Multi-wavelength studies of substructures and inhomogeneities in galaxy clusters

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SZE (RX J1347)

ΔSx (A3667)

Infrared (Coma)
1. How can we study ICM physics with the SZE?
Contours: SZE, OVRO/BIMA  
(FWHM $\sim 70''$ @ 30GHz)  
Color: X-ray, ROSAT  
(FWHM $\sim 5''$)  
Appeared to be a relaxed cluster  

Contours: SZE, MUSTANG  
(FWHM $\sim 10''$ @ 90GHZ)  
Color: X-ray, Chandra  
(FWHM $\sim 0.5''$, smoothed to 10'')  
X-ray: $\sim 100$ clusters  
SZE: only 1 cluster so far
Why SZE?

• For the same thermal plasma,

\[ I_{SZ} \propto \int n_e T_e \, dl \quad \text{independent of } z \quad : \text{Inverse Compton} \]
\[ I_X \propto \int n_e^2 \Lambda(T_e) \, dl / (1+z)^4 \quad : \text{Bremsstrahlung} \]
\[ \Lambda(T_e) \sim T_e^{1/2} \quad \text{for bolometric} \]

• Spatially resolved X-ray spectroscopy (& weak lensing) become difficult at high z

• Higher frequency of major mergers at z>0.5

⇒ Unique probe of thermal structures in distant clusters
   - gravitational potential
   - merger shocks
   - missing SZE relative to X-rays?
   etc.
SZE & X-ray: Temperature profile

$T_e$ & $n_e$ deprojection without X-ray spectroscopy

Assuming spherical sym.,

$I_{SZ} \propto \int n(r)T(r) \, dl$
$I_X \propto \int n^2(r) \Lambda [T(r)] \, dl$

(Yoshikawa et al. 1999)

⇒ Applicable to
“X-ray faint gas”
- distant clusters
- outskirts

RX J1347-1145 excluding subclump & point source
(TK, Komatsu, Ota et al. 2004)
High resolution SZE images of RX J1347-1145
(largest $L_X$, strongest SZE: $y_{\text{max}} \sim 10^{-3}$, $z=0.45$)

90GHz (Mason+10)
MUSTANG on GBT 100m
9” beam + 4” smoothing
$\rightarrow$ 1 $\sigma$ = 0.3 mJy/beam

150GHz (Komatsu+01; TK+04)
NOBA on Nobeyama 45m
13” beam + 15” smoothing
$\rightarrow$ 1 $\sigma$ = 0.7 mJy/beam

350GHz (Komatsu+99; TK+04)
SCUBA on JCMT 15m
15” beam + 15” smoothing
$\rightarrow$ 1 $\sigma$ = 3.0 mJy/beam

Contours: Chandra 0.5-7 keV (Allen+02)

Contours: 1~5 $\sigma$
(Mason’s talk on Tue.)
SZE as a probe of violent mergers

※ If merger shock, Rankine-Hugoniot relation:

\[
\frac{T_2}{T_1} = \frac{[2\gamma M^2 - \gamma + 1] \left( \frac{\gamma - 1}{\gamma + 1} \right) M^2 + 2}{(\gamma + 1)^2 M^2}
\]

⇒ Mach number ∼ 2.1 (γ = 5/3)

\[V_{\text{preshock}} \sim 3900 \text{ km/s}\]
\[V_{\text{postshock}} \sim 1600 \text{ km/s}\]

(relative to the shock front)

cf. Bullet cluster (Markevitch 2006)

Chandra only: \(T_2 \sim 35 \text{ keV}, T_1 \sim 9\text{keV}\)

⇒ Mach number ∼ 3.0 (γ = 5/3)

\[V_{\text{preshock}} \sim 4700 \text{ km/s}\]
\[V_{\text{postshock}} \sim 1600 \text{ km/s}\]

SZE & Chandra joint analysis (TK+04)

\[n_{\text{excess}} = (1.45 \pm 0.58) \times 10^{-2} \text{ cm}^{-3}\]

\[L_{\text{excess}} = 250 \pm 190 \text{ kpc (l.o.s. extent)}\]

\[kT_{\text{excess}} = 28.5 \pm 7.3 \text{ keV}\]

cf. Chandra only: \(kT_{\text{excess}} > 21.5 \text{ keV}\)
Further evidences of merger in RX J1347-1145

