ABSTRACT

We present measurements of the angular power spectrum of millimeter-wave anisotropies with the APEX-SZ instrument. APEX-SZ has mapped 0.8 square degrees of sky at a frequency of 150 GHz with an angular resolution of 1'. These new measurements significantly improve the constraints on anisotropy power at 150 GHz over the range of angular multipoles 3000 < \ell < 10,000, limiting the total astronomical signal in a flat band to be less than 105 \mu K^2 at 95% CL. We expect both submillimeter-bright, dusty galaxies and to a lesser extent secondary CMB anisotropies from the Sunyaev-Zel'dovich effect (SZE) to significantly contribute to the observed power. Subtracting the SZE power expected for \sigma_8 = 0.8 and masking bright sources, the best fit value for the remaining power is \ell = 1.1^{+0.9}_{-0.8} \times 10^{-5} \mu K^2 (1.7^{+1.4}_{-1.3} Jy^2 sr^{-1}). This agrees well with model predictions for power due to submillimeter-bright, dusty galaxies. Comparing this power to the power detected by BLAST at 600 GHz, we find the frequency dependence of the source fluxes to be \nu \propto \nu^{2.6^{+0.2}_{-0.5}} if both experiments measure the same population of sources. Simultaneously fitting for the amplitude of the SZE power spectrum and a Poisson distributed point source population, we place an upper limit on the matter fluctuation amplitude of \sigma_8 < 1.18 at 95% confidence.

Subject headings: cosmic microwave background — cosmology: observations — cosmology: cosmological parameters — infrared: galaxies

1. INTRODUCTION

Primary anisotropy in the cosmic microwave background (CMB) radiation is produced by inhomogeneities in the hot baryon-photon plasma at the epoch of recombination. The amplitude of these anisotropies as a function of angular scale has been used to infer precise constraints on the parameters of the standard ΛCDM model [ Dunkley et al. 2009; Komatsu et al. 2009]. On angular scales below several arcminutes, the primary anisotropy is damped by photon diffusion and the observed power is expected to be dominated by sources of foreground emission and the interaction of the CMB with intervening structure. In particular, the inverse Compton scattering of CMB photons off hot plasma bound to clusters of galaxies [ Sunyaev & Zel'dovich 1972] gives rise to a spectral distortion of the CMB known as the Sunyaev-Zel'dovich effect (SZE). At frequencies less than \sim 220 GHz, the SZE produces a decrement in the CMB intensity in the direction of a galaxy cluster. Galaxy clusters produce (secondary) anisotropy power on arcminute scales corresponding to their angular size. The observed SZE power depends sensitively on the abundance of clusters and the history of structure formation. In particular, the amplitude of the SZE power scales as \sigma_8^2, where \sigma_8 is the rms fluctuation of matter on scales of 8h^{-1} Mpc, and serves as an independent probe of the amplitude of density perturbations [ Komatsu & Seljak 2002].

Evidence for small scale power beyond that expected from the primary CMB has been reported by the Berkeley Illinois Maryland Association (BIMA) and Cosmic Background Imager (CBI) interferometers operating at 30 GHz. These measurements find a level of SZE anisotropy power consistent with a value of \sigma_8 somewhat greater than those preferred by other contemporary measurements, which favor \sigma_8 \sim 0.8 [ Vikhlinin et al. 2009; Komatsu et al. 2009]. BIMA observations at 30 GHz covering a total of 0.1 deg^2 of sky produced a nearly 2σ detection of excess power in a flat band centered at a multipole \ell = 5237 [ Dawson et al. 2006]. Due to the non-Gaussian distribution of the SZE on the sky and the low significance of the detection, this resulted in only weak constraints on the matter power spectrum normal-
ization, $\sigma_8 = 1.03^{+0.20}_{-0.23}$ at 68% confidence. Observations with the CBI experiment at 30 GHz over a larger field were used to produce a $>3\sigma$ detection of excess power on angular scales $\ell > 2000$. However, recent observations with the CIBER experiment operating at 30 GHz and covering a total of 2$\text{deg}^2$ of sky, have determined an upper limit on the excess power in broad band centered at multipole $\ell = 4066$ which is significantly lower than the band powers reported by CBI and appears to be consistent with more conventional values of $\sigma_8 \sim 0.8$ (Sharp et al. 2009). The CIBER team interprets the higher power measured by CBI as potentially being due to an unsubtracted population of radio sources.

