4.4 Cosmology — Sunyaev-Zeldovich Effect

4.4.1 Science Goals

The Sunyaev-Zeldovich (SZ) effect will become, over the next decade, an important probe of cosmology and cluster formation astrophysics via wide-area blind surveys for galaxy clusters using the SZ effect. CCAT can play a significant complementary role to these surveys by pursuing the following SZ observations:

- Detailed thermal SZ (tSZ) effect mapping of clusters detected by wide-area blind tSZ surveys such as APEX-SZ, ACT, SPT, and Planck. CCAT will provide high-resolution SZ profiles to aid in calibrating and interpreting these surveys.
- Blind tSZ surveys reaching lower mass limits than wide-area surveys.
- Measurement of the tSZ anisotropy power spectrum at very high angular multipole number, $\ell \sim 2000 - 20000$.
- Low-resolution tSZ spectroscopic follow-up of clusters to aid in measuring relativistic effects and to possibly provide SZ-based gas temperatures.

We have considered other science goals (primary CMB anisotropy, kSZ searches in known clusters, kSZ anisotropy, SZ polarization) but judged that they are marginal based on conservative confusion-limit estimates, better accomplished by other instruments, or beyond the reach of CCAT.

4.4.2 Motivation/Background

The Sunyaev-Zeldovich effects consist of scattering of cosmic microwave background (CMB) photons by the hot electrons in the intracluster medium (ICM) of galaxy clusters. The thermal SZ (tSZ) effect is a Compton-scattering-induced spectral distortion of the CMB. The kinetic SZ (kSZ) effect is a Doppler shift of the CMB due to scattering by a moving cluster.

The tSZ effect has been detected in tens of clusters; John Carlstrom and collaborators dominate the count, having used the BIMA and OVRO interferometers to image about 60 clusters at 1 cm. The SuZIE experiment has the largest millimeter-wave sample, with a total of 11 clusters with measurements at 1.1, 1.4, and 2.1 mm. No cluster has been found "blindly" in the tSZ yet. The kSZ effect has not been detected. A significant deficiency of the existing data is their relatively poor angular resolution (about 1 arcmin) and their lack of ability to probe extended structure (because the sample is dominated by interferometric measurements).

We believe that the tSZ will provide an important new probe of galaxy clusters in the coming years. Historically, free-free X-ray emission has been the primary probe of intracluster gas, but it is a complicated observable: it scales with the product of the square of the electron density, n_e^2, and the nontrivial electron-temperature dependent emissivity function, $\Lambda(E_X,T_e)$. While Chandra and XMM have taught us a great deal, they have also highlighted the complexity of the ICM, with cold fronts, bubbles from AGN, evidence of mergers, etc. tSZ would provide another, simpler ICM observable, the line-of-sight integral of the pressure. tSZ profiles of clusters would enable more detailed study of the thermodynamic state of the gas, including the level of entropy injection by star formation or other heating processes, the importance of radiative cooling, and cluster merger histories. tSZ may also give us more information about the shape of the gravitational potential well – the dark matter – because it will extend to larger radius.

Regular observation of the kSZ effect, while extremely challenging, would provide a new and unique observable for cosmology: a probe of the peculiar velocity field at high redshift (z up to 2 or 3). It may also be possible to study internal bulk motions in galaxy clusters using the kSZ effect.

An exciting prospect is the advent of wide-area "blind" surveys in the tSZ. The tSZ provides a largely redshift-independent method for detecting galaxy clusters; a flux-limited tSZ survey is, to a factor of 2, a mass-limited survey. Thus, measurement of cluster abundance as a function of redshift via the tSZ would be free of the extremely redshift-dependent selection functions of optical or X-ray surveys. Such an abundance measurement would constrain cosmological parameters, in particular Ω_m, Ω_Λ, and the equation of state parameter w. Many such surveys will be undertaken in the coming years by the Atacama Pathfinder Experiment-SZ (APEX-SZ — MPIfR and Berkeley), the Atacama Cosmology Telescope (ACT — Princeton, Penn, Goddard), the South Pole Telescope (SPT — Chicago, Case Western, and Berkeley), and the Planck satellite.

