Clusters Detected by WMAP

Eiichiro Komatsu (Texas Cosmology Center, Univ. of Texas at Austin)
SZX Huntsville, September 21, 2011
Outline

• Coma
  • *Coma is sitting on a $-100\mu K$ CMB fluctuation*

• A good agreement between SZ and X-ray data on **individual** clusters

• Effects of dynamical state (more precisely cool-core vs non-cool-core) on SZ
  • *Also seen by Planck*

• Lessons learned from the stacking analysis
  • *Scaling relations...*
WMAP has collected 9 years of data, and left L2.

- June 2001: WMAP launched!
- February 2003: The first-year data release
- March 2006: The three-year data release
- March 2008: The five-year data release

- **January 2010**: The seven-year data release
WMAP 7-Year Science Team

- C.L. Bennett
- G. Hinshaw
- N. Jarosik
- S.S. Meyer
- L. Page
- D.N. Spergel
- E.L. Wright
- M.R. Greason
- M. Halpern
- R.S. Hill
- A. Kogut
- M. Limon
- N. Odegard
- G.S. Tucker
- J. L. Weiland
- E. Wollack
- J. Dunkley
- B. Gold
- E. Komatsu
- D. Larson
- M.R. Nolta
- K.M. Smith
- C. Barnes
- R. Bean
- O. Dore
- H.V. Peiris
- L. Verde
WMAP 7-Year Papers

The SZ Effect: Decrement and Increment

• RXJ1347-1145 (high-resolution SZ maps)
  – Left, SZ increment (350GHz, 15” FWHM, Komatsu et al. 1999)
  – Right, SZ decrement (150GHz, 12” FWHM, Komatsu et al. 2001)
Where are clusters?

Coma

Virgo

\[ z \leq 0.1; \quad 0.1 < z \leq 0.2; \quad 0.2 < z \leq 0.45 \]

Radius = \( 5\theta_{500} \)
We find that the CMB fluctuation in the direction of Coma is \(\approx -100\,\mu\text{K}\).

(This is a new result!)

\[ y_{\text{coma}}(0) = (7\pm2) \times 10^{-5} \quad (68\% \text{CL}) \]

- “Optimal V and W band” analysis can separate SZ and CMB. The SZ effect toward Coma is detected at \(3.6\sigma\).
A Question

• Are we detecting the **expected** amount of electron pressure, $P_e$, in the SZ effect?

• Expected from X-ray observations?

• Expected from theory?
Arnaud et al. Profile

- A fitting formula for the average electron pressure profile as a function of the cluster mass ($M_{500}$), derived from 33 nearby ($z<0.2$) clusters (REXCESS sample).
A significant scatter exists at $R < 0.2R_{500}$, but a good convergence in the outer part.
Coma Data vs $P_{\text{universal}}$

- $M_{500} = 6.6 \times 10^{14} \text{h}^{-1} M_{\odot}$ is estimated from the mass-temperature relation (Vikhlinin et al.).
- $T_{X,\text{coma}} = 8.4 \text{keV}$.
- Arnaud et al.'s profile overestimates both the direct X-ray data and WMAP data by the same factor (0.65)!
- To reconcile them, $T_{X,\text{coma}} = 6.5 \text{keV}$ is required, but that is way too low.

The X-ray data (XMM) are provided by A. Finoguenov.
Well...

- That’s just one cluster. What about the other clusters?
- We measure the SZ effect of a sample of well-studied nearby clusters compiled by Vikhlinin et al.
WMAP 7-year Measurements
(Komatsu et al. 2011)
## SZ seen in the WMAP

<table>
<thead>
<tr>
<th>Mass Range$^a$</th>
<th># of clusters</th>
<th>X-ray Data</th>
<th>$P_{universal}$</th>
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<tbody>
<tr>
<td>$6 \leq M_{500} &lt; 9$</td>
<td>5</td>
<td>$0.90 \pm 0.16$</td>
<td>$0.73 \pm 0.13$</td>
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<tr>
<td>$4 &lt; M_{500} &lt; 6$</td>
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<td>$2 \leq M_{500} &lt; 4$</td>
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<td>$0.71 \pm 0.31$</td>
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<td>$1 \leq M_{500} &lt; 2$</td>
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$^a$ In units of $10^{14} \, h^{-1} \, M_\odot$. Coma is not included.

d: ALL of “cooling flow clusters” are relaxed clusters.

e: ALL of “non-cooling flow clusters” are non-relaxed clusters.
## Signature of mergers?

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d: ALL of “cooling flow clusters” are relaxed clusters.

e: ALL of “non-cooling flow clusters” are non-relaxed clusters.
SZ: Main Results

• The X-ray data on the individual clusters agree well with the SZ measured by WMAP.

• Distinguishing between relaxed (CF) and non-relaxed (non-CF) clusters is important, even for SZ.

• This is confirmed by Planck (with a LOT more signal-to-noise!)
In Arnaud et al., they reported that the cooling flow clusters have much steeper pressure profiles in the inner part.
• The SPT measured the secondary anisotropy from (possibly) SZ. The power spectrum amplitude is $A_{SZ}=0.4–0.6$ times the expectations. Why?
Lower A_{SZ}: Two Possibilities

\[ C_l = g^2 \int_{0}^{z_{\text{max}}} dz \frac{dV}{dz} \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn(M, z)}{dM} |\tilde{y}_l(M, z)|^2 \]

- [1] The number of clusters is less than expected.

