Spectral Measurements of the S-Z Effect in Clusters of Galaxies with SuZIE,

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Introduction

The Cosmic Microwave Background (CMB) acts as a uniform backlight to the rest of the observable universe. Inverse Compton scattering of CMB photons by hot Intra-Cluster (IC) gas residing in the gravitational potential wells of clusters of galaxies is known as the Sunyaev-Zel'dovich (S-Z) effect. The S-Z effect has two components, the thermal effect, due to the random thermal motions of the scattering electrons, and the kinematic effect, due to the bulk motion of the IC gas relative to the Hubble flow. For typical clusters the kinematic effect is expected to be much smaller than the thermal effect (see Figure 1). In practice, separation of the two is most easily achieved with measurements at millimeter wavelengths because of the distinct spectral shape of the thermal effect.

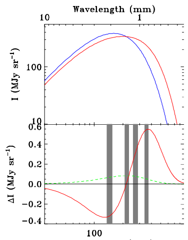

Fig. 1. (*Top*) The CMB spectrum before (*blue*) and after (*red*) passage through a cluster with y_0=600x10^{-4}. (*Bottom*) The difference spectrum of the S-Z effect for a cluster with more typical cluster parameters of y_0=3x10^{-4} and v_{pec}=–1000 km s^{-1}. The red curve is the spectrum of the thermal effect and the green curve is the spectrum of the kinematic effect. SuZIE II can be configured to observe in any three of the four bands shown (indicated by the shaded regions).

What is SuZIE?

The Sunyaev-Zel'dovich Infrared Experiment (SuZIE) is an experiment at the Caltech Sub-millimeter Observatory (CSO) (see Figure 2) designed to measure the S-Z spectrum near the zero-point of the thermal effect in intermediate redshift (0.15 < z < 0.8) clusters of galaxies. The current receiver (SuZIE II, see Figure 3) is a 2 by 2 array of 3 color photometers that observe the sky simultaneously in each frequency band, with band centers of 145, 221, and 355 (or 273) GHz. Each frequency is detected with a 300 mK spider web bolometer, consisting of a NTD germanium thermistor attached to an absorbing silicon nitride substrate. Each photometer defines a 1.5' FWHM beam, with each row separated by 2.3' and each column by 5' on the sky (see Figure 4). Bolometers in the same row that are sensitive to the same frequency are differenced electronically to give an effective chop throw on the sky of 5'. This reduces the level of common-mode atmospheric emission as well as common-mode bolometer temperature, and amplifier gain fluctuations.

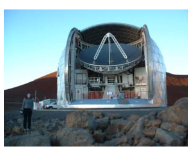

Fig. 2. *Left:* The Caltech Sub-millimeter Observatory located on Mauna Kea in Hawaii.

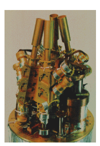

Fig. 3. The SuZIE II focal plane.

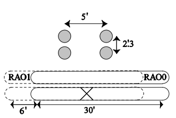

Fig. 4. *Left Top:* Layout of pixels in the SuZIE II focal plane. *Left Bottom*: Pattern traced out on the sky by a single column of the array. The cross indicates the nominal pointing center

Atmospheric Subtraction

There are two sources of residual atmospheric noise in SuZIE data,with different temporal spectra. The first is incomplete subtraction of the signal that is common to each beam because of the finite common mode rejection ratio (CMRR) of the electronic differencing. The second is a fundamental limitation introduced by the fact that the two beams being differenced pass through slightly different columns of atmosphere; consequently there is a percentage of atmospheric emission that cannot be removed by differencing. By forming a linear combination of our frequency channels which contains no S-Z signal we are able to achieve a significant improvement in the performance at each frequency (see Figure 5).

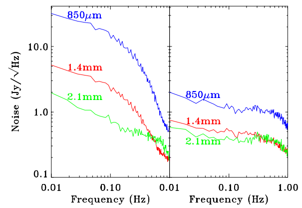

Fig. 5. (*Left*) The Power Spectral Density (PSD) vs. temporal frequency for each frequency channel before any atmospheric subtraction from observations taken at the CSO in τ(225GHz)= 0.13 weather. The blue curve is our 355 GHz differential channel, the red our 221 GHz differential channel, and the green our 145 GHz differential channel. (*Right*) The same three channels after atmospheric subtraction.

