The Sunyaev-Zeldovich Effect with ALMA Band 1

and some current observational results from the CBI...

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State of the art

SZ and CMB...
The SZE: a refresher

• The Sunyaev-Zeldovich Effect
  – Compton upscattering of CMB photons by keV electrons
  – decrement in I below SZ null (220 GHz), increment above
  – negative extended sources (absorption against 3K CMB)
  – massive clusters mK, but shallow profile $\theta^{-1} \rightarrow -\exp(-v)$
SZE vs. X-rays: a refresher

- gas density profiles:
  \[ n_e(r) = n_{e0} \left(1 + \frac{r^2}{r_0^2}\right)^{-\frac{3\beta}{2}} \]

- X-ray surface brightness:
  \[ b_X(E) = \frac{1}{4\pi(1+z)^3} \int n_e^2(r) \Lambda(E, T_e) \, dl \]

- SZE surface brightness:
  \[ \Delta I_{SZE} \propto T_e \int n_e \, dl \]

- dependence on parameters:
  \[ b_X \propto n_{e0}^2 \theta_0 D_A \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-3\beta+1/2} \]
  \[ \Delta I_{SZE} \propto T_e n_{e0} \theta_0 D_A \left(1 + \frac{\theta^2}{\theta_0^2}\right)^{-\frac{3}{2}\beta+\frac{1}{2}} \]

\[ D_A \sim h^{-1} \quad n_{e0} \sim h^{1/2} \rightarrow \Delta I_{SZE} \sim h^{-1/2} \quad \Delta I^2_{SZE} / b_X \sim D_A \sim h^{-1} \]
Example: $z<0.1$ SZE @ 30 GHz w/CBI

\[ V(u, v) = I_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(\theta) \left( 1 + \frac{\theta^2}{\theta_0^2} \right)^{-\frac{\beta}{2} + \frac{1}{2}} e^{2\pi i (u \theta + v \theta_0)} \, dx \, dy \]

SZ Visibility functions

- Xray: $\theta^{-3}$ ($\beta \sim 2/3$)
- SZE: $\theta^{-1} \rightarrow -\exp(-v)$
- dominated by shortest baselines (1m=100$\lambda$ for CBI at 30 GHz)
Example: A478 (z=0.088) with CBI

A478 – relaxed cooling flow cluster, X-ray cavities from AGN
SZE measures IGM pressure $\rightarrow$ baryon surface density $\times$ kT
comparison with X-ray $\rightarrow$ effective path length ($L \sim \Sigma_{SZ}/\Sigma_X$)
Example: A478 (\(z=0.088\)) in X-rays

A478 – relaxed cooling flow cluster, X-ray cavities from AGN

Compare substructure in SZ with X-ray to determine pressure

Chandra: Sun et al. astro-ph/0210054

(inner region + 1.4 GHz radio)
Example: CBI SZ program

- Udomprasert et al. 2004 (and PhD thesis)
  - define sample of 24 clusters accessible to CBI
    - $f_{0.1-2.4\text{keV}} > 1.0 \times 10^{-11} \text{erg cm}^{-2} \text{sec}^{-1}$
    - $z < 0.1$
    - $L_{0.1-2.4\text{keV}} > 1.13 \times 10^{44} h^{-2} \text{erg s}^{-1}$
    - declination $-70^\circ < \delta < 24^\circ$
  - sub-sample of 15 most luminous observed by CBI
  - reported results for 7 clusters:
    - A85, A399, A401, A478, A754, A1651, A2597
    - covers a range of luminosities and cluster types
  - would like to study similar samples out to high redshift!
    - should scale like CBI with $D_A$ (e.g. ALMA = $12 \times \text{CBI}$)
Example: CBI SZ cluster gallery

CLEANed images (after point source subtraction)

Integration time 11-16 hours split between cluster and lead and trail fields
The SZ CMB foreground

astro-ph/0402359

\[ \frac{C_l}{2\pi} \left[ \mu K^2 \right] \]

CMB Primary

SZE Secondary

CMB/SZ x-over
\[ l = 2\pi B/\lambda \sim 1500 \]
B \sim 250\lambda
Arcminute CMB Polarization Results

7-band fits ($\Delta l = 150$ for $600<l<1200$) matched to peaks

Interferometers are able to measure $\mu K$ polarization signals!

Science 306, 836-844
Arcminute CMB Polarization goals

BB-lensing within reach of ground-based instruments
Future: Cluster CMB lensing

Note: clusters will lens CMB polarization signal might prove interesting for probing nearby cluster potentials
SZE Interferometry Issues

• Analysis issues
  – currently limited in sensitivity & angular dynamic range
  – joint SZ & Xray modelfitting (MCMC code)
  – removal of contamination
    • CMB sub-dominant beyond $250\lambda \rightarrow l > 1500$
    • point radio sources
  – substructure! more sensitivity on small scales…

• ALMA!
  – shortest baselines $1200\lambda$ at 1cm (shadowing limit)
  – many short baselines
    • good surface brightness sensitivity
  – long baselines for source subtraction
  – science driver is cluster astrophysics rather than cosmology
Example: ACBAR SZ A3266

First ACBAR Cluster Image: A3266

Use 220 GHz (SZ null) to remove CMB signal

z = .0545

$T_x = 6.2$ keV

$L_x = 9.5 \times 10^{44}$

Courtesy ACBAR group
Arcminute-scale SZE @ 30 GHz

BIMA for SZE
- 600\(\lambda\) diameter antennas

OVRO for SZE
- 1050\(\lambda\) diameter antennas

cf. ALMA for SZE
- 1200\(\lambda\) diameter antennas
- 700\(\lambda\) for ACA

Note that astrophysics is now limited by attainable sensitivity over a range of angular scales!