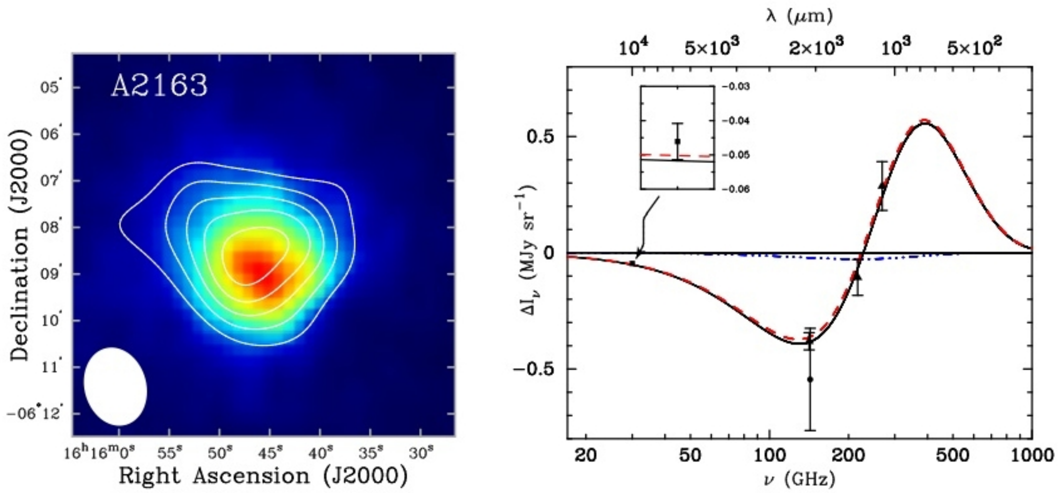

Figure 4.17: Sunyaev-Zeldovich observations of Abell 2163. The left plot shows the ROSAT X-ray map (color) overlaid with contours of SZ obtained with the BIMA interferometer at 30 GHz. The right plot shows the spectrum of the SZ effect in A2163 from combined measurements with BIMA (30 GHz), SuZIE (1.1, 1.4, and 2.1 mm), and Diabolo (2.1 mm).

Interpretation of these surveys will require careful characterization of the tSZ mass determination. The surveys intentionally leave the emission spatially unresolved in order to maximize survey efficiency. Thus, they obtain little information about the tSZ emission aside from its total flux. Follow-up imaging using CCAT would provide 3 to 4 times finer angular resolution. This detailed tSZ information will be useful for understanding how cluster astrophysics affect the tSZ mass determination, whose scatter and bias dominates cosmological interpretation of survey yields.

4.4.3 Technique

There is a large literature on calculating the abundances of clusters, the expected dark-matter and gas profiles of galaxy clusters, and the resulting tSZ and kSZ profiles. We have reviewed this literature in a technical note[1], calculated simple approximate formulae for quantities of interest, made judgments about what projects are feasible and efficient uses of CCAT time, and outlined a set of key projects. We list some of the basic assumptions and parameters and a summary of key projects here.

Table 4.5: Cluster abundances

Mass $[10^{14}\ M_\odot]$	Abundance $[\mathrm{deg}^{-2}]$	Number in 20000 deg^2
1	40	10^6
3.5	6	10^5
10	0.25	few x 10^3
35	0.012	10^2

Table 4.6: Assumed beam sizes

wavelength	beam FWHM
1.1 mm	0.24 arcmin = 14 arcsec
1.4 mm	0.30 arcmin = 18 arcsec
2.0 mm	0.44 arcmin = 26 arcsec
3.0 mm	0.66 arcmin = 40 arcsec

4.4.3.1 Assumptions

The fiducial cluster we will study is one at the mass limit of the wide-area tSZ surveys such as APEX-SZ, ACT, and SPT, with $M \approx 3.5\times10^{14}\ M_\odot$. Other fiducial targets are clusters with masses of $10^{14}\ M_\odot$, $10^{15}\ M_\odot$, and $3.5\times10^{15}\ M_\odot$. The Planck all-sky survey will detect clusters above a mass limit of $M \approx 8\times10^{14}\ M_\odot$. We list the integral cluster abundances (N > M) at these fiducial masses in Table 4.5.