At 150 GHz, we expect the SZ and emission from distant dusty galaxies to contribute significantly to the power on angular scales corresponding to $\ell > 2500$. The ACBAR experiment reported a $\sim 1\sigma$ excess power at $\ell > 2000$, that if interpreted as the SZ, would be consistent with the higher value for $\sigma_8$ preferred by CBI (Reichardt et al. 2006). However, the ACBAR results are in excellent agreement with a more standard value $\sigma_8 \sim 0.8$ when one considers the expected foreground emission from IR point sources. The QUaD collaboration has recently released a 150 GHz power spectrum for $\ell > 2000$ (QUaD collaboration; R. B. Friedman et al. 2009). The QUaD bandpowers appear (numerical values have not yet been released) to be systematically lower than those produced by ACBAR with no evidence for contributions from secondary anisotropy or foreground emission. Bolocam has recently published new results for anisotropy power at 150 GHz on angular scales above $\ell = 3000$ (Sayers et al. 2009). They report upper limits on the power of $1080\,\mu K^2$ at 95% confidence in a wide bin centered at $\ell = 5700$ and determine that $\sigma_8 < 1.57$ at 90% confidence. New high resolution and sensitivity bolometer arrays operating at millimeter wavelengths such as those currently deployed on the APEX, SPT, and ACT telescopes have the capacity to drastically improve constraints on the SZ and point source contributions to the high-$\ell$ power spectrum.

This paper presents new measurements of small scale anisotropy power made with the APEX-SZ bolometer array on the Atacama Pathfinder Experiment (APEX) telescope from its high elevation site in the Atacama Desert. APEX is a 4.6m diameter, master stabilized, transition edge superconducting (TES) bolometer array centered on a moderately massive, X-ray detected cluster, XLSSU J022145.2-034614, with an X-ray temperature of 5 keV (Willis et al. 2005; Pacaud et al. 2007). A joint analysis of the X-ray and SZ data will be undertaken in a separate paper. A circular scan strategy was used instead of a raster scan to improve the observing efficiency. The scan strategy concentrates the integration time at the center of the map causing the time per pixel to increase steadily from the edges of the map to the center. The total integration time is 2.9k detector-hours. The map center reached a depth of 12 $\mu K$ per 1 pixel. More details on the instrument and scan strategy can be found in Halverson et al. (2009) (hereafter H08) and Schwan et al. (2009).

3. Beam and Calibration

The average beam of the APEX-SZ bolometers is measured with daily observations of Mars. At 8$''$ diameter, Mars is nearly a point source for the 1$''$ APEX-SZ beam, and it is sufficiently bright to map the beam near sidelobes to below -25 dB. The measured beam agrees well with the ZEMAX simulated beam profiles when optical cross-talk is taken into account. The near sidelobes increase the real beam solid angle by 32% compared to the best fit Gaussian beam. We divide the measurement uncertainty on the beam into two parts. The main lobe is well-fit by a Gaussian, and we estimate the measurement uncertainty on the FWHM to be 2.5%. Due to the large angular scale of the sidelobe structure, a mis-estimation of beam sidelobe will effectively cause a mis-calibration of the band powers. We include the uncertainty in the total beam area in the calibration error.

The observations of Mars are used to establish the absolute calibration of the APEX-SZ instrument. The temperature of Mars for our observation frequency and dates is taken from the Rudy model (Rudy et al. 1987; Muhleman & Berge 1991), that has been updated and maintained by Bryan Butler. The Rudy model is compared with measurements of the brightness temperature of Mars made with the WMAP satellite at 93 GHz during five periods across several years (Hill et al. 2009). The WMAP measurements of Mars have uncertainties of $<1\%$ and we adjust the normalization of the Rudy Model down by 5% to bring it into agreement with the WMAP measurements. Combining the $\sim 1\%$ uncertainty in the WMAP Mars measurements, the 1.0% scatter in the 93 GHz WMAP to Rudy Model comparison, and 0.9% for the uncertainty in the extrapolation from 93 GHz, where the Rudy Model is calibrated, to our observing frequency, we find the total uncertainty in the

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15 http://www.zemax.com
16 http://www.aoc.nrao.edu/~bbutler/work/mars/model/
Mars brightness temperature to be 1.7%.

The calibration of each detector is set by comparing the peak amplitude in a map of Mars to the expected amplitude given the temperature and size of Mars and the size of the detector’s beam. A correction factor for the atmospheric opacity is applied which is always less than 3%. The overall calibration uncertainty is estimated to be 5.5% in temperature, with the dominant errors due to a 4% uncertainty in the beam area, a 3% uncertainty to account for temporal variations between the model prediction and the temperature measured by APEX-SZ, the 1.7% uncertainty in the temperature of Mars, and a 1.4% uncertainty in the conversion of brightness temperature to CMB temperature for the measured APEX-SZ band. More details on the beam estimation and calibration can be found in H08.

