A MEASUREMENT OF ARCMINUTE ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND WITH THE SUNYAEV-ZEL’DOVICH ARRAY

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ABSTRACT

We present 30 GHz measurements of the angular power spectrum of the cosmic microwave background (CMB) obtained with the Sunyaev-Zel’dovich Array (SZA). The measurements are sensitive to arcminute angular scales, where secondary anisotropy from the Sunyaev-Zel’dovich effect (SZE) is expected to dominate. For a broad bin centered at multipole 4066 we find \(60^{+65}_{-55} \mu K^2\), of which \(26 \pm 5 \mu K^2\) is the expected contribution from primary CMB anisotropy and \(20 \pm 28 \mu K^2\) is the expected contribution from undetected radio sources. These results imply an upper limit of \(149 \mu K^2\) (95% C.L.) on the secondary contribution to the anisotropy, lower than that reported previously by other 30 GHz instruments. The SZA interferometric observations employed a hybrid configuration of antennas including short and long antenna separations to provide high sensitivity to arcminute anisotropy while simultaneously detecting 30 GHz radio sources at much higher resolution. The hybrid configuration was also used to check whether SZE anisotropy power was suppressed by projecting out SZE power from clusters of galaxies correlated with radio sources. No significant effect was found. The level of SZE anisotropy power is consistent with expectations based on recent determinations of the normalization of the matter power spectrum, i.e., \(\sigma_8 \sim 0.8\).

Subject headings: cosmic microwave background – cosmology: observations – cosmological parameters – large-scale structure of universe – techniques: interferometric

1. INTRODUCTION

Density perturbations at the epoch of recombination are imprinted onto the Cosmic Microwave Background (CMB), leaving temperature anisotropy that has now been well-studied on a wide range of angular scales. On scales of several arcminutes and smaller, corresponding to multipole moments of \(\ell \geq 3000\), the level of CMB anisotropy power from primordial fluctuations is strongly suppressed by photon diffusion, and secondary sources of power, including the Sunyaev-Zel’dovich effect (SZE), are expected to play a significant role (e.g., Hu & Dodelson 2002). The SZE results from the inverse Compton scattering of CMB photons by the hot electron gas within clusters of galaxies (Sunyaev & Zeldovich 1972). This interaction leaves a small spectral distortion in the CMB which produces anisotropy power on scales of \(\ell \sim 2000 – 10000\), detectable as a decrement in the CMB intensity at 30 GHz. The amplitude of this power is extremely sensitive to the history of structure formation and, specifically, to the value of \(\sigma_8\), the normalization of the matter power spectrum (e.g., Komatsu & Seljak 2002). Evidence for anisotropy above that expected from the primary CMB on these small angular scales has been detected at 30 GHz by the Cosmic Background Imager (CBI) and Berkeley Illinois Maryland Association (BIMA) experiments (Readhead et al. 2004; Dawson et al. 2006). Recent constraints on excess power at these scales from the Arcminute Cosmology Bolometric Array Receiver (ACBAR) at 150 GHz indicate that the spectrum of the reported excess is inconsistent with thermal CMB fluctuations, but could be consistent with SZE fluctuations (Reichardt et al. 2008). Taken together, these measurements indicate a level of SZE anisotropy power consistent with a value of \(\sigma_8\) somewhat greater than those preferred by other contemporary measurements of the parameter (Voevodkin & Vikhlinin 2004; Komatsu et al. 2008).

In this paper, we describe a new, high-sensitivity measurement of power in the CMB on scales ranging from \(\ell \sim 3000 – 6000\) made at 30 GHz with the Sunyaev-Zel’dovich Array (SZA).

2. OBSERVATIONS

2.1. SZA Data

The CMB anisotropy data presented here were obtained with the Sunyaev-Zel’dovich Array (SZA), an eight-element interferometer located at Caltech’s Owens Valley Radio Observatory near Bishop, Cali-
The SZA antennas are equipped with sensitive, wide-bandwidth receivers operating at 30 GHz and 90 GHz. For these observations we used the 30 GHz receivers, tuned to detect sky frequencies of 27–35 GHz. The receivers are based on low-noise, cryogenic high electron mobility transistor (HEMT) amplifiers (Pospieszalski et al. 1995), with characteristic receiver temperatures $T_{\text{rx}} \sim 11 - 20$ K. Including atmospheric and other noise contributions, the typical system temperatures were 35–45 K. The 3.5-m SZA antennas have a primary beam that is well-described by a Gaussian with a FWHM of 12° at the center of the 30 GHz band. Cross-correlations of the signals from pairs of the eight antennas (visibilities) are formed in a digital correlator, which processes the 8 GHz IF bandwidth in 16 bands of 500 MHz, each of which is further subdivided into 17 channels of 31 MHz, allowing rejection of narrow-band interference.

