CMB and SZ Science with a 25-m Atacama Telescope

Sunil Golwala
Caltech
October 11, 2003
CMB and SZ Science Topics

- Pointed observations of known clusters to measure peculiar velocities
- Blind surveys for clusters using thermal SZ
- Secondary anisotropy due to thermal SZ
- Secondary anisotropy due to kinetic SZ
- High-l Polarization

Running assumptions:
- \( \text{NET per pixel} \sim 400 \ K_{\text{CMB}} \sqrt{s} \)
- Assume \( \sim 1 \text{ deg}^2 \text{ FOV} \)
- \( \rightarrow \text{can map} \ 100 \text{ deg}^2 \text{ to} \ 5 \ K_{\text{CMB}} \text{ per beam in 1 live-week} \)
- Not crazy: ACBAR had \( 400 \ K_{\text{CMB}} \sqrt{s} \) with 40K of loading and mapped 10 \( \text{deg}^2 \) to 5 \( K_{\text{CMB}} \) per beam in 16 weeks (austral winter at south pole) with 8 pixels
The Sunyaev-Zeldovich Effect in Galaxy Clusters

- Thermal SZE is the Compton up-scattering of CMB photons by electrons in hot, intracluster plasma.

\[ \frac{\Delta T_{\text{CMB}}}{T_{\text{CMB}}} \] depends only on cluster \( y \sim \) line-of-sight integral of \( n_e T_e \). Both \( \Delta T_{\text{CMB}} \) and \( T_{\text{CMB}} \) are redshifted similarly \( \rightarrow \) ratio unchanged as photons propagate and independent of cluster distance.

- Thermal SZE causes nonthermal change in spectrum. CMB looks colder to left of peak, hotter to right.

Sunyaev & Zeldovich (1980)

galaxy cluster with hot ICM
\( z \sim 0 - 3 \)

scattered photons (hotter)

observer \( z = 0 \)

CMB photons
\( T = (1 + z) \times 2.725 \text{K} \)

last scattering surface
\( z \sim 1100 \)
The Sunyaev-Zeldovich Effect in Galaxy Clusters

- **Kinetic SZE**: essentially a Doppler shift
  - Cluster sees CMB dipole due to its peculiar motion, but scatters isotropically in rest frame, producing anisotropy in CMB rest frame
  - $\Delta T_{\text{CMB}}/T_{\text{CMB}} = -\tau_e (v/c)$ where $\tau_e$ is the Thomson optical depth.
  - Change in spectrum is completely thermal (identical to CMB primary anisotropy); like dipole anisotropy due to motion relative to CMB rest frame.
  - Polarity: if cluster is moving toward observer, CMB appears hotter toward cluster
The Sunyaev-Zeldovich Effect in Galaxy Clusters

- Beautiful images of SZ from Carlstrom group using OVRO/BIMA interferometers at 30 GHz
- Spectrum confirmed by measurements from Rayleigh-Jeans tail through the null
- To date, only seen in pointed observations of massive clusters
In principle, could measure peculiar velocities of a large catalog of galaxy clusters using kinetic effect

Raw sensitivity is there:
- POTENT: typical error \( \sim 250 \text{ km/s} \) on 3000 galaxy sample; \( \sigma / \sqrt{N} \sim 4.5 \text{ km/s} \)
- SZ: suppose one does the 100 MACS clusters; need \( \sigma \sim 45 \text{ km/s} \) to compete
- \( \Delta T \sim (0.01) \frac{45}{300000} (2.7) = 4 \ K_{\text{CMB}} \)

Really a matter of systematics and scan strategy
- No experience yet in detecting kinetic effect with bolometer arrays
- Much harder to simulate than finding point sources because the clusters are big
- Not especially well-suited to 25 m: clusters will be overresolved, so collecting area is to some extent wasted
- But high resolution could be helpful for understanding cluster astrophysics systematics that might otherwise prove limiting factor
“Unbiased” Cluster Detection via the SZE

- “Unbiased” = mass-limited
- Effect is intrinsically redshift-independent: $\Delta T/T$ depends only on cluster properties, $\Delta T$ and $T$ experience same redshift
- Integrated SZE over cluster provides largely $z$-independent mass limit (Barbosa et al, Holder et al, etc.)

\[
S_{tot} = \frac{2k_B^2\nu^2 g(x)\sigma_T T_{CMB}}{m_e c^4 d_A(z)^2} \langle T_e \rangle_n \frac{M_{200} f_{ICM}}{\mu_e m_p}
\]

- Integrate $n_e T_e$ over cluster face
- $dA^2$ factor tends to reduce flux as $z$ increases ($1/r^2$ law)
- But for a given mass, a cluster at high redshift has smaller $R$ and hence higher $T$
- These two effects approximately cancel
- Influence of cluster gas physics:
  - $SZ \propto n_e T_e =$ pressure  $X$-ray $\propto n_e^2 \sqrt{T_e}$  optical $\propto ?$
  - Pressure is the smoothest physical parameter – see simulations.
  - X-ray generically clumpier than SZ.
“Unbiased” Cluster Detection via the SZE

- Holder, Mohr, et al. (2000) modeled the mass limit of an interferometric SZE survey using simulations of cluster growth
- Simulations bear out expectation of weak $z$-dependence of mass limit
- Very different selection function from optical/x-ray surveys
- For any survey, careful modelling will be required to determine this precisely, understand uncertainties

Science with Unbiased Surveys for Clusters

- Redshift distribution of clusters is sensitive to cosmological parameters ($\Omega_m$, $\Lambda$, $w$) and amplitude of density fluctuations ($\sigma_8$)

- e.g. SPT 4000 deg$^2$ in 1 season to $10$ K$_\text{CMB}$ per 1 arcmin beam, with photo-z’s for 3000 deg$^2$
Science with Unbiased Surveys for Clusters