4. ANALYSIS

4.1. Map-Making

The filtering and map-making process used in this analysis follows the approach detailed in H08 for analysis of the Bullet cluster. We briefly outline the major steps here, while highlighting any differences in the filtering between this work and the Bullet cluster analysis. The time-series processing was designed to remove or down-weight the following signal contributions: 1/f noise, atmospheric fluctuations, and correlated terms from the instantaneous noise. The scan pattern includes boresight elevation changes which modulate the air mass along the line of sight. This signal is removed by fitting for a cosecant(\(\alpha\)) term. 1/f noise in the system is filtered from the time-series using a 0.3 Hz 8-pole Butterworth high-pass filter (HPF). The typical length scale of atmospheric fluctuations is much larger than the field of view (FOV), so fluctuations are highly correlated across the APEX-SZ array. This correlated term is removed by fitting for a low order spatial polynomial across the focal plane at each time sample. We remove a 2nd order spatial mode in this work. The cumulative effect of the filtering is to completely remove structures corresponding to angular multipoles below \(\ell \approx 1400\). After filtering, the time-series are weighted according to the filtered time-series RMS and binned into 20\(^{\circ}\) map pixels.

4.2. Power Spectrum Estimation

The band powers, \(q_B\), are reported in CMB temperature units of \(\mu K^2\) and parametrize the power spectrum according to

\[
\frac{\ell(\ell + 1)}{2\pi}C_\ell = D_\ell = \sum_B q_B \chi_{B\ell} \tag{1}
\]

where \(\chi_{B\ell}\) are top hat functions; \(\chi_{B\ell} = 1\) for \(\ell \in B\) and 0 for \(\ell \notin B\). We use a pseudo-\(\tilde{C}_\ell\) power spectrum estimator (Hivon et al. 2002). In this formalism, the map spectrum (also called the pseudo-\(C_\ell\) or \(\tilde{C}_\ell\)) depends on the true spectrum (\(C_\ell\)) as:

\[
\tilde{C}_\ell = M_{\ell\ell^\prime}T_\ell B_{\ell\ell^\prime}^2 C_{\ell^\prime}. \tag{2}
\]

\(\tilde{C}_\ell\) is calculated using the flat-sky approximation, in which the spherical harmonic transform of the sky reduces to a Fourier transform of the map. This is an excellent approximation for a sub-degree sized map. The experimental beam function is described by \(B_\ell\), and the mode-coupling due to finite sky coverage is denoted by \(M_{\ell\ell^\prime}\). \(T_\ell\) represents the transfer function of the map-making process which would ideally be equal to one. In practice, the HPF applied to the APEX-SZ time-series eliminates power on scales \(\ell < 1400\) so \(T_\ell = 0\) on these scales and remains below one at all \(\ell\). Following the MASTER algorithm (Hivon et al. 2002), we measure the transfer function using a set of Monte-Carlo sky realizations that have been passed through the full pipeline, from the time-series to the maps. These simulated sky maps include a lensed WMAP5+ACBAR best fit CMB model (Hill et al. 2009; Reichardt et al. 2009), realizations of the SZE signal (Shaw et al. 2009), and realizations of the point source populations (Negrello et al. 2007; Granato et al. 2004; de Zotti et al. 2005). This set of signal-only simulations is also used to estimate the cosmic variance contribution to the band power uncertainties.

The mode-coupling matrix \(M_{\ell\ell^\prime}\) is calculated analytically for the two sky masks used to estimate the APEX-SZ band powers. These masks describe the weighting applied to each pixel in the map before calculating the Fourier transforms and are analogous to windowing data in a 1D Fourier transform. We begin by applying an inverse-noise weighting to each pixel, based on the diagonal elements of the pixel-noise covariance matrix. This effectively de-weights the noisy edges of the map, and is near-optimal in the low signal-to-noise per pixel regime. We modify this simple mask to exclude pixels near detected clusters or point sources. There are two X-ray detected clusters in the field: XLSSU J022145.2-034614 and XLSSU J022157.4-034001. The field was centered on the first and more massive of these clusters, which would introduce a bias into the determination of the SZE amplitude. The central cluster is masked to a diameter of 6\(^{\circ}\) in the first mask, hereafter the Cluster mask. The second cluster is fainter, and was detected only in a joint analysis of X-ray and optical data (Andreon et al. 2005). We tested the effects of masking the second cluster as well and did not see a significant change in the band powers. The second mask removes the 27 point sources detected in the APEX-SZ map in addition to the central cluster. These sources are found by using SExtractor (Bertin & Arnouts 1996) to select sets of neighboring pixels above 3\(\sigma\) in an optimally filtered map. This corresponds approximately to a detection threshold of 2 mJy. We discuss these sources further in §5.1. This mask will be referred to as the Cluster + Sources mask. We tested the effect of masking all NVSS or bright Spitzer sources within the field, and observed no significant change in power.