For the anisotropy measurements reported here, the SZA antennas were arranged in a hybrid configuration to provide simultaneous sensitivity to the arcminute-scale structure of the SZE signal from galaxy clusters and the finer-scale contamination from radio sources (details of the configuration can be found in Muchovic et al. 2007). Six of the eight antennas were packed closely together (spacings of 4.5–11.5 m), yielding 15 baselines with typical projected lengths of 400–1400 $\lambda$, corresponding to arcminute angular scales; the window function for our anisotropy measurement is determined by the baselines formed from combinations of these six antennas. By convolving the distribution of projected baseline lengths in the unflagged data with the autocorrelation of the antenna illumination pattern, we obtain the $\ell$-space window function shown in Figure 1. This is the filter through which we observe the power spectrum; multiplying this function by $\ell(\ell + 1)C_\ell/2\pi$ and integrating over $\ell$ yields our measurement, where $C_\ell$ is the CMB angular power spectrum. The mean value of the window is $\ell = 4066$, with 68% of the area encompassed by the interval $\ell = 2929 - 5883$. In addition to the central six antennas, two antennas were positioned ~50 m from the array center. The 13 baselines involving these antennas are sensitive to ~20° scales, corresponding to multipoles of $\ell \sim 30000$, and can be used to identify radio sources that contaminate the short-baseline data.

Between November 2005 and June 2007, we devoted 1340 hours of observations to 44 SZA deep fields, comprising 2 square degrees. These fields were selected to pass nearly overhead at the $\sim 37°$ latitude of the telescopes, and arranged in right ascension to accommodate other large SZA observing programs. Within these constraints, the fields were placed at locations with low Galactic emission in the IRAS 100 $\mu$m survey. No consideration was given to the presence of radio sources to avoid any bias that might be introduced by the correlation between radio sources and galaxy clusters. One of the 44 fields was found to contain a 700 mJy radio source ($> 4000\sigma$); unable to exclude this source from our data with sufficient precision, we are forced to omit this field from our analysis. Using simulated SZE sky maps we have verified that even in the pessimistic case in which this single field contains the most power of any of our fields, the bias introduced by excluding it is 10%.

Observations were designed to allow subtraction of ground contamination. Fields were observed at constant declination in groups of four, spaced by four minutes of right ascension. We observed the fields in 16-minute blocks between observations of a nearby phase calibrator. Each field, starting with the westernmost field of the group, was observed for just under four minutes at a time, so that after including time lost to slews and calibration we tracked all four fields through precisely the same azimuth/elevation path. This ensures that each sees the same contribution from the ground, which can be removed by subtracting the mean of the four fields (in practice we implement this subtraction by means of a constraint matrix, described in § 3). At an integration time of 20 seconds, we obtain 10 integrations per field in each cycle. The total integration time per field was ~25 hours. Of this, approximately 20% of the data were discarded due to hardware problems, antenna shadowing, excessive noise, or jumps in calibrator phase or system temperature which occurred on a time-scale faster than our calibrations. An additional ~5% of the data were flagged for showing unexpected correlations among baselines and bands or statistically unlikely noise behavior on a single antenna. These cuts significantly improved the results of the jackknife tests discussed in § 3; the data quality cuts were refined using only the jackknifed datasets to avoid biasing ourselves against signal. The first member of each group of four SZA fields is listed in Table 1 along with its position, the total, unflagged, on-source integration time, and the achieved RMS noise level for the field, both with and without data from the long baselines.

The absolute calibration of the flux density scale is derived from bimonthly observations of Mars. We use the Rudie (1987) model to predict the brightness temperature of Mars as a function of frequency and time. Since the planet is partially resolved by our longest baselines, a strong, unresolved source is used to transfer the cali-
The map sensitivity of the achieved sensitivity in the 8 GHz maps has a profile in our SZA data. The integration time is tapered of this mosaic pattern, less than 1/6 of the noise level. Their contribution to the covariance matrix from the CMB signal, \( \kappa_{\text{CMB}} \), would be the identity matrix times the level of CMB power, \( \kappa \). We assume a flat band power, i.e., constant \( \ell(\ell + 1)C_\ell/2\pi \). However, in practice, visibilities can be correlated, depending on the separation of the Fourier-space \((u,v)\) coordinates they sample. A visibility \( \Delta \) of visibilities and a likelihood estimator that is a function of \( \Delta \) and the CMB power \( \kappa \), assumed to be constant across the range of angular scales probed by the SZA. We expect our data, and thus the likelihood function, to be Gaussian, so that the likelihood is given by:

\[
\mathcal{L}(C) = \frac{1}{(2\pi)^{N/2}|C|^{1/2}} \exp \left( -\frac{1}{2} \Delta^T C^{-1} \Delta \right)
\]

where \( N \) is the length of the data vector \( \Delta \), and the covariance \( C \) of the data is written as the sum of a contribution from the CMB, the diagonal instrument noise, and a set of constraints (see below):

\[
C = \kappa C_{\text{CMB}} + C_{\text{noise}} + C_{\text{constraints}}.
\]