Results

An overview of our entire analysis routine can be found in Benson *et al.* 2003. In Figure 6 we show the S-Z spectra of the 11 clusters detected with SuZIE II with the best-fit thermal and kinematic spectra overlaid. An S-Z like spectrum appears to be present in all clusters.

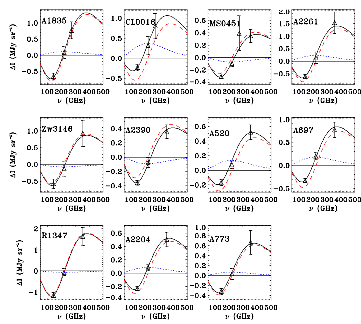

Fig. 6. The S-Z spectra measured with the 2nd generation of SuZIE. For each cluster, the solid black line is the best-fit S-Z spectrum, the dashed red line is the best-fit thermal spectrum, and the dotted blue line is the best-fit kinematic spectrum.

In Figure 7 we show the precision to the radial component of each cluster's peculiar velocity, plotted against the redshift of the cluster. We include previous peculiar velocity measurements of the clusters A1689 and A2163 observed with the SuZIE I receiver by Holzapfel *et al.* 1997. The cross-hatched region shows the region of redshift space that has been probed by existing optical surveys.

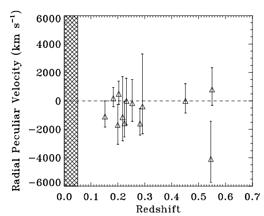

Fig. 7. Measurements of each cluster's peculiar velocity plotted against redshift. The cross-hatched region shows the range that has been probed using optical measurements of peculiar velocities.

Sub-millimeter Point Source Confusion

It is significant to note that if we calculate the average peculiar velocity of the entire set of SuZIE clusters, taking into account the likelihood function of each measurement based on statistical uncertainties only, we find an average of –300 (+280, –260) km s^{-1}. There are also several clusters (A520, A697, A2204, A2261, Cl0016) with 1-sigma *negative* (approaching) peculiar velocity detections with velocities around –1100 to –1700 km s^{-1}. Conversely there are *no* clusters with 1-sigma positive peculiar velocity detections. This may indicate an unknown systematic error in our measurements. The simplest explanation for this would be a population of sub-millimeter point sources confusing our measurements. Benson *et al* 2003 showed that sub-millimeter confusion consistent with measured 850 um fluxes from SCUBA would bias SuZIE measurements towards negative peculiar velocities by several hundred km s^{-1}.

Comparing the Comptonization Results from SuZIE to OVRO/BIMA

Reese *et al.* 2002 have an impressive catalog of S-Z observations taken with the OVRO and BIMA interferometers at 30 GHz. A total of 10 clusters have been measured by both SuZIE and OVRO/BIMA. A comparison of the central Comptonization, y_0, derived from OVRO/BIMA data to that from SuZIE reveal an interesting trend (see Figure 8). The sample of non-cooling flow clusters show good agreement, however SuZIE measures a significantly higher central Comptonization for each cooling flow cluster. We note that the Comptonization plotted in Figure 8 is calculated from the SuZIE II 150 GHz channel only, (with an assumed peculiar velocity of zero for comparison with the OVRO results), to reduce biases from possible sub-mm point source contamination that are present when the high-frequency data are included. In Figure 9 we plot 2-d likelihood contours of two representative clusters (one cooling flow and one non-cooling flow) to show that even when peculiar velocities are included in the fit discrepancies still exist in derived optical depths for cooling flow clusters.