The measured band powers will be the sum of the signal and noise band powers,

\[
D_\ell = D_\ell^S + D_\ell^N \tag{3}
\]

and we must subtract the expected noise contribution to recover the underlying signal spectrum. The noise contribution to the APEX-SZ band powers is estimated from the average power in a set of 2200 jackknife maps between two randomly selected half sets of the \(~1100\) complete observations of the field. These difference maps effectively remove sky signal, while preserving correlated noise in the time-series on time scales shorter than
the few minute length of a scan with randomized phase. Noise on longer time scales has been removed by the 0.3 Hz HPF. The expectation value of the noise band powers, \( (D_\ell^N) \), is taken to be the mean band powers measured across the set of 2200 jack-knives. The approach is similar to that used in the analysis of the Bolocam power spectrum (Sayers et al. 2009). We apply the same procedure to signal-only simulated maps and confirm that any residual signal power due to the small pointing, filtering and weighting differences between observations is negligible.

5. Band Powers and \( \sigma_8 \)

The power spectrum presented in Figure 1 is the product of applying the analysis in Section 4 to APEX-SZ observations of the XMM-LSS field. The band powers for angular multipoles from 3000 to 10,000 are tabulated in Table 1. The band powers can be compared to a theoretical model using the window functions. The numerical values for the band powers and window functions can be downloaded from the APEX-SZ website\(^{17}\).

The APEX-SZ band powers show a tendency to increase on smaller angular scales, suggestive of the \( \ell^2 \) shape that a Poisson distribution of point sources will have in a plot of \( \ell(\ell + 1)C_\ell/2\pi \). The contribution of the primary CMB will be small at these small angular scales, and we subtract the estimated contribution for the best fit WMAP5+ACBAR lensed \( \Lambda \)CDM power spectrum before fitting for the amplitude of a constant \( C_\ell \). The beam and calibration uncertainty is incorporated by averaging the likelihood function over a set of 200 Monte Carlo realizations. The best fit power is \( C_\ell = 1.0^{+0.9}_{-0.6} \times 10^{-5} \) \( \mu K^2 \), which includes both the point source and SZE contributions. Results for both masks are tabulated in the first row of Table 2. If the expected SZE power spectrum for \( \sigma_8 = 0.8 \) is subtracted in addition to the primary anisotropies, the average \( C_\ell \) drops slightly to 0.9\(^{+0.9}_{-0.6} \times 10^{-5} \) \( \mu K^2 \). At the best-fit point source amplitude for \( \sigma_8 = 0.8 \), 92% of the astronomical power in the map is produced by point sources rather than the SZE. These results are obtained after masking the bright, central cluster. Leaving the central cluster unmasked increases the fit power by \( \sim 1.0 \times 10^{-5} \) \( \mu K^2 \). We also report the results after masking the sources internally detected in the map at \( > 3\sigma \) in the second row of Table 2. These results are consistent with and improved over the previous ACBAR constraints from \( \ell < 3000 \) of \( C_\ell = 2.7^{+1.1}_{-2.6} \times 10^{-5} \) \( \mu K^2 \). However, these numbers should be compared with caution as the two experiments have different flux cuts for source masking, and the excess power will depend on the flux to which sources have been masked.

We also investigate the effects of allowing the amplitude of the SZE power spectrum to float freely. The SZE power spectrum template is based on the simulations in Shaw et al. (2009). The simulations are for a WMAP5 cosmology with \( \sigma_8 = 0.77 \). The amplitude of the SZE power spectrum is expected to scale approximately as \( \sigma_8^4 \), so the derived SZE amplitude can be related to \( \sigma_8 \). In practice, the APEX-SZ data set lacks the sensitivity to make a detection of SZE power; however, the results can be used to place an upper limit on \( \sigma_8 \). The upper limits on \( \sigma_8 \) and the point source amplitudes for the joint fit are reported in Table 2. We assume a flat prior on \( \sigma_8 \). The exact amplitude of the SZE spectrum is only poorly understood, leading to a 10% systematic uncertainty on \( \sigma_8 \) (Komatsu & Seljak 2002). This systematic uncertainty is not included in the reported upper limits.