If our visibilities were independent of one another, the contribution to the covariance matrix from the CMB signal, \( \kappa C_{\text{CMB}} \), would be the identity matrix times the level of CMB power, \( \kappa \). We assume a flat band power, i.e., constant \( \ell(\ell + 1)C_\ell/2\pi \). However, in practice, visibilities can be correlated, depending on the separation of the Fourier-space \((u,v)\) coordinates they sample. A visibility corresponding to a given \((u,v)\) coordinate is in fact an integral over a small patch of the Fourier plane, weighted by the antenna’s aperture autocorrelation function; the overlap integral of this function centered on two neighboring \((u,v)\) coordinates yields the correlation between adjacent measurements. We calculate these overlap integrals for each of our visibilities, and insert the resulting

### Table 1: SZA Anisotropy Fields

| Group of 4 Fields | 1st Field RA | Declination | Integration time | RMS noise (short baselines) | RMS noise (all baselines) |
|-------------------|--------------|-------------|------------------|------------------------------|----------------------------|
| cmb07             | 02:07:37.00  | +34:00:00.0 | 22.9             | 0.18                         | 0.12                       |
| cmbA1             | 02:12:00.00  | +33:00:00.0 | 19.7             | 0.21                         | 0.14                       |
| cmbB1             | 02:12:00.00  | +32:37:08.2 | 22.8             | 0.21                         | 0.14                       |
| cmbB2             | 02:12:15.60  | +32:11:24.8 | 32.3             | 0.18                         | 0.12                       |
| cmbB3             | 02:12:00.00  | +31:51:24.4 | 23.0             | 0.18                         | 0.12                       |
| cmbEE1            | 14:18:39.24  | +35:31:52.3 | 20.9             | 0.19                         | 0.14                       |
| cmbXXb            | 21:28:50.60  | +24:59:35.0 | 18.2             | 0.21                         | 0.15                       |
| cmbDD1            | 14:18:40.10  | +35:01:42.0 | 18.0             | 0.26                         | 0.17                       |
| cmbAA1            | 21:24:38.70  | +25:29:37.0 | 19.6             | 0.22                         | 0.16                       |
| cmbCC1            | 02:11:31.30  | +33:27:43.0 | 21.9             | 0.19                         | 0.14                       |
| cmbBB1            | 21:24:38.10  | +25:59:24.0 | 18.8             | 0.21                         | 0.15                       |

Away from the Galactic plane, the most significant contributor of non-CMB power on arcminute angular scales at 30 GHz is compact radio sources. Since the power from these sources is constant as a function of \( \ell \), their contribution to \( \ell(\ell + 1)C_\ell/2\pi \) can be quite large at small angular scales. While the brightest sources at 30 GHz can be detected by the long baselines of the SZA, sources near our noise level (and hence undetectable in our data) can still contribute substantial power to the measurement. We therefore supplement our data with a higher-sensitivity search for radio sources in our fields using the NRAO’s Very Large Array (VLA).

The large disparity between the VLA (25 m) and SZA (3.5 m) antenna sizes makes it impractical to survey the SZA fields at 8 GHz. We reached a noise level of \( \sim 30 \mu \text{Jy} \) at the center of this mosaic pattern, less than 1/6 of the noise level in our SZA data. The integration time is tapered at pointings away from the center of the mosaic, such that the achieved sensitivity in the 8 GHz maps has a profile that matches that of the SZA at 30 GHz, determined by our primary beam pattern.

The VLA data were calibrated and mosaicked in AIPS. The map sensitivity \( \sigma \) was determined from the mosaic of Jupiter to those of WMAP and CBI [Page et al. 2003; Readhead et al. 2004]. Based on these measurements, we conservatively estimate that our absolute flux scale is accurate to better than 10% (20% in power).

### 2.2. VLA Data

The VLA data were calibrated and mosaicked in AIPS. The absolute calibration was cross-checked by comparing SZA observations of Jupiter to those of WMAP and CBI [Page et al. 2003; Readhead et al. 2004]. Based on these measurements, we conservatively estimate that our absolute flux scale is accurate to better than 10% (20% in power).

### 3. Analysis

#### 3.1. Likelihood Analysis

As an interferometer, the SZA directly measures the Fourier components of the sky brightness. Since it is precisely the variance of these components that the power spectrum describes, interferometers are ideally suited for measuring the power spectrum, without the intervening stage of map-making (e.g., White et al. 1999).

