZ
- sync. + SZ

Observation at 15 GHz

OCCAM’S RAZOR?
A non-negligible effect ($\approx 10$ GHz)

Simulated interferometric observation at 10 GHz

10%-50% flux loss 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 ($M = 2.5$)</td>
<td>$&lt;1%$</td>
<td>$&lt;1%$</td>
<td>$4%$</td>
<td>$11%$</td>
<td>$24%$</td>
<td>$58%$</td>
</tr>
<tr>
<td>($M = 3.5$)</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 ($M = 3.5$)</td>
<td>$&lt;1%$</td>
<td>$&lt;1%$</td>
<td>$3%$</td>
<td>$9%$</td>
<td>$18%$</td>
<td>$43%$</td>
</tr>
<tr>
<td>($M = 4.5$)</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 ($M = 2.5$)</td>
<td>$&lt;1%$</td>
<td>$3%$</td>
<td>$23%$</td>
<td>$53%$</td>
<td>$81%$</td>
<td>$&gt;100%$</td>
</tr>
<tr>
<td>A2256 relic ($M = 2.0$)</td>
<td>$1%$</td>
<td>$3%$</td>
<td>$28%$</td>
<td>$66%$</td>
<td>$96%$</td>
<td>$&gt;100%$</td>
</tr>
</tbody>
</table>

Basu et al. (2016), A&A, 591
First measurement of shock heated gas in SZ
Kitayama et al. (2004) using Nobeyama telescope, in the galaxy cluster RXC J1347 (see also Ferrari et al. 2011)

Direct detection of shock jump followed much later.
Shock fronts 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

The first measurement of a relic shock in SZ

Mach number derived from the y-jump: \( M = 2.9^{+0.8}_{-0.6} \)
A much better SZ shock imager

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

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

(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)

High-resolution single dish measurements are also on the way..
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 $\sim 2$h on-source
ALMA noise rms $\sim 6 \mu$Jy/3" beam (enough to detect $M \sim 2$ shock with $>5\sigma$)

How ALMA sees a shock


Model  |  Data  |  Residual

$M = 4$

$M = 2$

$M = 1$
The “multi-messenger” view

Magnetic field at $z \approx 0.9$

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

$$\mathcal{W}_{\text{relic}} \approx v_d \, t_{\text{sync}}$$

$$t_{\text{sync}} = 3.2 \times 10^{10} \, \text{yr} \, \frac{B^{1/2}}{B^2 + B_{\text{CMB}}^2} \, \frac{1}{\sqrt{\nu(1+z)}}$$
The shock Mach number

**ALMA SZ only**
(with a mass prior)

**Chandra X-ray only**

ALMA SZ data alone points to a weak shock:

\[ \mathcal{M} = 1.4^{+1.2}_{-0.2} \]

X–ray brightness jump suggests stronger:

\[ \mathcal{M} = 3.5^{+6.4}_{-1.3} \]

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

ALMA SZ with Chandra X-ray prior

Future results: **Sausage & Toothbrush**

MUSTNAG-2 @ GBT and NIKA-2 @ IRAM 30m can both make sensitive images of cluster merger shocks, with obs time typically much smaller than the X-ray observing time.

NIKA-2 data analysis: Charles Romero

Simulated image of a $M=3$ Sausage relic shock with M2, for 20 h mapping

Real image of the Toothbrush relic shock with NIKA2, with 12 h of data

Preliminary! rms not low enough
ALMA-SZ takes the *Bullet*: Data

Deep ALMA pointing of the Bullet shock at 100 GHz

- 4 h on-source, 6 μJy rms

**PI: T. Mroczkowski**
ALMA-SZ takes the Bullet: Method

Matching X-ray and SZ models closely

MCMC model fitting directly to the ALMA uv-data (computationally expensive!)

ALMA SZ modeling only

GGM-filtered X-ray image
ALMA-SZ takes the *Bullet*: Method

Matching X-ray and SZ models upstream

ALMA SZ
modeling only

ALMA SZ with X-ray prior

Using X-ray priors

$9.4 \pm 1.2 \text{ keV}$

$7.9 \times 10^{-4} \text{ cm}^{-3}$

Markevitch (2006)
ALMA-SZ takes the *Bullet*: the Upshot

![Graph showing the temperature profile and shock in a cluster.](image)
More than the *thermal SZ*: kSZ, rSZ, ..

The **thermal SZ (tSZ)** effect measures the line-of-sight electron pressure.

The kinetic SZ (kSZ) effect measures the bulk motion of the scattering electrons.

The **relativistic SZ (rSZ)** effect (or distortions) measures the electron temperature.
ICM temperatures from the rSZ effect


With current Planck data, roughly $2.3\sigma$ significance detection of cluster temperature can be obtained after stacking 772 clusters.

With CCAT-prime temperature of a single massive cluster can be measured at $5-10\sigma$.
ICM temperatures from the rSZ effect


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With **CCAT-prime** temperature of a single massive cluster can be measured at $5–10\sigma$.

See Tony’s talk on Friday, or visit and find out more (and register yourself) at [http://atlast-telescope.org/](http://atlast-telescope.org/)
Shocks with $kSZ$? $ntSZ$? $pSZ$?

**Non-thermal SZ (ntSZ)** will come from scattering off the relativistic, non-thermal electrons.

Effect is across the $tSZ$ spectrum, but can be \( \geq \text{two orders of magnitude smaller} \) than the thermal signal.

Also, accurate modeling of the spectral shape is lacking.

Current SZ measurements of (mostly transverse) shocks are contaminated by $kSZ$ at most 2–3% level.

But under more favourable projection the $kSZ/tSZ$ ratio can be larger.

Polarized SZ ($pSZ$) effect can have several origins.

The relatively dominant effect measures the square of the tangential velocity of the electrons (sometimes called the $kpSZ$ effect).

Again, extremely difficult due to the smallness of the signal and multiple $pSZ$ contributions.

Maybe with polarization sensitive bolometers in 10-20 years??
Take home messages

**SZ observations of more than one radio relic shocks are now online, excellent complement to X-ray**

**ALMA SZ measurement of the Bullet shock provides tentative support to adiabatic heating at the shock fronts**

**Upcoming and future SZ data will not only measure the pressure, but also temperature and velocities of the shocks directly**