Sunyaev-Zeldovich Effect Observations and Prospects for Future Surveys

Secondary Anisotropies

**Inhomogeneous Reionization:**
- Universe Reionized by $z \sim 6$
- Motion of Ionized regions.

**Ostriker-Vishniac Effect:**
- $2^{nd}$ order interaction of velocities and density.
- Scales as density squared; small angular scale.

**Lensing:**
- Small scale CMB anisotropy distorted by the intervening mass distribution (subtle).

**Sunyaev-Zeldovich Effect:**
- Scattering of CMB by Hot Plasma Bound to clusters of galaxies
  - **Dominant Contribution, Spectrally distinct**
  - Kinetic – Doppler shift of scattered photons (Nonlinear O-V)
CMB Secondary Anisotropy Contributions

CMB photons pass through structure in the universe that introduces secondary anisotropies that dominate the primaries above \( l \sim 3000 \).

Sunyaev-Zel’dovich Effect

Inverse scattering of CMB Photons by Hot Intracluster Plasma

\[ I_{\text{cmb}} + \Delta I_{\text{SZ}} \]

\( \sim 1\% \) of CMB is scattered

Two Components of the Electron Velocities

- Thermal (Te\( \sim 100,000,000 \) K)
- Bulk Motion (Doppler Shift)

Produce Two Components of the SZ effect
**SZ Thermal Effect**

- Due to Thermal Velocity of Electrons
- Mean Energy of Photons Increased

\[
\Delta I_T = I_{comb} \cdot g(x) \quad I_{comb} = \frac{2h \nu^3}{c^2 (e^x - 1)}
\]

**Measure of Integrated Pressure:**

\[
y = \int \frac{kT \nu}{m_e c^2} n_e \sigma_T \, dl
\]

**Comptonization**

Non-Relativistic Limit: \( kT_e / mc^2 \ll 1 \)

\[
g(x) = \frac{x e^{-x}}{(e^x - 1)} \left[ \text{coth} \left( \frac{x}{2} \right) - 1 \right] \quad x = \frac{h \nu}{kT_{comb}}
\]

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**SZ Kinetic Effect**

- Due to Bulk Velocity of Electrons

\[
\Delta I_K = I_{comb} \cdot f(x) \int \frac{\bar{v}}{c} \, d\tau
\]

**Optical Depth**

\[
\tau = \int n_e \sigma_T \, dl
\]

**Spectrum Identical to dI/dTcmb**

\[
f(x) = \frac{x e^{-x}}{(e^x - 1)} \quad x = \frac{h \nu}{kT_{comb}}
\]

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**SZ Spectra**

**SZ Components Are:**
- Distinct
- Independent of Redshift
- Separable by mm wavelength Measurements

**SZ measurements**

Spectrum measured from the cm through sub mm

**BIMA**

LaRoque et al. 2002

A2163

Right Ascension (J2000)

Declination (J2000)
**SZ as a cosmological Probe**

**Baryon Fraction:**
- SZ and X-ray temperature gives baryon Mass
- Lensing or HSE give total Mass (and \( f_b \))
- \( \Omega_b/f_b = \Omega_m < 0.40 \) (Grego et al. 2000)

**Hubble Constant:**
- Clusters can be used as standard rods.
- Independent probe of expansion and acceleration.
- Reese et al. (in preparation) 18 clusters from \( z=0.14 \) to \( z=0.83 \)

**Peculiar Velocities:**
- Just limits so far...

**Growth of Structure:**
- The growth of structure is sensitive to the density and equation of state of the Universe.
- Source counts of SZ clusters can constrain cosmological models.

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**SZ surface brightness independent of z**

![Images showing SZ surface brightness at different redshifts](image)

X-ray surface brightness: \( S_X \propto (1 + z)^{-4} \)

Clusters should be visible out to the redshift of their formation. For \( \Lambda CDM \), \( z_f \sim 1/\Omega_m - 1 \sim 2 \)
Hydrodynamical Simulation of 1 square degree of SZ sky

Source counts are a steep function of flux

Springel, White, Hernquist 2001

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Mock Observations of Simulated Clusters

Establish Mass Limits for detected Clusters

Mass Limits from Mock Observations

Mass Limits as Function of Telescope Size

5σ detection (10 µK noise)

- 4.2x10^4 M☉ (10 µK)
- 3.8x10^4 M☉ (5 µK)
- 3.4x10^4 M☉ (2 µK)

5σ detection corresponds to:

- 4.2x10^4 M☉ (1.3' beam)
- 6.2x10^4 M☉ (1.8' beam)
- 1.6x10^5 M☉ (4.4' beam)
Galaxy Cluster Surveys and Survey Yields

Cluster surveys probe (1) volume-redshift relation, (2) abundance evolution, (3) structural evolution

\[ \frac{dN}{dzd\Omega} = \frac{dV}{d\Omega} n(z) (z) \]

High Resolution simulations by Daihuke Nagai & A. Kravtsov

Effect of Cluster Gas evolution

Effect of varying $w$ on SZE yield for flat universe

$w \equiv \frac{P}{\rho}$  \hspace{1cm} $\rho \propto R^{-3(1+w)}$

- Larger volume of $w = -1$ (Λ model) dominates at low $z$
- Retarded growth of density perturbations dominates at high $z$

Expected SZE Yield

Separating Survey volume from Cluster density

Haiman, Mohr & Holder 2000 astro-ph/0002336

(Wildly Optimistic) Constraints on Dark Energy Equation of State

Cluster Redshifts are essential for precise constraints

Mohr et al. 2002
Several Experiments are producing images of Known Clusters: BIMA, OVRO, Ryle, CBI, SuZIE, ACBAR, Diabolo.