We have used a maximum likelihood method in order to extract measurements of the power spectrum from our data. Following Bond et al. (1998), we construct a vector \( \Delta \) of visibilities and a likelihood estimator that is a function of \( \Delta \) and the CMB power \( \kappa \), assumed to be constant across the range of angular scales probed by the SZA. We expect our data, and thus the likelihood function, to be Gaussian, so that the likelihood is given by:

\[
\mathcal{L}(C) = \frac{1}{(2\pi)^{N/2}|C|^{1/2}} \exp \left( -\frac{1}{2} \Delta^T C^{-1} \Delta \right)
\]

where \( N \) is the length of the data vector \( \Delta \), and the covariance \( C \) of the data is written as the sum of a contribution from the CMB, the diagonal instrument noise, and a set of constraints (see below):

\[
C = \kappa C_{\text{CMB}} + C_{\text{noise}} + C_{\text{constraints}}.
\]
matrix into the total covariance matrix as indicated in equation (2). Visibilities that are more than 95% correlated are binned together.

The instrumental contribution to the noise, $C_{\text{noise}}$, dominates the weak signal from the CMB anisotropy and must therefore be accurately determined. We estimate the noise variance from the scatter of visibilities taken on 20 second timescales within a 4 minute scan. From the 10 visibilities within each scan, we subtract the mean of the real and imaginary parts from each sample and then compute a single sample variance from the 20 mean-subtracted numbers. All averages within the analysis are uniformly weighted, as weighting by variances derived from so few samples introduces substantial biases. The resulting noise estimates are independent of one another, so $C_{\text{noise}}$ in equation (2) is diagonal. We have verified through simulation that variances measured in this way produce an unbiased estimate of the noise, and, hence, of the CMB power level.

3.2. Constraining Radio Sources

We expect the sky signal to be dominated by radio sources that are pointlike at the SZA’s arcminute resolution, principally active galactic nuclei emitting synchrotron radiation at radio frequencies. Through the use of constraint matrices (Bond et al. 1998; Halverson et al. 2002), we can eliminate the modes of the data that are corrupted by these sources, provided that we know their positions. The constraint matrix is computed by writing a template vector of visibilities that describes the contribution of the contaminant in question to each $u$-$v$ component; in the case of a point source at position $(l, m)$ with respect to the interferometer’s phase center, the contribution $V^c_{pt}$ to the visibility measured with component $(u_j, v_j)$ is given by:

$$V^c_{pt} = Ae^{2\pi i (u_j l + v_j m)},$$

(3)

where $A$ is an unknown amplitude. By forming the outer product of this vector with itself, $C^{pt} = V^c_{pt} V^c_{pt}^*$, we find the covariance created among our $N$ visibilities by a source at this position; the amplitude of this covariance remains an unknown, but its shape is fixed by the (known) source location. Each constraint matrix is then multiplied by a large prefactor (as large as possible without causing the matrix to become poorly conditioned for inversion) and added to the total covariance matrix in our likelihood function, effectively setting to zero the weight of the mode corresponding to the source. The unknown amplitude is therefore unimportant; the operation is equivalent to marginalizing over the source’s unknown flux. We form such a matrix for each source that we wish to eliminate from our data; because each matrix is created from a single vector, each has rank one and eliminates one degree of freedom from the $N$ that we have measured. Radio sources in our data may have a wide range of spectral indices and cannot in general be excluded by a single constraint. Instead, we project three modes for each source: one flat spectrum and two of different spectral indices. We therefore lose three degrees of freedom for each source projected out. A linear combination of these components can approximate any spectral index, and the coefficients in this linear combination are irrelevant for our technique.

We remove a component common to the fields within a group of four (ground or antenna crosstalk) using a similar constraint. This constraint identifies each visibility among a group of four with its three matches in different fields, all of which are measured at the same antenna position. Projecting this constraint is equivalent to subtracting the mean of the four visibilities from each of them, and therefore reduces the sensitivity by 25%.

The radio source positions are derived from several data sets. The brightest sources at 30 GHz are identifiable directly in the SZA data. For purposes of source detection, we combine the long and short-baseline data (typical noise of $\sim 150 \mu$Jy), providing 30% better sensitivity to compact sources than would be obtained using only the short baselines from which our anisotropy measurement is determined. A total of 72 sources above 4$\sigma$ were detected at 30 GHz, of which $\sim 85\%$ have counterparts in the 8 GHz VLA data. Above a significance of 5$\sigma$ in the 30 GHz data, 45 of 47 detected sources have counterparts at 8 GHz; the remaining two sources were found to be extended even at the 20$''$ resolution of the long SZA baselines, and are likely heavily resolved by the VLA in its C array configuration (3$''$ resolution).