- In cosmology, this is parameterized by the so-called “σ_8” parameter.

\[ \frac{l(l+1)C_l}{2\pi} \simeq 330 \mu K^2 \sigma_8^2 \left( \frac{\Omega_b h}{0.035} \right)^2 \times \text{[gas pressure]}^2 \]

- σ_8 is 0.77 (rather than 0.81): Σm_ν ∼ 0.2eV?
Lower $A_{SZ}$: Two Possibilities

\[ C_l = g^2 \nu \int_0^{z_{\text{max}}} dz \frac{dV}{dz} \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn(M, z)}{dM} |\tilde{y}_i(M, z)|^2 \]

- [2] Gas pressure per cluster is less than expected.
  - The power spectrum is \([\text{gas pressure}]^2\).
  - $A_{SZ}=0.4–0.6$ means that the gas pressure is less than expected by $\sim0.6–0.7$.
- What would a dynamical state (more precisely, cool-core vs non-cool-core) do?
Effects of Dynamical State on $C_l$

At $l \sim 3000$, the effect is less than 20%. More significant on smaller angular scales.
Effects of Dynamical State on $C_l$

- Want a code? Google "Cosmology Routine Library"

Morphologically Disturbed
Median (Universal)
Cool Core

$\ell(\ell+1)/2\pi [\mu K^2]$ vs. Multipole, $\ell$
Conclusion I

• Coma is sitting on top of a $-100\mu$K CMB fluctuation

• WMAP could detect SZ toward a few other massive clusters, even seeing the difference between cool-core and non-cool-core

• Distinguishing relaxed and non-relaxed clusters is important, if you can resolve the profile of clusters
Statistical Detection of SZ

- Coma is bright enough to be detected by WMAP.
- Some clusters are bright enough to be detected individually by WMAP, but the number is still limited.
- By stacking the pixels at the locations of known clusters of galaxies (detected in X-ray), we detected the SZ effect at $8\sigma$.
- Many statistical detections reported in the literature:
742 clusters in $|b|>20$ deg (before Galaxy mask)

400, 228 & 114 clusters in $z \leq 0.1$, $0.1 < z \leq 0.2$ & $0.2 < z \leq 0.45$. 

$z \leq 0.1; 0.1 < z \leq 0.2; 0.2 < z \leq 0.45$

$\text{Radius} = 5 \theta_{500}$
Size-Luminosity Relations

• To calculate the expected pressure profile for each cluster, we need to know the size of the cluster, \( r_{500} \).

• This needs to be derived from the observed properties of X-ray clusters.

• The best quantity is the gas mass times temperature, but this is available only for a small subset of clusters.

• We use \( r_{500} - L_X \) relation (Boehringer et al.):

\[
\begin{align*}
\text{r}_{500} &= \frac{(0.753 \pm 0.063) \, h^{-1} \text{ Mpc}}{E(z)} \\
& \times \left( \frac{L_X}{10^{44} \, h^{-2} \text{ erg s}^{-1}} \right)^{0.228 \pm 0.015} \\
E(z) & \equiv \frac{H(z)}{H_0} = \left[ \Omega_m (1 + z)^3 + \Omega_\Lambda \right]^{1/2}
\end{align*}
\]

Uncertainty in this relation is the major source of sys. error.
Mass Distribution

Most of the signals come from $M_{500} > 0.8 \times 10^{14} h^{-1} M_{\odot}$.

$M_{500} \sim \text{(virial mass)}/1.6$
Scaling Relations...

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- Different scaling relations can give you a variety of results
- Need for a “consistent scaling relation” (Melin), but it is not so trivial to find one
- This limits accuracy of the stacking method
Missing P in Low Mass Clusters?

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- “Low $L_X$” has $0.45 < L_X/(10^{44}\,\text{ergs}^{-1}) < 4.5$
- $M_{500} < \text{a few} \times 10^{14} \, h^{-1} \, M_{\odot}$
This is consistent with the lower-than-expected $C_l^{SZ}$

- At $l>3000$, the dominant contributions to the SZ power spectrum come from low-mass clusters ($M_{500}<4\times10^{14}h^{-1}M_{\odot}$).

Komatsu and Seljak (2002)
However...

• This deficit of the pressure on low-mass clusters has not really been seen by Planck, for one of the scaling relations.

• And they have MUCH more signal-to-noise.

• However, they also do see that the results change significantly depending on the $L_x-M_{500}$ scaling relation adopted.

• For another scaling relation they used, they see the deficit.
A lesson [we] learned from the stacking analysis

• The stacking analysis is a potentially powerful technique for discovering unexpected phenomena
  • Optical vs SZ is very intriguing (Planck Paper XII)
• The scaling relation limits accuracy and complicates the interpretation of the results
• Once something is found, it is good to go back to individual clusters (the first part of the talk) and understand what is going on (CC vs NCC, for example)