The Sunyaev-Zeldovich Effect as a Probe of Black Hole Feedback

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OUTLINE

- The Cosmic Microwave Background
- The Sunyaev-Zeldovich Effect (SZ)
- Black Hole Feedback (AGN Feedback)
- SZ from Black Hole Feedback
- Analytic Model (Chatterjee & Kosowsky 07, ApJL, 661, L113)
- Data Analysis (Chatterjee, Ho, Newman & Kosowsky 09, To be submitted in ApJ)
- Conclusion and Future Work
Primary Anisotropy in the CMB

\[ \frac{\Delta T}{T} = 10^{-5} \]

Courtesy: WMAP science team
Secondary Anisotropies in the CMB

Hu 2000
Sunyaev-Zeldovich Effect

- Inverse Compton scattering of CMB photons by hot electrons in the intracluster plasma

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

- \( \Delta I_{\text{SZ}} \) depends on cluster parameters
- SZ effect is a spectral distortion

Photo Credit: BIMA group
Mathematical Description

\[ \Delta I = I_0 g(x) y \ldots \ldots (1) \]

\[ \Delta T = T_0 f(x) y \ldots \ldots (2) \]

\[ g(x) = \frac{e^x x^4}{(e^x - 1)^2} (x \coth(x/2) - 4) \]

\[ f(x) = (x \coth(x/2) - 4) \quad x = \frac{h\nu}{K_B T_0} \]

\[ y = 2 \int dl \sigma_T n_e(M, z) \frac{K_B T e(M, z)}{m_e c^2} \]
Sunyaev-Zeldovich Spectrum

Null Frequency
220 GHz
# Galaxy Cluster Facts

- **Cluster Temperature:** 1-10 kev ($10^7$-$10^8$ K)
- **Electron density:** $10^{-2} - 10^{-4}$ /cm$^3$
- **Y distortion:** $10^{-4}$
- **$\Delta T$** : 100 $\mu$K
- **Mass** : $10^{14}M_{\text{sun}}$-$10^{15}M_{\text{sun}}$

**SZ effect** is an effective probe for detecting accumulation of hot gas in the universe.
Bullet Cluster at 148 GHz

Atacama Cosmology Telescope (Hincks et al. 2009)

Black: X-ray contours; Orange: Weak Lensing contours;
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Gas in clusters are heated: cluster potential well

Self-similar models suggest \( L_X \sim T^2 \) for the gas in clusters.

But observations show \( L_X \sim T^3 \) roughly.

Departure from self-similar

\[
\log L_X = (42.44 \pm 0.11) + \log h^{-2} + (2.79 \pm 0.14) \log T
\]

Recently confirmed by Andersson et al. 2009 with XMM
The Cooling Flow Problem

- X-ray surface brightness peaks at cluster centers
- Cooling is maximum at cluster centers
- Cooling inflow due to pressure gradient
- Lack of expected cooling flow

See Peterson & Fabian 2006 for a review

The Missing Piece (Feedback from AGN)

(e.g. Binney & Tabor 1995)

- Non-Gravitational heating mechanism in clusters
- Lack of cooling flow
Black Hole Feedback in Galaxy Cluster

HST image of MS0735.6 + 7421 cluster
Chandra X-ray image in blue
VLA radio image in red

McNamara & Nulsen 2007
Study of hot gas in black hole environments via SZ distortion

(Natarajan & Sigurdsson 99, Platania et. al 02, Lapi et. al 03)
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Theoretical Model

The energy outflow from an AGN

- Scannapieco & Oh 2004

- Energy is ejected into the IGM in the form of a spherical bubble.

- This bubble expands as a blast wave into the surrounding medium. (Sedov-Taylor solution)

- The radius and temperature of the bubble is given as a function of time.

- Uniform temperature and density within the bubble.
y-Distortion from the Model

\[ y(\theta) = \frac{4\sigma_T K_B}{m_e c^2} T_e n_e R_s \left[ 1 - \frac{D_A^2 \theta^2}{R_s^2} \right]^{1/2}. \]
Need the number density of AGNs
Use halo model to get number density of halos
Each dark matter halo hosts an AGN
All the AGNs eject their energy at redshift \(z_{in}\)
Assume a mass range of halos \(M_{\text{min}}-M_{\text{max}}\)
\(M_{\text{BH}} \sim 0.0001M_{\text{halo}}\) (Marconi & Hunt 03; Dubinski et al. 96)
Expansion into spherical harmonics.
Angular Power spectrum
$l(l+1)C_l / 2\pi$

$z=3.0$

$z=2.5$

Chatterjee & Kosowsky 2007
Power Spectrum to Signal

Assume a Gaussian Beam

$$\left\langle \frac{\delta T^2}{T} \right\rangle = \frac{1}{4\pi} \sum_l (2l + 1) W_l^2 C_l,$$

$$W_l = \exp(-l^2 \sigma^2 / 2).$$

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Resolution (arcseconds)</th>
<th>Temperature (μK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>60</td>
<td>-2.18</td>
</tr>
<tr>
<td>220</td>
<td>60</td>
<td>0.09</td>
</tr>
<tr>
<td>265</td>
<td>60</td>
<td>1.63</td>
</tr>
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Chatterjee & Kosowsky 2007
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Simulation

- N-body (Tree Particle-Mesh)
- Hydro (Smoothed Particle Hydrodynamics)
- Particles: $2 \times 486^3$
- Box: $33.75 \text{ h}^{-1} \text{ Mpc}$
- Star formation, Supernova & AGN feedback
- Dark Matter mass: $2.75 \times 10^7 \text{h}^{-1} M_{\text{sun}}$
- Gas mass: $4.24 \times 10^6 \text{h}^{-1} M_{\text{sun}}$

DiMatteo et al. 2008
Black holes are introduced in halos above a mass threshold of $10^{10}$ solar masses.