As sources below our 30 GHz detection threshold can still contribute significant anisotropy power, we also constrain sources detected in the 8 GHz survey. We examined several combinations of detection significance thresholds in the 8 GHz and 30 GHz catalogs, and conclude that neither catalog is adequate on its own. As can be seen in Table 2, the measured power continues to decrease as the detection threshold in either catalog is lowered, while projecting sources from both catalogs reduces the power below that which can be achieved with either catalog alone. Additionally, the 30 GHz catalog contains sources with no counterparts at 8 GHz, implying a population of sources at 30 GHz too inverted, or variable, to be detected in the 8 GHz survey. We find good agreement in the power resulting from the 5$\sigma$/6$\sigma$ and 4$\sigma$/5$\sigma$ (30/8 GHz) thresholds and we adopt the latter for our analysis. The two fields without 8 GHz coverage are excluded from the analysis shown in Table 2 but are included in our final result; for these we constrain all NVSS sources. We have verified that excluding these fields does not significantly change our result.

For each field, we assemble the noise and constraint components of the covariance matrix and vary the level of CMB power, evaluating the likelihood of the data according to equation (1) over a range of values for the power $\kappa$. Treating our fields as independent samples, we take the product of each of their likelihood curves to form a global likelihood for the experiment; we report the maximum of this curve as the most likely power, and the points which enclose 34% of the curve’s area on either side of the maximum define the 68% confidence interval. The likelihood is allowed to extend below zero power.

We tested this analysis pipeline extensively with simulated data, including tests in which the data generation and power spectrum analysis were performed by different parties, using independent software packages, and found consistent results in all cases.

3.3. Jackknife Tests

Processing the data as described above, we can compute the relative likelihood of different levels of CMB
power, given our data. We now subject the data to three jackknife tests to rule out contaminating power from non-astronomical sources or from inaccuracies in our noise variance estimation. In the jackknife tests, the data are split into halves, each of which measures very nearly the same set of spatial Fourier components. The data are taken in such a way that three of these splits are possible: i) a frequency jackknife, wherein we separate even and odd frequency bands, as neighboring bands sample very nearly the same \( u-v \) points, ii) a jackknife in which the data are separated into halves by time, and iii) a jackknife in which the data are separated into even and odd days. The latter two jackknife tests take advantage of the fact that the SZA observed the same fields in the same way for many days.

After dividing the data into halves, we difference the matching pairs of visibilities. Emission from astronomical sources, which is common to both halves, is removed, while any contamination that varies with time or frequency will remain in the differenced (jackknifed) data. Note that the requirement that there be matching, unflagged visibilities in both halves for each test results in some additional loss of data and degradation of the measurement sensitivity, particularly in the two time-jackknife tests. We compute variances from the differenced visibilities, and compute the power in each jackknifed dataset just as for our unjackknifed data, with the expectation that the measured power will be consistent with zero. The jackknife tests also verify our noise model; if the noise in our data has been mis-estimated, we expect to see a lower signal to noise of the data. We now subject the data to three jackknife tests all pass, as seen in Table 3, with probabilities to exceed the \( \chi^2 > 0.1 \). We therefore employ ground subtraction to determine anisotropy power in all the analyses presented in this paper. Our analysis procedure is blind to the final result, as we have refined our data cuts and analysis treatment based only on the jackknife tests.

### 3.4. Results

Repeating the analysis on the complete, ground-subtracted, unjackknifed data gives \( 60_{-55}^{+65} \mu K^2 \). In the next section we estimate the various contributions to this power.

### 4. Anisotropy Contributions

To set constraints on secondary CMB anisotropy, we must estimate the residual power contributions to the SZA measurement from other astronomical sources. In this section, we first consider contributions from primary CMB anisotropy, undetected radio sources, and diffuse Galactic emission, and we end with our constraint on the level of secondary anisotropy.

We note that contributions from undetected radio sources and diffuse Galactic emission are in principle distinguishable from the CMB by their spectral signature across the 25% fractional bandwidth of the SZA data. However, it is not possible to distinguish a preferred spectral index given the low signal to noise of the data.

#### 4.1. Primary CMB

At a multipole of \( \ell = 4000 \), the WMAP5 cosmology predicts no significant primary CMB anisotropy (Table 3). However, our window function has limited sensitivity to the larger scales at which the primary CMB signal is strong. We estimate this contribution and its variance with simulated observations. We generate CMB skies according to WMAP5 cosmological parameters using CMBFAST (Seljak & Zaldarriaga 1996). We use 35 sets of 43 fields with identical noise realizations but different CMB realizations and sample them according to the SZA \( u-v \) coverage and noise. From these simulations, we determine that the primary CMB contributes a mean power of \( 26 \pm 5 \mu K^2 \) to our measurement. Integrating the CMB primary power spectrum multiplied by our window function yields a very similar estimate.
To assess the level of residual fluctuations from sources that are undetected at 8 GHz and 30 GHz at our 5σ/4π thresholds (see § 2), we simulate 30 GHz source populations using two independent estimates of the source density as a function of flux. The first of these is derived from the SZA blind cluster survey (Muchovej et al. 2009, in prep.), which provides source counts down to 1 mJy; we extrapolate to lower flux levels according to a power law. This survey is the deepest available at this frequency. We also use the source density estimated by de Zotti et al. (2003) from analysis of lower-frequency surveys. To assign 8 GHz fluxes to our simulated population of sources we use the spectral index distribution of Muchovej et al. (2009, in prep.) measured for 200 sources between 5 and 30 GHz. We simulate SZA observations with these source populations, applying the source rejection procedure described above. We find that residual power from undetected sources is small, changing the power measured in simulated fields by 20 ± 28 μK².