[1] This technical note is available at http://gabba.astro.cornell.edu/twiki/bin/view/Main/Cosmology.

Minimizing excess optical loading is critical in the long-wavelength SZ bands, so we assume a Gaussian illumination of the 25-m diameter primary with a conservative −10 dB edge taper (σ = 5.8 m, FWHM = 13.7 m). This results in the beam sizes given in Table 4.6, which are coarser than those usually quoted in these bands for CCAT.

4.4.3.2 Expected Sensitivity

- **Photometric Sensitivity**

  A background-limited 150 GHz photometric camera, at a site as good as CCAT's, will be limited by telescope optical loading. Neglecting the factor of 1.414 (square root of 2) chopping/sky-subtraction degradation that is included elsewhere in sensitivity estimates, such a camera would achieve 2.3 mJy-s$^{1/2}$ (310 μK_{CMB}-s$^{1/2}$) assuming 10% telescope emissivity and 1.5 mm PWV conditions. If the telescope emissivity is reduced to 5%: the sensitivity improves by 1.414 to 1.6 mJy-s$^{1/2}$ (220 μK_{CMB}-s$^{1/2}$). To provide the desired edge taper, we assume ~ $2(F/\#)\lambda$ pixels, where the $F/\#$ is referenced to uniform illumination of the primary. At that pixel size, a 1000-pixel focal plane covers a 20 arcmin × 20 arcmin field-of-view.

  If we include other frequencies under the same conditions, we obtain the sensitivities given in Table 4.7 . The 100 GHz and 150 GHz sensitivities are telescope-limited. The 220 GHz and 275 GHz bands would improve by about 1.414 if either the telescope emissivity were reduced by 2 or if the atmospheric opacity were reduced by 2.

Table 4.7 Background-limited sensitivities for SZ bands*

frequency [GHz]	atmospheric transmission	NET_{RJ} [μK_{RJ}-s$^{1/2}$]	NET_{CMB} [μK_{CMB}-s$^{1/2}$]	NEFD [mJy-s$^{1/2}$]
275	0.86	190	1000	2.5
220	0.905	170	530	2.2
150	0.93	180	310	2.3
100	0.93	210	270	2.7

*assuming 10% telescope emissivity and 1.5 mm PWV conditions.

- **Spectroscopic Sensitivity**

  A background-limited waveguide spectrometer operating near 150 GHz with 3 GHz resolution should achieve a sensitivity of ≈ 5×10^{-19} Wm^{-2}s$^{1/2}$ for the conservative 10% emissivity assumption. A reduction to 5% emissivity would improve this by about 40%, again a significant gain.

- **Confusion Limits**

  The dominant source of confusion at SZ frequencies is extragalactic infrared point sources. We present confusion limits in Table 4.8. The confusion limit at 150 GHz is higher than the tSZ signal level in the wings of 3.5×10^{14} $M_\odot$ and 10^{15} $M_\odot$ clusters and is comparable to the tSZ signal level at r_g (the geometric mean of the core and virial radii) in 3.5×10^{14} $M_\odot$ clusters. Confusion is clearly a challenge.

Table 4.8: *One-source-per-beam* confusion limits*

Frequency [GHz]	Flux density [μJy]	Temperature [μK_{CMB}]	Compton y parameter
275	66	27	1.1×10^{-5}
220	89	21	N/A
150	44	6	2.3×10^{-6}
100	21	2.1	5.1×10^{-7}

*for the conservatively large beam sizes in Table 4.6. Limits provided by A. Blain.

We will subtract confusion noise using maps made by CCAT at higher frequencies. In the table of key projects, we list, for the desired key project flux limit, the number of confusing sources per 490 GHz beam at that flux limit when the flux limit is scaled to 490 GHz. This gives a rough estimate of whether sources are removable to the desired flux limit. ALMA follow-up is too slow to do point source removal.[2]

4.4.3.3 Candidate SZ Key Projects

A number of key SZ science projects suggest themselves, listed in Table 4.9. We have aimed for a number of programs that each require no more than 100 to 200 hours per year and are conducted over 5-year periods. Based on the observed PWV distributions, it would be reasonable to have about 5 of these projects running at any given time.