Suzaku 0.4-60 keV spectrum
150ks (Ota et al. 2008)
Combined with spatially resolved
Chandra 0.5-7 keV data,

\[ kT_{\text{excess}} = 25.3^{+6.1}_{-4.5} \text{ keV} \] (X-ray only)

\[ \text{cf. } kT_{\text{excess}} = 28.5 \pm 7.3 \text{ keV} \] (SZE+Chandra)

Contours:
- Radio halo
- XMM
  (Gitti et al. 2007)
- Lensing mass
- Grey scale:
  VLT
  (Miranda et al. 2008)
Hard X-ray missions in near future

- **NuStar** (2012-): Hard X (E=5-80 keV), HPD=43”

- **ASTRO-H** (2014-):
  - Micro-calorimeter: E=0.3-10 keV, ΔE=7eV, HPD=1.7’
  - Hard X: E=5-80 keV, HPD=1.7’
  - etc.

- **IXO** (2021-): E=0.3—7 keV, HPD=5”
  - 7—40 keV 30”

High resolution (<10”) SZE obs. are important and complementary.
SZE imaging with ALMA (Yamada et al.)

Merits:
◆ Spatial resolutions (<10")
◆ Removal of point sources

Challenges:
◆ Limited FOV, sensitivity to extended emission
  → combination of 12m & ACA, mosaicing
  ⇒ Mock simulations

12m × 50
Higher resolutions
ACA (Atacama Compact Arrays)
7m × 12 &
12m SD × 4
Lower resol.
Mock Obs. : Set up

INPUT:
Simulated merging cluster from Takizawa (2005)
Place it at $z=1$, Dec=-23 deg
Add noise & point sources

100"=0.8Mpc at $z=1$

90GHz

3 sources
3 mJy
1 mJy
0.3 mJy
Mock obs. with point sources @ 90GHz

Raw map
(Dirty beam uncorrected)
Most compact configuration

12m long baseline map
⇒ remove sources self-consistently

Final map

Completely blind

Mixed side lobes
2. What about even smaller scales?
Inhomogeneities in simulated clusters

“Local Universe Simulations (SPH)”
by Dolag et al. (2005)
Smoothing IRAS map to linear scale
→ initial conditions
    + cooling, SF, SN feedback, etc.

Left: $\delta_n = n(r, \theta, \phi)/\langle n \rangle(r)$
Right: $\delta_T = T(r, \theta, \phi)/\langle T \rangle(r)$

red: simulation data for an entire cluster
black: log-normal distribution

Both $n_e$ & $T_e$ have fluctuations
(nearly log-normal).
Observed inhomogeneities in $S_X$

$S_X \text{ (cnt/s/cm}^2/$arcmin$^2) \quad \delta_{S_X} \equiv \frac{S_X(R)}{\bar{S}_X(R)}$

Chandra images of A3667 at $z=0.06$, after masking point sources and smoothing over 4'' x 4'' = 3 kpc/h (Non-cooling flow cluster with highest counts)

→ inhomogeneities in $n_e$ with

$\Delta \log n_e \sim 0.4$

(Kawahara et al. 2008 ApJ 687, 936)
Observed inhomogeneities in $T_e$

Hydra A, XMM spectroscopy

→ Broad $T_e$ distribution, nearly lognormal with $\Delta \log T_e \sim 0.2$ (Simionsescu et al. 2009)
Systematic errors in $H_0$ ($d_A$) from SZE/X-ray

Sources for overestimation
- clumpiness $<n^2>/<n>^2$
- unresolved radio sources

$$H_0 \propto \frac{1}{d_A} \propto \frac{I_X T^2 \theta_\perp}{I_{SZ}^2 \Lambda(T)}$$

Sources for underestimation
- inhomogeneous $T_e$
- radial gradient of $<T_e>$
  if central $I_{SZ}$ is used.

Others
- asphericity
  if $R_\parallel > R_\perp$, underestimate
  $< \quad$ overestimate

The effects marked in “red” should yield, in total, 10~15% underestimate in $H_0$, if isothermal $\beta$ model is used.


Another probe of SZE/X-ray intensity ratio
What about the real measurements?