### 4.2. Undetected Radio Sources

The emission from the Galaxy via synchrotron and free-free radiation contribute significantly to the sky brightness, as can be seen in the WMAP 22 GHz all-sky map (Gold et al. 2008). We lack sensitivity to the sky brightness, as can be seen in the WMAP chrotron and free-free radiation contribute significantly. In this frequency range we expect contributions from thermal dust emission at 30 GHz. Such emission is expected to peak at frequencies of tens of GHz and to be tightly correlated with Galactic dust (Draine & Lazarian 1998). Dust-correlated emission within this frequency range has been observed on various angular scales (Leitch et al. 1997; Kogut et al. 1996; de Oliveira-Costa et al. 2002; Finkbeiner et al. 2002; Finkbeiner 2004; Watson et al. 2005; Dickinson et al. 2007). During the SZA blind cluster survey, increased map noise was indeed observed in fields with more obvious IRAS structure.

To estimate the contribution of spinning dust to the SZA measurement, we take the power spectrum of the IRAS 100-μm maps of our fields, fit it to log_10 Power = Aℓ + B, and extrapolate it to the smaller angular scales that we are sensitive to, but to which IRAS is not. We then take the highest measured emissivities of dust-associated emission at 30 GHz, as tabulated by Dickinson et al. (2007), and scale this power spectrum to match the observations. Multiplying by the window function shown in Figure 1 and integrating over ℓ, we get a contribution for each of the observed emissivities lying in the range from < 1 μK² to 16 μK². Note that the highest emissivity (Leitch et al. 1997) is substantially higher than other measurements, and so the corresponding 16 μK² is likely a substantial overestimate of the contribution of this foreground to our measurement.

### 4.3. Galactic Synchrotron Radiation and Free-Free Emission

At lower frequencies, emission from the Galaxy via synchrotron and free-free radiation contribute significantly to the sky brightness, as can be seen in the WMAP 22 GHz all-sky map (Gold et al. 2008). We lack sensitivity, high-resolution measurements of these components and are forced to estimate their contribution from lower-resolution maps and forecasts derived from them. Tegmark et al. (2000) used degree-resolution templates to predict that this emission should contribute less than 1 μK² at ℓ ∼ 4000. Renormalizing their model using an analysis of foregrounds measured with WMAP (Tegmark et al. 2004), we estimate a contribution of 2 μK² at 30 GHz from synchrotron and free-free emission combined.

### 4.4. Galactic Spinning Dust

A final source of potential foreground contamination in our power spectrum measurement comes from Galactic dust. While the predictions of Finkbeiner et al. (1999) for thermal dust emission at 30 GHz imply < 1 μK² contribution, there has been evidence that dipole radiation from small, spinning dust grains may dominate the emission at 30 GHz. Such emission is expected to peak at frequencies of tens of GHz and to be tightly correlated with Galactic dust (Draine & Lazarian 1998).

### Table 4 Anisotropy Contributions

| Source                  | Power Contribution [μK²] |
|-------------------------|--------------------------|
| Primary CMB             | 26 ± 5                   |
| Undetected Radio Sources| 20 ± 28                  |
| Galactic Synchrotron and Free-Free | 2          |
| Galactic Spinning Dust  | < 16                     |
| Secondary CMB (SZE)     | 14 ± 10                  |
| and upper limit at 95% C.L. | 149         |

## 5. DISCUSSION

### 5.1. Constraints on σₘ from cluster simulations

To understand the implications of our measurement for the value of σₘ, we compare to simulated SZE maps. Several groups have carried out large-scale cosmological structure simulations and converted three-dimensional, simulated universes into two-dimensional projections of the Compton y parameter, the frequency-independent measure of the magnitude of the SZE. We take these maps as inputs to mock SZA observations, and attempt to estimate the mean level of power that would be measured by the SZA, as well as the scatter in these measurements.

We use 60 maps, each 0.5° × 0.5°, from the hydrodynamical simulation of White et al. (2002), generated with σₘ = 0.9, and including cooling and feedback. Schulz & White (2003) provide 360 maps from dark mat-
tter simulations with $\sigma_8 = 1.0$ and gas pasted into cluster haloes after the simulation is complete. [Shaw et al. (2008)] follow a similar method, producing 100 maps with $\sigma_8 = 0.77$. Finally, [Holder et al. (2007)] use the Pinocchio algorithm of [Monaco et al. (2002)] to generate halo distributions and merging histories, resulting in 900 maps over a range of $\sigma_8$.