Table 4.9: Candidate SZ key projects*

Science Target	Per beam sensitivity μK_{CMB}	μJy	S/N	# of objects per year	# of hours per year	# of objects in 5 years	# of hours in 5 years	confusion (# srces/ 490 GHz beam)
tSZ profiles								
High-mass ($> 3.5\times10^{15}$ $M_\odot$)								
mapping	2	15	5	10	130	50	650	1 / 30
Medium-mass (1×10^{15} $M_\odot$ to 3.5×10^{15} $M_\odot$)								
mapping	1	7.5	3	3	160	15	800	~ 1 / 10
radial profile	10	75	0.3	200	100	1000	600	<< 1 / 30
Low-mass (3.5×10^{14} $M_\odot$ to 1×10^{15} $M_\odot$)								
radial profile	3	23	0.3	20	120	100	600	< 1 / 30
tSZ pt-src survey, $S/N = 5$ at 1×10^{15} $M_\odot$ on 10 deg^2 fields								
	10	75	5	1	50	5	150	<< 1 / 30
tSZ spectroscopy, one beam, $S/N = 5$ per $\Delta\nu = 3$ GHz bin								
High-mass ($> 3.5\times10^{15}$ $M_\odot$)								
9 pos, $\theta < \theta_g$	14	100	5	4	140	20	700	< 1 / 30
Medium-mass (1×10^{15} $M_\odot$ to 3.5×10^{15} $M_\odot$)								
1 pos, $\theta < \theta_g$	3	20	5	2	140	10	700	~ 1 / 30
kSZ at r_g, $S/N = 1$ per 150 GHz beam (for 4 μK_{CMB} signal level)								
150 GHz	4	30	1	5	17	25	80	< 1 / 30
220 GHz	5.9	25	0.7	5	20	25	110	1 /10
275 GHz	7.3	18	0.6	5	50	25	260	~ 1 / 1?
tSZ anisotropy survey, $S/N = 5$ at 1×10^{15} $M_\odot$ on 0.5 deg^2 fields								
	1.4	10	5	1	120	5	600	1 / 10 – 1 / 30
kSZ anisotropy survey, $S/N = 1$ per 150 GHz beam, FoV-side fields								
150 GHz	2	15	1	1	13	1	65	1 / 30
220 GHz	2.9	12	0.7	1	19	5	95	~ 1 / 1?
275 GHz	3.7	9	0.6	1	40	5	200	~1 / 1?

*The "confusion" column refers to the number of sources per 490 GHz beam at the flux level obtained by scaling the low-frequency per-beam sensitivity to 490 GHz using $\nu^{3.7}$. θ_g = angle corresponding to r_g, which is the geometrical mean of the core radius and the virial radius.

[2] The field-of-view of ALMA is too small to cover the bulk of a cluster to sufficient depth in a reasonable time (see the technical note[1] for integration times, as well as Section 4.2.4 of this note).