In general, X-ray/SZE used to give low $H_0$:
- ROSAT/ASCA + OVRO/BIMA, 18 clusters (Reese et al. 2002)
  \[ H_0 = 60 \pm 4^{+18}_{-13} \text{ km/s/Mpc} \] using isothermal $\beta$ model

On the other hand,
- Chandra + OVRO/BIMA, 38 clusters (Bonamente et al. 2006)
  \[ H_0 = 73.7^{+4.6}_{-3.8} +9.5_{-7.6} \text{ km/s/Mpc} \] using isothermal $\beta$ model

cf. SNIa + Cepheid,,, (Riess et al. 2009)
  \[ H_0 = 74.3 \pm 3.6 \text{ km/s/Mpc} \]

CMB (Komatsu et al. 2010)
  \[ H_0 = 71.0 \pm 2.5 \text{ km/s/Mpc} \]
Impact of Chandra calibration
(Reese et al., arXiv:1006.4486)

38 clusters from Bonamente+06

CALDB versions
3.1.0 (2005), 4.1.4 (2009) vs. 4.2.2 (2010)
- effective area of mirror
- ACIS contaminations model etc.

$\Delta T_e/T_{e,4.2} \sim 10\%$ change in $T_{\text{spec}}$
$\Rightarrow \sim 15\%$ change in $H_0 \propto 1/d_A \propto T^{1.5}$
$v3.1: H_0=70.0\pm 3.7$
$v4.1: H_0=55.4\pm 2.9$
$v4.2: H_0=63.7\pm 3.3$ (stat. error)

Should affect cluster cosmology widely!

SZ (OVRO/BIMA) + X-ray (Chandra)
3. Are there dust grains in ICM?
## Search for intracluster/intergalactic dust

**Extinction of background sources**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Sample Description</th>
<th>$A_V$~0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>Zwicky</td>
<td>Coma</td>
<td></td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Sample Description</th>
<th>$E(g-i)$=0.008±0.003</th>
<th>$A_V$=0.013±0.004</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Chelouche et al.</td>
<td>$10^4$ SDSS clusters</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(both field &amp; cluster)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Menard et al.</td>
<td>$2\times10^7$ SDSS galaxies</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(both field &amp; cluster)</td>
<td></td>
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</table>

**IR emission**

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Sample Description</th>
<th>$I(120 , \mu m)$~0.2 MJy/sr</th>
<th>$I(100 , \mu m)$~0.03 MJy/sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Stickel et al.</td>
<td>Coma</td>
<td>no detection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ISO)</td>
<td>5 Abell clusters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>Montier, Giard</td>
<td>11507 clusters</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(IRAS)</td>
<td></td>
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</tbody>
</table>

※ Galaxies are not removed!

If real, dust should be newly supplied (τ_sputt~10^8 yr for grain size 0.1 μm). Dust can contaminate the SZE, SNIa,„„
Limits on intracluster dust in Coma by Spitzer


Spitzer/MIPS, 40 ksec

24 μ (FWHM 6”) : < 5 × 10^{-3} MJy/sr within 100kpc
70 μ (18”) : < 6 × 10^{-2} MJy/sr
160 μ (40”) : < 7 × 10^{-2} MJy/sr

\[ \frac{M_{\text{dust}}}{M_{\text{gas}}} < 10^{-5}, \quad A_V < 0.02 \text{ at } r < 100\text{kpc} \]

Source are masked.

red: bin size = 3.6’ = 100 kpc
green: 7.2’ = 200 kpc
black: collisional heating model that matches the ISO result
\[ I(120 \mu m) = 0.2 \text{ MJy/sr} \]
Summary

1. High resolution (<10") SZE obs.
   - Unique probe of the ICM physics, especially at high z
   - Sample size and precision will improve, e.g., by ALMA

2. ICM has small-scale fluctuations
   & X-ray calibration uncertainty is not negligible: $\Delta T_{\text{spec}} \sim 10\%$

   $\rightarrow$ Impacts on cluster cosmology ($H_0$, $\sigma_8$, scaling relations,,,) 

3. Upper limit on the intracluster dust in Coma
   $M_{\text{dust}}/M_{\text{gas}} < 1/1000$ of Galactic ISM at $r<100\text{pkc}$