For each set of simulated maps, we form 50 groups of 43 fields; we pick the maps from the available set randomly with replacement. For each map, we simulate SZA observations, reproducing the $u\nu$ coverage and noise properties of the actual data. We process these mock observations just as we do the real data, and produce a maximum likelihood power for each set of 43 fields. We compute the mean and scatter of these powers from the 50 independent realizations.

Results for each set of simulated maps are shown in Figure 2. The strong dependence of the detected power on the value of $\sigma_8$ is clear, as are significant systematic differences among simulations. The maximum likelihood power for the secondary CMB anisotropy measured by the SZA is shown by shaded horizontal bar in the figure. The width of the bar indicates the $\pm 1\sigma$ uncertainty due to the absolute calibration and the subtraction of power from primary CMB anisotropy and undetected radio sources.

Figure 2 shows that the range of $\sigma_8$ values consistent with the SZA anisotropy measurement is large, reflecting significant differences among the simulations. The figure shows there is no tension between the SZA anisotropy measurement with values of $\sigma_8$ in the range 0.7 – 0.8 determined from recent measurements using other techniques, while values higher than 0.9 appear highly unlikely.

We note that the power spectra derived from simulated $y$-maps have greater sample variance than maps of Gaussian noise with the same rms power. While we can measure the variance in simulation by measuring the scatter of many realizations of our experiment, in the actual data we assume Gaussianity in calculating our error bars. We are therefore underestimating the sample variance in our measurement. Using the simulated $y$-maps, we find that the magnitude of this underestimate has a weak dependence on the value of $\sigma_8$, but for $\sigma_8 \sim 0.8$ the confidence region of our measurement is likely 1.5 times broader than the uncertainties on the Gaussian power spectrum measurement suggest.

5.2. Correlations Between Radio Sources and Clusters

We investigate the possibility that we may bias our measurement low by projecting out radio sources associated with the very clusters that provide the SZE signal. Because the short baselines have a similar response to compact radio sources and clusters, in projecting away the contribution of the source we may remove considerable flux from the cluster if only the short-baseline data are used. This introduces no bias if sources and clusters are randomly distributed with respect to each other, but we expect radio sources to be spatially correlated with clusters, as indeed there is some observational evidence to suggest (e.g., [Coble et al. (2007), Lin & Mohr (2007) and references therein]). We find that in a pessimistic simulation, in which every cluster contains at least one source that is projected out using only the short baselines, we recover only one-quarter of the actual SZE power in the fields.

Although the short baselines are unable to discriminate between radio sources and clusters, the long baseline data are well-suited to making this distinction. On spatial scales probed by the long baselines, signal from a cluster is exponentially damped with respect to the short-baseline response, while signal from a point source remains constant. In simulations, we confirm that where source-cluster correlations bias our measurement low, including the long baselines in the analysis reduces the bias by a factor of three.

In practice, we include the long baseline data in the analysis by adding a second bin containing zero cluster signal at $\ell \sim 30000$, and tying the two bins together with constraints for the radio sources. As this procedure increases the size of the covariance matrix beyond what can be manipulated in a reasonable amount of time, adding this bin requires further compression of the data by averaging adjacent scans. Much of the averaged data remains $> 90\%$ correlated, and we discard any data that is not ($\sim 15\%$). We have checked that this additional compression does not bias the power detected in a single bin in $\ell$-space. The measured power when including the long-baseline data is $50^{+14}_{-14} \mu K^2$. The consistency between the power measurements with and without the long-baseline data suggests that source-cluster correlations do not significantly decrease the measured power.

5.3. Comparison with CBI and BIMA

Previous measurements at 30 GHz have suggested a high-$\ell$ excess over the primary CMB anisotropy at a level in apparent conflict with the results of this paper, and

![Figure 2](image-url)
implying values of $\sigma_8$ inconsistent with other contemporary measurements of the parameter. To explore whether the higher excess power could instead be consistent with residual power from radio sources, we examine two additional prescriptions for projecting sources from the SZA data. We also note that accounting for the non-Gaussian sample variance discussed above reduces the significance of the discrepancies between the measurements.