- The densest SPH particle is converted to a black hole particle of seed mass $10^5 h^{-1} M_{\text{sun}}$.

- Black holes grow via accretion and merging.


- 10% of the mass energy is radiated.

- Energy is radiated isotropically.

- 0.5% of the mass energy (5% of the radiated energy) couples as feedback energy.
Simulation Box

DiMatteo et al. 2008

SZ map around individual black hole
Chatterjee et al. 2008
The SZ effect is enhanced due to AGN feedback.

The enhancement is more centrally concentrated at higher redshifts.

The effect is predominant at angular scales within 5-20 arcseconds.

Chatterjee et al. 2008
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Detection Schemes

➢ Direct Observations by future millimeter wave telescopes
  ❑ Spatially resolve the source
  ❑ Prospects are marginal with Atacama Large Millimeter Array (ALMA), Cornell Caltech Atacama Telescope (CCAT)

➢ Stacking Microwave Maps in the direction of known Quasars.
  ❑ Cross-correlate quasars from Optical surveys with CMB maps
Cross-Correlation Of SDSS and WMAP

K: 23 GHz  
Ka: 33 GHz  
Q: 41 GHz  
V: 61 GHz  
W: 94 GHz

At WMAP frequencies we look for anti-correlation of temperature with QSOs

(Data credit: WMAP Science team): Figure (Chatterjee : Thesis)
\[ \Delta T = \frac{\sum_i N_i T_i}{\sum_i N_i} \]

- \( N_i \) = Number of QSOs in the \( i^{th} \) pixel
- \( T_i \) = Temperature of the \( i^{th} \) pixel
Systematics

- Galactic foregrounds: Synchrotron, Free-Free, Dust (Foreground reduction+ dust masks)
- Radio sources (Radio masking by matching with radio catalogs)
- Primary CMB (Spatial filter)
- Detector noise (Filter)
- SZ from galaxy cluster: (Estimated by cross-correlating with luminous red galaxies)
Cross-Correlation Spectrum

$y = (5.8 \pm 1.8) \times 10^{-7}$

Chatterjee et al. 2009 (To be submitted in ApJ)
We see a deficit in the flux (anti-correlation)

Significance of Correlation

- Randomize positions of QSOs (1000 realizations)
- 0.1% (Q), 1.3% (V) 6% (W) of the random cases have more prominent anti-correlation than the observed data
- QSOs are significantly correlated with temperature pixels in WMAP
Interpretation of Results

- QSOs tend to be in halos of mass $3 \times 10^{12} M_{\text{sun}}$ at redshift 1.0 (Coil et al. 2007)
- If a fraction (~10%) of QSOs reside in halos of bigger size it can explain the observed signal
- AGNs put more energy into the IGM (e.g. Natarajan & Sigurdsson 1997)
- Need future high resolution experiments (ACT/SPT) to resolve galaxy clusters and have better constraint

<table>
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<th>Object</th>
<th>Expected Signal from WMAP</th>
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<tbody>
<tr>
<td>Clusters</td>
<td>$10s \text{ mJy}$ (Diego &amp; Partridge 2009)</td>
</tr>
<tr>
<td>AGN feedback</td>
<td>$10-100 \mu \text{Jy}$</td>
</tr>
<tr>
<td>Observed</td>
<td>$1 \text{ mJy}$</td>
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Conclusion

- We show that the SZ effect is an effective tool in quantifying feedback energy from AGN.

- The resulting signal obtained from analytic model of AGN feedback is of the order of a $\mu$K.

- Predominant at angular scales of 10-15 arcseconds.

- We perform one of the first high resolution SZ simulations of AGN feedback.

- The highest mass black holes produce an SZ distortion of $\sim \mu$K.
Marginal prospects of detection with future high resolution mm wave telescopes

We show that cross-correlation with optical quasars and CMB maps provides another route of detection.

We perform the first cross-correlation analysis with SDSS QSOs and WMAP CMB maps.

The result is consistent with SZ.

Better constraints expected from ACT/SPT.
We have used a traditional tool in cosmology, namely the CMB …

… to study an astrophysical phenomenon, namely the feedback from AGNs, which has substantial impact on theories of structure formation.

Structure formation itself is an important question in cosmology!
Future Work

- Studying the X-ray signal from the simulation and comparing with observations
- Stacking Galaxy clusters from X-ray and Optical catalogs to investigate the SZ effect
- Detecting the signal with ACT

Chatterjee et al. 2009 (in prep)
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