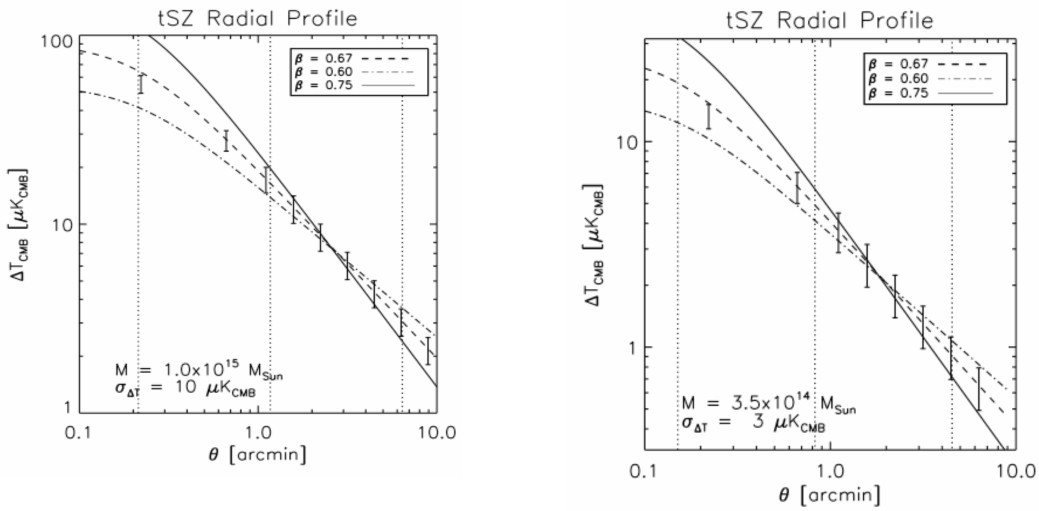

Figure 4.18: Expected errors on tSZ radial profiles. Cluster masses and assumed per-beam sensitivities are indicated. Each plot also shows three different β profiles that would yield the same integrated SZ Comptonization parameter within the virial radius. Profiles are shown for gas concentration factor $c_g = 5$; c_g is the ratio of the dark-matter halo NFW scale radius to the gas β-profile core radius. The vertical dotted lines indicate the three characteristic radii r_c, r_g, and R_v (core, geometrical mean of core and virial, and virial). The radial binning of the data is linear at small radius and logarithmic at large radius; no bin is allowed to be smaller than the beam FWHM at 150 GHz. The increase with radius of the area per bin yields approximate constant $S/N \approx 5$ at large radius.

In addition to full mapping projects, we will also undertake two tSZ "radial profile" key projects using azimuthal averaging for large catalogs of sources. The per-beam sensitivity needed to obtain these radial profiles is a factor of 10 less demanding than what is needed for full mapping, enabling the study of 100 times as many clusters. Expected profiles with uncertainties are shown in Figure 4.18. The choice of sensitivities for these projects was made to achieve $S/N \approx 5$ in each radial bin at large radius. To illustrate the use of such profiles, we have overlaid three different β gas profiles with exponents β = 0.6, 0.67, and 0.75; we can easily distinguish them.

Quantitative evaluation of the scientific merit of these projects awaits detailed simulation work during the ongoing CCAT study. But one can reach some basic conclusions:

- The most worthwhile programs are pure tSZ mapping and radial profile studies because the number of objects obtained is large and confusion is negligible.
- Blind tSZ surveying down to $M = 10^{14}\ M_\odot$ ($S/N = 5$) over many square degrees is feasible and not limited by confusion noise.
- tSZ spectroscopy is fast enough that we can observe a reasonable sample of objects. Because it requires a special-purpose low-R spectrometer, we view spectroscopy as a follow-on project to tSZ profiles.
- The kSZ studies are stymied by confusion noise. The raw sensitivity is more than sufficient, but confusion will be limiting at 220 GHz and 275 GHz, even with shallow surveys (S/N = 1 per 150 GHz beam) and higher-frequency bands to remove confusing sources. Even using ALMA for subtraction, kSZ detection seems very difficult.[3,4]
- For similar reasons, attempts to confirm tSZ signals using 220 GHz and 275 GHz are difficult except for the most massive clusters.

---

3 Observing down to 10 μJy at 275 GHz over 10 arcmin^2 — the size of the core of a cluster out to θ_g — would require about 1 Msec. The 100 arcmin^2 needed to observe kSZ anisotropy would take 10 Msec. Even covering 1 arcmin^2 would require 100 ksec.

4 For an explanation of why CCAT seems to suffer worse confusion limitations than APEX, ACT, or SPT, see the companion technical note[1].

One should not take the last two conclusions as the final word because: 1) They depend critically on the infrared galaxy number counts, which are not yet precisely constrained — part of the reason to build CCAT!; 2) More detailed and accurate predictions of tSZ and kSZ signal levels may result in larger values; we have expressly been conservative; 3) Multi-frequency simulations may indicate that confusion is more removable than we have estimated here; and 4) Gravitational lensing by the clusters will mitigate confusion, but has not been taken into account. But, given the large uncertainty in the ability to do SZ work at 220 GHz and 275 GHz, it seems safe to conclude that the initial focus should be on 150 GHz tSZ observations.

4.4.4 CCAT Requirements

The telescope requirements for SZ observations are summarized in Table 4.10.