Readhead et al. (2004) used NVSS to identify sources for removal from the CBI 30 GHz anisotropy measurement, with a limiting 1.4 GHz flux of 3.4 mJy. They estimate the residual contribution from undetected sources in the CBI data at $\sim 20\%$ of their highest-$\ell$ bandpower, or $\sim 90 \mu K^2$. A more precise estimate of the CBI residual power is given by Mason et al. (2003); for their high-$\ell$ bin they estimate $115 \pm 57 \mu K^2$. We repeat the SZA analysis using the CBI prescription for identifying sources to constrain, i.e., sources with NVSS fluxes greater than 3.4 mJy and with no reference to our 30 GHz source catalog. This test resulted in a measurement of $378 \pm 87 \mu K^2$ after correction for primary CMB, an excess of $364 \pm 168 \mu K^2$ over our nominal result. If we attribute this excess to residual point source power and extrapolate it to the $\ell_{\text{eff}}$ of the CBI measurement according to the respective window functions of the two experiments, we find our estimates for the CBI residual power to be $189 \pm 45 \mu K^2$ for the Mason et al. (2003) result and $114 \pm 27 \mu K^2$ for the Readhead et al. (2004) result. These indicate roughly 50\% higher residual source contamination than estimated by CBI.

Dawson et al. (2006) used a 4.8 GHz VLA survey, with depth comparable to our 8 GHz survey, to generate source constraints for the BIMA experiment. They estimate negligible power for residual radio sources in their measurement. We approximate applying their selection criteria to the SZA data by constraining only sources detected at $5\sigma$ in our 8 GHz data, again ignoring our 30 GHz catalog. We find a significant increase in power, to $107 \pm 65 \mu K^2$. After subtracting the primary CMB contribution this implies $81 \pm 65 \mu K^2$ secondary anisotropy, or $67 \mu K^2$ higher than we measure. If we attribute this instead to residual point source power and scale to the BIMA effective $\ell$, we would predict $96 \pm 93 \mu K^2$ of residual radio source power for the BIMA measurement. Subtracting this residual power from their measurement gives $124^{+168}_{-152} \mu K^2$ secondary CMB power, consistent with our result.

The analysis above suggests that both CBI and BIMA may have underestimated the residual contribution from undetected radio sources. By contrast with CBI, the 8 GHz VLA survey of the SZA fields provides a sensitive measurement of the source population at a frequency close to the observing frequency, permitting removal of 30 GHz power from a typical radio source with $\alpha \sim 0.7$ ($S_{\nu} \propto \nu^{-\alpha}$) down to $\sim 15 \mu$Jy, about one tenth of the noise level in the SZA CMB fields, and from the most inverted sources down to $\sim 0.6$ mJy, comparable to our detection threshold at 30 GHz, and roughly an order of magnitude lower than the 30 GHz detection threshold for CBI.

Several of the SZA sources detected at 30 GHz lacked counterparts at 8 GHz, implying that they have spectral indices more inverted than those we measured between 5 and 30 GHz ($\alpha < -1$ in the most extreme case), or were not detected at 8 GHz when the VLA survey was obtained due to variability. The former is consistent with the expected bias toward more inverted spectral indices with decreasing flux density, while the latter is consistent with the properties of inverted-spectrum sources, which are known to be highly variable (e.g., Toffolatti et al. 2005). As can be seen in Table 2, excluding these 30 GHz sources from the analysis leads to higher detected power, indicating inverted sources near the SZA 30 GHz detection threshold are significant contributors to the residual source power. They are also the most difficult population to identify. Indeed, Toffolatti et al. (2005) demonstrate that with slightly different assumptions about this population derived at lower flux levels, a majority of the excess power detected by CBI could be explained by residual source power.

### 6. Conclusions

We present results from 30 GHz measurements of the CMB angular power spectrum with the Sunyaev-Zeldovich Array (SZA), on scales where the secondary anisotropy from the Sunyaev-Zeldovich effect (SZE) is expected to dominate. For a broad bin centered at multipole 4066, we find $60^{+65}_{-55} \mu K^2$, of which $26 \pm 5 \mu K^2$ is the expected contribution from primary CMB anisotropy and $20 \pm 28 \mu K^2$ is the expected contribution from undetected radio sources. The resulting constraint on secondary anisotropy is $14^{+71}_{-32} \mu K^2$, implying an upper limit of $149 \mu K^2$ at 95\% C.L. (78 $\mu K^2$ at 68\%).

The SZA results indicate lower secondary anisotropy power than previously reported by experiments at 30 GHz. We show that this discrepancy can be partially attributed to different methods of identifying the contaminating radio sources. The SZA observations employed a hybrid configuration of antennas that includes both short and long antenna separations, providing high sensitivity to arcade anisotropy while simultaneously enabling the detection of radio sources at much higher resolution. Accounting for radio sources detected in the 30 GHz SZA data, and those found with deep VLA observations of the SZA fields at 8 GHz, results in the low anisotropy power measurement.

The hybrid configuration was also used to check whether anisotropy power was suppressed by removal of radio sources correlated with clusters. No significant effect was found.

We show that the level of SZE anisotropy power implied by the SZA measurement is in good agreement with expectations based on simulated $y$-maps made with $\sigma_8 \sim 0.8$, but in conflict with values of $\sigma_8$ of 0.9 and higher. The differences among various simulations, however, prevent a more quantitative determination of $\sigma_8$.

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