These Experiments do not have the sensitivity to search for significant numbers of unknown Clusters.

A new generation of Instruments is under development:

Interferometers: AMI, SZA, AMIBA

Extremely high point source sensitivity - Ideal for producing detailed images

Bolometer Arrays: BOLOCAM, APEX, SPT, ACT

Large format arrays - Ideal for surveying large regions of sky
Ryle Telescope

Eight 13 meter dishes
15 GHz
E-W array

Arcminute MicroKelvin Imager

ten 3.5 meter dishes
12-18 GHz
Sited in Cambridge
Under Construction

Simulated AMI image of A1914
Kneissl et al, astro-ph/0103042
BOLOCAM
151 Element
Bolometer Array
Observes from the
CSO.

Still in commissioning
Stages

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OVRO/BIMA and SZA
SZE Imaging

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OVRO-BIMA SZE Imaging People

John Carlstrom, Marshall Joy, Bill Holzapfel

POSTDOCS:
- Amber Miller (UC Hubble Fellow → Columbia Assist Professor 9/2002)
- Joe Mohr (UC postdoc → U. I. Assist Professor)
- Kim Coble (UC NSF Fellow)

STUDENTS:
- Laura Grego (UC → CfA)
- Gil Holder (UC → IAS Keck Fellowship)
- Erik Reese (UC → Chandra Fellow, UCB)
- Sandy Patel (NASA/MSFC → NRC Fellow)
- Sam LaRoque (UC)
- Kyle Dawson (UCB)
- Daisuke Nagai (UC)

At OVRO and BIMA:

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OVRO / BIMA SZE imaging

OVRO: six 10.4 meter Dishes
2 GHz Bandwidth

BIMA: ten 6.3 meter Dishes
800 MHz Bandwidth
**SZE Imaging**

- Low-noise mm-wave receivers 1st installed on OVRO during summer
- Array maintained in 1994
- Produce high s/n detection and image of the SZE
- Now 60 clusters imaged and fine scale CMB anisotropy detected

Exploit the stability of interferometry to image low surface brightness emission

Need a compact array:
- Match angular scale of clusters
- Maximum brightness sensitivity
Sample from 60 OVRO/BIMA imaged clusters, $0.07 < z < 1.03$
Extreme example of spatial separation of SZE and point source emission

\( \Omega_{\text{Matter}} \) from SZE derived Gas mass ratios
- Total mass from SZE imaging and assumption of hydrostatic equilibrium
- Results agree with X-ray, M/Light, LSS

\[ \frac{(d \Omega_{\text{Matter}})}{d \Omega_{\text{U}}} \]

68% Confidence Upper Limit

Best Guess: \( \Omega_{\text{Matter}} \sim 0.25 \)


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Hubble constant from 18 OVRO/BIMA Observations (blue pts)

\[ H = 60 \pm 4 \pm 13 \text{ km} \text{s}^{-1} \text{Mpc}^{-1} \]

<table>
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<th>$H$</th>
<th>$\Omega_M$</th>
<th>$\Omega_{\Lambda}$</th>
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Systematics are now being addressed - no show stoppers

Carlstrom, Holder, ReeseARAA v40, in press

Check of SN Type Ia results at high redshift

SZA survey will provide nearly unbiased sample to $z \sim 2$
BIMA Blank Field Search:

Ten independent fields selected for low dust (IRAS 100\,\mu m) contrast and low radio point source (VLA NVSS and FIRST) emission

- Observed in summers of 1998 to 2001
- 50-81.2 hours per field
- 0.63-1.1 k\Lambda \sim 150\mu Jy/beam
- 1.1-1.7 k\Lambda \sim 150\mu Jy/beam
- \sim 15\mu K rms (2’ beam)

As of August 15 Finished Run to Double Sky Coverage

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BIMA Blank Field Survey

Time = 77.6 hours

\begin{align*}
\text{u-v} & > 2.4 \, \text{k}\Lambda, \\
\text{Beam} & = 21'' \times 22'' \\
\text{RMS} & \sim 130\mu \text{Jy/beam}
\end{align*}

\begin{align*}
\text{u-v} & = 0.63-1.2 \, \text{k}\Lambda, \\
\text{Beam} & = 98'' \times 116'' \\
\text{RMS} & \sim 110\mu \text{Jy/beam} \sim 12\mu K
\end{align*}

Now have 10 fields
Of comparable depth

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Point Sources Analysis:

- Sources identified in 4.8 GHz VLA Maps centered on BIMA fields

- \( \sim 25 \text{ uJy RMS in each map} \)