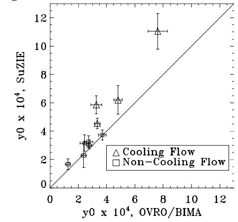

Fig. 8. The central Comptonization measured by SuZIE vs. OVRO/BIMA for the 10 clusters measured by both experiments. Cooling (Non-cooling) flow clusters are plotted as triangles (squares).

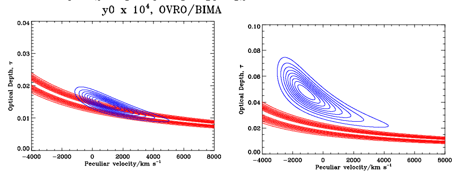

Fig. 9. Two dimensional likelihood contours over optical depth and and peculiar velocity for MS0451 (*left*) and A2261 (*right*). A2261 is a cooling flow cluster. The contours are spaced in 10% intervals ranging from 10% to 90% confidence. The blue curves are derived from SuZIE data, and the red curves from OVRO/BIMA.

The discrepant central Comptonizations could be the result of an inadequate IC gas model for the cooling flow clusters. Recent high spatial resolution X-ray measurements with XMM have suggested that a double Beta model, one Beta model for the core and the other for the outer region, better fits the IC gas distribution in cooling flow clusters (Majerowicz *et al.* 2002). Because of SuZIE's relatively large beams (1.5') and chop throw (5') one would expect it to be sensitive to both distributions. In Table 1 we show the calculated central Comptonization from SuZIE observations of each of our cooling flow clusters for a range of Beta models derived from different X-ray observations. We note that the PSPC and HRI instruments on ROSAT have spatial resolutions of 25" and 2" respectively, while Chandra and XMM have approximately 1" and 5" resolution.

Table 1. SuZIE vs OVRO: The Central Comptonizations of Cooling Flow Clusters for Different β Models

Cluster	$y_0(\times 10^4)$ OVRO	$y_0(\times 10^4)$ SuZIE	β	θ_c (arcsec)	X-Ray Data Ref.
A1689	$3.34^{+0.20}_{-0.23}$	$4.54^{+0.37}_{-0.37}$	$0.609^{+0.005}_{-0.005}$	$26.6^{+0.7}_{-0.7}$	HRI&PSPC (1)
	···	$3.55^{+0.29}_{-0.29}$	$0.78^{+0.03}_{-0.03}$	$67.8^{+7.2}_{-7.2}$	PSPC (2)
A1835	$4.81^{+0.29}_{-0.34}$	$6.21^{+1.01}_{-1.01}$	$0.595^{+0.007}_{-0.005}$	$12.2^{+0.6}_{-0.5}$	HRI&PSPC (1)
	···	$3.55^{+0.57}_{-0.57}$	0.704^{b}	41.0^{b}	XMM (3)[a]
	···	$5.78^{+0.95}_{-0.95}$	0.72^{b}	18.3^{b}	PSPC (4)
	···	$7.09^{+1.13}_{-1.13}$	$0.53^{+0.01}_{-0.01}$	$7.9^{+0.6}_{-0.6}$	Chandra (5)
A2261	$3.27^{+0.39}_{-0.39}$	$5.86^{+0.63}_{-0.63}$	$0.519^{+0.014}_{-0.013}$	$15.7^{+1.2}_{-1.1}$	HRI&PSPC (1)
	···	$6.37^{+0.69}_{-0.69}$	$0.553^{+0.016}_{-0.016}$	$18.5^{+1.5}_{-1.5}$	Chandra (6)
RXJ1347	$7.62^{+0.68}_{-0.68}$	$11.05^{+1.26}_{-1.26}$	$0.604^{+0.011}_{-0.012}$	$9.0^{+0.5}_{-0.5}$	HRI&PSPC (1)
	···	$13.85^{+1.57}_{-1.57}$	$0.535^{+0.003}_{-0.003}$	$4.29^{+0.10}_{-0.10}$	Chandra (7)

[a] In Beta model fit the authors exclude central 42" in X-ray surface brightness.

[b] No confidence intervals were given for these parameters.