Table 4.10: Telescope requirements arising from science goals.

Item	Req'ment	Goal	Notes
Aperture	≥ 20 m	—	Uniqueness
Surface roughness	< 30 μm	—	λ/20 at 620 μm
Blockage/loading	< 10%	< 5%	goal: telescope loading no worse than atmosph. and dewar loading
Wavelength range	2 mm 620, 850 μm	1 – 2 mm same	SZ obs IR pt src removal
FoV (diameter)	10 arcmin	20 arcmin	contain entire cluster
Pointing			
on-the-fly	25 arcsec	12 arcsec	1 beam @ 1–2 mm
reconstructed	1.25 arcsec	0.6 arcsec	beam/20 @ 1–2 mm
on-the-fly	6 arcsec	same	1 beam @ 620 μm
reconstructed	0.3 arcsec	same	beam/20 @ 620 μm
Tracking			
one hour	1.5 arcsec	same	do 1 hour obs w/o added pointing jitter
20 min	same	same	
10 sec	same	same	
Elevation limits	>30	—	Planck sources
Scan speed	10 arcmin/sec	30 arcmin/sec	sky noise, on FoV-sized fields (Lissajous)
acceleration	10 arcmin/sec^2	30 arcmin/sec^2	
Spectroscopy	—	Δν = 3 GHz, 120 – 325 GHz	2 bands, 120 – 180 GHz and 200 – 325 GHz
Pol. capability	—	—	

4.4.5 CCAT Uniqueness and Synergies

SZ observations with CCAT will probe a unique combination of angular scales and frequencies and would complement other SZ projects:

- For a significant subsample of clusters detected in wide-area surveys, CCAT will provide spatially resolved SZ profiles to aid in the characterization of the tSZ-mass relationship and consequently in cosmological interpretation. SZ data may be critical for such work, as the Chandra and XMM-Newton missions will end ~2010 and Constellation-X will launch no earlier than 2016.
- A CCAT blind tSZ survey would have a lower mass limit, 10^{14} $M_{\odot}$, than the wide-area surveys, enabling a check of these surveys' detection efficiencies.
- The Sunyaev-Zeldovich Array (SZA) is an interferometer designed for blind tSZ surveying at 30 GHz and for high-resolution studies at 90 GHz. It is sited at CARMA and is currently taking survey data. The SZA, being an interferometer, will have better control of instrumental and observing systematics than CCAT but likely will have poorer instantaneous sensitivity. Together, SZA and CCAT will provide SZ spectral coverage at high angular resolution from 30 GHz to 150 GHz (and possibly 275 GHz).
- The Penn Array will be a 64-pixel 90 GHz bolometric array to make use of the Green Bank Telescope (GBT) with angular resolution 0.13 arcmin FWHM and 0.5 arcmin FoV. It will complement CCAT by investigating SZ substructure on 0.1 to 0.5 arcmin scales (larger scales will be lost to sky noise).
- The Large Millimeter Telescope (LMT) will provide information on scales comparable to GBT or midway between CCAT and GBT. The LMT design provides a 4-arcmin field-of-view, and currently planned instrumentation (AzTEC) will cover a 1.5-arcmin field-of-view. The angular resolutions of the LMT at 150 GHz and the GBT at 90 GHz are comparable. Atmospheric conditions may favor 90 GHz operation instead, in which case LMT provides angular resolution midway between that of CCAT and GBT. The better angular resolution of the LMT in the 150 − 300 GHz range as compared to CCAT is cancelled by CCAT's ability to remove confusion using the 350 GHz and 490 GHz bands, which are inaccessible to LMT.
- Interferometers like CARMA and ALMA will have exquisite point-source sensitivity over a field-of-view of a fraction of an arcmin^2 at the frequencies of interest for SZ. They will provide high angular resolution probes of substructure in the SZ, but will have poor fidelity on scales much larger than 1 arcmin, as well as being too slow to map fields appreciably larger than 10 arcmin^2.

Lastly, we note that SZ observations make the least stringent demands on telescope performance and weather, except on telescope optical loading, and so may be most effective in delivering cutting edge science from the earliest commissioning phase and during the poorest weather periods.