- Redshift distribution of clusters is sensitive to cosmological parameters ($\Omega_m, \Lambda, w$) and amplitude of density fluctuations ($\sigma_8$)
- e.g. SPT 4000 deg$^2$ in 1 season to $10 \ K_{CMB}$ per 1 arcmin beam, with photo-z's for 3000 deg$^2$
Secondary CMB Anisotropy

• Rather than looking at single objects, consider cumulative secondary anisotropy imprinted by ensemble of large-scale structure
  
  ♦ Thermal SZ:
    • cumulative thermal SZ from clusters and the globally reionized IGM
    • dominant, but separable from primary and other secondary by frequency spectrum
  
  ♦ Kinetic SZ: gives rise to many different effects
    • no “first-order” effect: because velocity flows $v(k) \propto \text{mass fluctuations } \delta(k)$ and therefore are irrotational to 1st order, there is cancellation along line-of-sight in $n_e(v/c)$ (every $+v$ has an associated $-v$)
    • many “second-order” effects
      – “Ostriker-Vishniac” or “Vishniac” – retain linear relation between $v$ and $\delta$, but include second-order evolution of perturbations → see effects due to interaction of $v(k_1)$ with $\delta(k_2)$, so line-of-sight cancellation does not occur
      – “Nonlinear Kinetic” or “Nonlinear Ostriker-Vishniac” – allow for nonlinear gravitational collapse, breaking down linear relation between $v(k)$ and $\delta(k)$
      – “Patchy Reionization” – fluctuations in $n_e$ due to details of onset of reionization
Secondary CMB Anisotropy

- $l = 10000 \rightarrow 1$ arcmin
- Nontrivial spread in predictions
- All within factor of a few of $1 \mu K_{\text{CMB}}^2$ for OV
- All agree that patchy reion. is subdominant
Secondary CMB Anisotropy

- Why bother with kinetic effects?
  - Thermal is dominated by largest objects because it depends on $T$ in addition to $n_e$; lower-mass objects and the IGM are much colder
  - OV and non-linear OV less biased, dominated by “2-halo” effects (because dependent on velocity field)
  - Patchy reionization traces redshift of reionization; angular PS and non-Gaussianity trace size of reionized bubbles
Secondary CMB Anisotropy

- Current state of the art
- Significant improvement likely between now and 25m first light
  - APEX, SPT (and maybe ACT) will come online before 25m
  - The thermal SZ signal will be measured
  - SZ signal will be cross-correlated with redshift surveys

Goldstein *et al*, astro-ph/0212517

\(\Delta T^2 [\mu K^2]\)

\(\sigma_{\delta Z} = 0.98\)

\(30\text{GHz}\)

\(150\text{GHz}\)

\(\Delta T_{\text{CMB}}\) at 30 and 150 GHz (~ x 2)
• Thermal signal
  - ~ few to 10 $\mu K_{\text{CMB}}$ on 1 arcmin scales
  - dominated by most massive clusters
  - can possibly do cosmological params/dark energy (with redshift info)

• Kinetic signal
  - 1 $\mu K_{\text{CMB}}$ or less on 1 arcmin scales
  - OV more sensitive to lower masses → say more about LSS than cosmology
  - Patchy reionization may give access to reionization physics, but order of magnitude smaller and difficult to separate from OV

• Does a 25-m telescope help? Yes! Error on $C_l$ scales as $\exp(l^2\sigma^2)$.
  - APEX: 1 arcmin → factor of 5 degradation at $l = 10000$
  - SPT: 1.3 arcmin → factor of 13 degradation at $l = 10000$
  - 25m: 0.5 arcmin → factor of 1.5 degradation at $l = 10000$
  - (these assume conservative edge tapers on primary)
Polarization Anisotropies

- Hu (2000) calculates polarization on small scales arising from assorted quadrupole effects:
  - "Thomson scattering of quadrupole anisotropies, kinetic (second order Doppler) quadrupole anisotropies and intrinsic quadrupole anisotropies."
  - All these signals are really small (Hu’s OV effect has peak amplitude $2 \mu K_{\text{CMB}}$)

FIG. 2.— Polarization for the fiducial $\Lambda$CDM model with $\tau = 0.1$ separated into $E$ (solid lines) and $B$ (dashed lines) contributions. Secondary anisotropies from the primordial quadrupole are labeled (Prim. $Q$): (upper) homogeneous scattering; (lower) density ($\delta_b$) and ionization ($X$) modulated scattering following Fig. 1. For the kinematic quadrupole, the homogeneous and density modulated signals are shown; the ionization modulated and intrinsic quadrupole signals falls below this range. Note that the $B$-parity polarization induced by gravitational lensing is much larger than any of these secondary $B$ signals.
• Measure polarization of SZ in galaxy clusters
  ◆ Each cluster measures the quadrupole for its last-scattering surface
  ◆ Overcomes cosmic variance limit on quadrupole
  ◆ Quadrupole sensitive to dark energy via ISW effect
  ◆ Provides measurement of evolution of dark energy → eqn of state
  ◆ “a truly challenging measurement”
CMB/SZ Summary

• Raw sensitivity is there for peculiar velocities, but systematics and scan strategy are the issue
• Blind thermal SZ surveys doable and interesting for cosmological parameters/LSS
• Detection of OV effect probably doable and interesting for LSS
• Patchy reionization and polarization anisotropy both v. difficult and probably not all that interesting
• Cluster SZ polarization interesting but probably too hard
• Better angular resolution of a 25m could provide significant gains at high $l$ with respect to projects already underway (APEX, ACT, SPT)
• To do: realistic expected sensitivities, input from theorists (Cooray, Kamionkowski at Caltech)