- All 6\( \sigma \) sources have their positions recorded and are weighted in the noise correlation matrix to remove their contribution. Lost degrees of freedom are negligible.

\[
\begin{align*}
\text{No point Sources:} & \quad \Delta T_1 = 17.7^{+5.2}_{-5.6} \text{ uK} \\
12\sigma \text{ sources removed:} & \quad \Delta T_1 = 16.7^{+5.0}_{-5.8} \text{ uK} \\
8\sigma \text{ sources removed:} & \quad \Delta T_1 = 17.1^{+5.2}_{-5.9} \text{ uK} \\
6\sigma \text{ sources removed:} & \quad \Delta T_1 = 16.4^{+5.3}_{-5.9} \text{ uK}
\end{align*}
\]
CARMA (OVRO+BIMA) + SZA
Unique Heterogeneous Array for mm-wave Science

→ 1\textsuperscript{st} KEY PROJECT: SZE survey and follow-up
  - Survey 12 sq degrees at 27-35 GHz for galaxy clusters
  - SZE follow-up at 30 and 100 GHz
  - Detailed Images essential for Understanding Surveys

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The SZA: eight 3.5m telescopes

- For $1 \text{ cm} \leq \lambda \leq 1 \text{ mm}$ observing:
  - 30 um RMS surface
  - 1 arcsec rms pointing spec
- Allow close pack configuration:
  - 1.2 diameter minimum spacing
- 8 GHz correlation bandwidth
- 26 – 36 GHz & 85 – 115 GHz receivers
- operational by end of 2003
- used as stand alone sub-array or heterogeneous array with CARMA

Designed with Vertex/RSI, lead designer: Eric Chauvin, based on initial design by Dave Woody

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SZA Instrument People and Funding

Chicago: John Carlstrom, Clem Pryke, Erik Leitch, John Cartwright, Amber Miller, Marcus Runyan, Brian Epley, Chris Greer, Michael Loh, Dan Siegal

Caltech: David Woody, David Hawkins, James Lamb, ...

NASA/MSFC: Marshal Joy, Georgia Richards

Funding: NSF-ATI grant, CfCP, McDonnell Foundation, U. Chicago, Packard Foundation

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Improved UV coverage much better imaging

→ Allows detailed SZE imaging with 5" resolution!

Needed to address cluster gas properties and evolution

Yields from SZA Survey

• Mass of clusters is most important. Yields are highly sensitive to cosmology:
  - abundance and volume-redshift relationship

Expected Cosmological Constraints
With SZA Survey Yield

and determine $\sigma_8$ to 5%

Dark Energy Equation of State $w$
with the SZA? (nope)

Determination of $w$ requires:
- better stats (much larger sample)
- controled systematics (better understanding of cluster gas properties and evolution)

$\Rightarrow$ Use SZA+CARMA imaging of SZA survey yields combined with optical, lensing, x-ray observations & simulations to determine gas properties and evolution
Corrugated Scalar Feed

Circular to Rect trx

Low-noise MMIC 1st stage
Isolator

Low-noise MMIC 2nd stage
Isolator

82 GHz High Pass filter

Mixer RF: 85 – 115 GHz
LO: 66.5 – 97 GHz

SZA Dual band Receiver
85 – 115.5 GHz Channel

- Matches OVRO & BIMA RF and IF bands
- Response SSB for improved Tsys
- Uses low-noise MMIC (NSF/UMASS chips, OVRO machining, Chicago assembly and test)
- Prototype working (35 – 65K)

18-28 GHz bandpass

2nd Mixer RF: 18.5-26.5 GHz
SZA LO: 17.5 GHz

Final IF
1 – 9 GHz
William Holzapfel, UCB (KITP New Cosmology Conference 8-20-02) Far Future Observations: Overview

**SZA Dual band Receiver**

1\(^{st}\) LO: 66.5 – 97 GHz
for sky: 85 – 115.5 GHz

- 100% compatible with CARMA LO reference system
- 17.5 GHz offsets 1\(^{st}\) LO and Rx IF → phase noise cancels
- W-Band mixer from Pacific Millimeter Products

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**Caltech-OVRO Broadband Reprogrammable Array (COBRA) Correlator**

by Daves Hawkins and Woody

1 GHz Digitizer board for PCI crate 500 MHz,
2-bit, 32 multiplex

500 MHz correlator section
(SZA: 8 GHz total bandwidth)

Status: integration testing with simulated signals starting this month. First goal is 4 GHz correlator on six element OVRO mm-array.
Each card: 5 baselines, 500 MHz, 50 lags.
(SZA will double speed to 125 MHz)

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Summary

- Sunyaev-Zel’denovich Effect will be an important tool for the "precision cosmology" era, probing fundamental physics.
- The SZA will provide deep survey over 12 square degrees finding all clusters with $M_{200} > 2 \times 10^{14} h^{-1} M_{\odot}$.
- Provide strong constraints on cosmology.
- Detailed SZE follow-up of survey sample will provide understanding of cluster evolution.

- SZA first light expected by Fall 2003