CL 0016+16, z = 0.55 (Carlstrom et al.)
ALMA Band 1 SZE
the case and some questions...
The power of SZ observations

OVRO/BIMA SZE vs. X-ray (insets)

- X-ray emission brightness falls off sharply with distance
- SZE brightness independent of distance \((h\nu/kT_{\text{cmb}} \text{ const.})\)
  - only depends on profile (potential well growth) with \(z\)
  - can locate very distant clusters, if they exist…
The Cosmic Web

Chart the Cosmic Web

- clusters lie at the center of the filamentary web
- hierarchy of substructure
- mergers and groups
- ALMA would study individual (sub)structures

The SZE sky
- SZE simulation (hydro)
- supercluster!
A Universal Surveyor

Angular Diameter Distances

• SZE + Xray → standard candles
  – Chandra/XMM now
  – what in 2012+???

• astrophysical scatter
  – very large samples

\[
\begin{align*}
\Omega_M &= 1.0, \; \Omega_\Lambda = 0.0 \; (\text{solid}) \\
\Omega_M &= 0.3, \; \Omega_\Lambda = 0.0 \; (\text{dash}) \\
\Omega_M &= 0.3, \; \Omega_\Lambda = 0.7 \; (\text{dot–dash})
\end{align*}
\]
Illuminating the Dark Sector

Dark Energy Dark Matter

- SZE probes largest bound objects
- growth & volume factors sensitive to cosmology
- controlled by dark matter $\Omega_m$ and dark energy $\Omega_\Lambda$ (and its equation of state $w$)

**SZ Survey**
- fast bolometer array or interferometer
- e.g. SPT, APEX, SZA, AMI

![Cluster Abundance vs Redshift](image)

Limiting mass

<table>
<thead>
<tr>
<th>Redshift</th>
<th>$M_{lim}[10^{14} M_\odot]$</th>
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<tr>
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<tr>
<td>2.5</td>
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$\Omega_m = 0.3$

$\Omega_\Lambda = 0.7$

$\Omega_m = 1$
**SZE Surveys: high yield!**

**Finding clusters**
- fast instruments
- single dishes with bolometer cameras
  - SPT, APEX, ACT, etc.
- or small interferometers
  - SZA, Amiba, etc.
- ALMA for follow-up!

**SZ Survey**
- fast bolometer array or interferometer
- e.g. SPT, APEX, SZA, AMI
Imaging the SZE with ALMA Band 1

ALMA observes SZE

SZE simulation (left)  4 hours ALMA (center)  after 4kλ taper (right)
2.5 \times 10^{14} \text{ M}_\odot \text{ z=1}  34 \text{ GHz in compact config.}  \text{ equiv. 22" FWHM}
\sim 5\sigma \text{ SZA survey detection}  1.5 \mu\text{Jy (14 \mu K) 9.7" beam}  2.8 \mu\text{Jy (2.7 \mu K)}

ALMA will provide images of high redshift clusters identified in surveys from other instruments like AMI, SZA, SPT, APEX-SZ, ACT

ALMA & SZ, RadioNet in Paris – April 7-8, 2005
ALMA Band 1 Issues

• Site proven!
  – TOCO, CBI, ATSE, APEX, eventually ACT, CCAT, …

• Cost
  – somewhat less than Band 3
  – estimated $7M - $10M (USD’05)?
  – possibly cheaper?? (would have to diverge from stand. cartridge)

• Who will build this?
  – technology is straightforward (current CMB groups capable)

• Complementary instruments
  – survey telescopes
  – big dishes + FPA (GBT, LMT, CCAT, etc.)
  – optical / IR survey telescopes (CFHT, LSST, …)
  – X-ray survey telescopes (Con-X too far away)
ALMA Band 1 Issues (continued)

- Multi-bands
  - ALMA Band 3 dish diameter ~3600\(\lambda\) (array 3” untapered)
- SZE spectrum
  - SZE \(\Delta T\) down by 20% at 90 GHz, 50% at 150 GHz
  - allow CMB subtraction and kinetic SZE
  - want matching resolution out to SZ null (220 GHz) and beyond
  - 50m dish w/FPA (LMT) at ~200 GHz
  - 25m dish w/FPA (CCAT) at 90-150 GHz
  - also IRAM 30m, GBT 100m with bolo arrays

ALMA is complimentary with other instruments:
A powerful global suite of telescopes for cluster astrophysics & cosmology!
Open questions

• What do realistic simulations tell us?
  – What is the level of substructure from various astrophysical sources (shocks, fronts, jets, lobes)?
  – Is an interferometer like ALMA a good way to image these?
  – Need to simulate ALMA interferometer data and reconstructed images – not just convolved images – data is in Fourier domain! May need to develop new imaging algorithms…

• How strong a case should we make for Band 1?
  – A number of us feel that this would be a very powerful cosmology tool (not just for SZ!)
  – How to proceed?
    – Historical note: Band 1 was ranked 2nd among bands beyond first 4 for further development

• What about Band 2?
  – My guess this is not as useful as Band 1 (quite close to Band 3)