References. — (1) Reese, E.D., *et al.*, 2002, ApJ, 581, 53, (2) Daines, S., *et al.*, 1996, preprint, (3) Majerowicz, S., *et al.*, 2002, A&A, 394, 77, (4) Ettori, S., *et al.*, 1999, MNRAS, 305, 834, (5) Schmidt *et al.*, 2001, MNRAS, 327, 1057, (6) Fabian, A.C., 2002, private comm., (7) Allen *et al.*, 2002, MNRAS, 335, 256.

The Temperature of the CMB vs. Redshift

The spectrum of the S-Z effect can also be used to measure the temperature of the CMB as a function of redshift. Taking ratios of the difference intensity at multiple frequencies to measure the temperature of the CMB was suggested by Rephaeli (1980). This method has the desirable property that it would be independent of cluster Comptonization. The first realization of this was achieved by Battistelli *et al.* (2002) using a combination of SuZIE, OVRO, BIMA, and MITO observations of the Coma cluster and A2163. We apply this same method to our data set, to calculate $T_{cmb}(z)$ (see Figure 10). The mean CMB temperature of our sample, at a redshift of zero is consistent with the results from the COBE FIRAS expt.

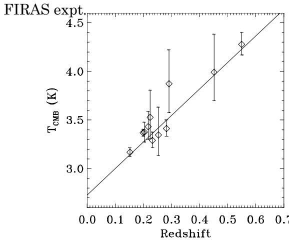

Fig. 10. The temperature of the CMB versus redshift derived from a set of 11 clusters measured with SuZIE.

In calculating Figure 10 we have ignored several important systematic effects, the most important of which are peculiar velocity and sub-mm point source confusion. The derived temperature is highly degenerate with cluster peculiar velocities over the SuZIE frequency range (see Figure 11). In addition, sub-mm point sources can cause significant confusion in measurements of the CMB temperature. In Figure 11 we plot the effect of sub-mm point source confusion in measuring the CMB temperature for A520. We note that SCUBA measurements at 850 microns in one quadrant of the field of view of A520 detected two sub-mm point sources totaling 49.2 mJy.

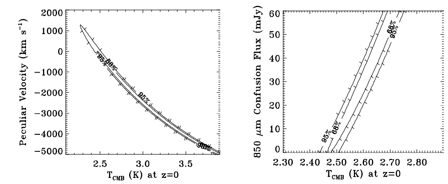

Fig. 11. The effect of systematic errors in measuring the temperature of the CMB from S-Z measurements of A520. (*Left*) The 2-d likelihood of peculiar velocity versus CMB temperature at zero redshift assuming no sub-mm point source confusion. (*Right*) The 2-d likelihood of 850 um point source confusion versus CMB temperature at zero redshift assuming a zero peculiar velocity. The 68.3% and 95.4 % confidence regions are shown in each plot.

Conclusions

Spectral measurements of the S-Z effect with SuZIE have been made in 13 clusters of galaxies. These results have been used to calculate the peculiar velocity and central Comptonization in each cluster. An overall average negative peculiar velocity may be indicative of sub-mm point source contamination in our observations. A comparison of the derived central Comptonization to that from the OVRO/BIMA interferometers indicates a systematic discrepancy in cooling flow clusters, which may be evidence for an inadequate model of the IC gas. The S-Z measurements have also been used to measure the temperature of the CMB as a function of redshift. Preliminary analysis indicates that peculiar velocity uncertainty and sub-mm source confusion will need to be accounted for in future measurements.

Literature cited

Battistelli, *et al.*, 2002, *ApJ*, 580, L101.
Benson, B.A., *et al.*, 2003, *Astrophysics Journal*, accepted.
Holzapfel, W.L., *et al.*, 1997, *ApJ*, 480, 449.
Majerowicz, S., *et al.*, 2002, *A&A*, 394, 77.
Rephaeli, Y., 1980, *ApJ*, 445, 33.
Reese, E.D., *et al.*, 2002, *ApJ*, 2002, 581, 53.

Acknowledgments

The SuZIE program is supported by the NSF and NASA. The CSO is operated by Caltech under contract from the NSF.