The non-Gaussian distribution of the SZE is very important on small patches of sky (Cooray 2001; Zhang et al. 2006). We incorporate the non-Gaussian statistics into our analysis by returning to the set of simulated SZE skies (Shaw et al. 2009). We extract 7500 independent realizations of the APEX-SZ map and calculate the power in each realization under the two masks. The maps have been convolved by the experimental beam and do not include noise. This process maps out the full, non-Gaussian cosmic variance of the expected SZE power for \( \sigma_8 = 0.77 \). We scale this to other cosmologies by assuming that the probability of measuring a power \( X \) will scale with \( \sigma_8 \) as

\[
P(X|\sigma_8) = \left( \frac{\sigma_8}{0.77} \right)^7 P\left( \frac{0.77}{\sigma_8} \right)^7 X|\sigma_8 = 0.77 \right). \quad (4)
\]

Bayes’ theorem with a flat prior in \( \sigma_8 \) is applied to find a posterior probability density, \( P(\sigma_8|X) \). We determine the probability of a given SZE power from the data by marginalizing over a point source component as described in the last paragraph. Finally, the likelihood function of \( \sigma_8 \) given the APEX-SZ data \( d \) is calculated by

\[
P(\sigma_8|d) = \int dX P(\sigma_8|X) P(X|d) \quad (5)
\]

and integrated to find the 95% CL upper limit on \( \sigma_8 \). The limit rises to \( \sigma_8 < 1.18 \), substantially weaker than the limit of \( \sigma_8 < 0.94 \) derived under Gaussian assumptions (see the third row of Table 2 labeled “Unconstrained \( \sigma_8 \)”). The marginalized likelihood function for both \( \sigma_8 \) and \( C_\ell^{PS} \) are plotted in Figure 2 while the 2d likelihood surface for both parameters is shown in Figure 3. The upper limit is sensitive to the prior chosen since APEX-SZ does not make a detection of SZE power. A flat prior on power, \( \sigma_8^4 \), strongly prefers higher values of \( \sigma_8 \) than the flat prior on \( \sigma_8 \), and raises the upper limit from 1.18 to \( \sigma_8 < 1.50 \) at 95% CL. This is entirely due to the weighting by the prior as the prior probability for \( \sigma_8 = 2 \) is 240 times the probability of \( \sigma_8 = 0.8 \).

Finally, we combine the four APEX-SZ band powers into a single band to facilitate the comparison to other data sets. The resulting upper limit is \( \sim 100 \) \( \mu K^2 \) after including the APEX-SZ calibration and beam uncertainty as shown in the last row of Table 2. “Flat Excess”. We have assumed that \( D_\ell \) is constant across the four bands and subtracted the contribution due to the primary CMB anisotropies. However, this upper limit does not include a non-Gaussian contribution to cosmic variance.

5.1. Radio and IR source contributions

Submillimeter bright galaxies and radio sources are expected to dominate the primary temperature anisotropies for \( \ell \gtrsim 2500 \) at 150 GHz. The exact contribution from point sources, especially radio sources, will

\(^{17}\) http://bolo.berkeley.edu/apexsz/index.html
Fig. 1.— Band powers derived from the APEX-SZ map plotted over a model (thick black line) including the primary CMB anisotropies, a SZE model for $\sigma_8 = 0.8$ (short dashed purple line), and the predicted point source contribution for a 2 mJy cut threshold (long dashed purple line). This model is not a fit to the APEX-SZ band powers. We also plot for comparison the theory spectrum (thin black line) if we increase $\sigma_8$ to APEX-SZ’s 95% CL upper limit of 1.18. The APEX-SZ band powers for the Cluster mask are plotted with blue squares, while the Cluster + Sources mask results are shown as black circles. The Cluster mask band powers have been shifted by $\Delta \ell = 200$ to the right for clarity. BIMA (turquoise diamond and upper limit - Dawson et al. (2006)), SZA (green circle - Sharp et al. (2009)), and Bolocam (red upper limit - Sayers et al. (2009)) have previously released band-powers centered at $\ell > 3000$. The upper limits are shown at 95% CL. BIMA and SZA operate at 30 GHz where there will be four times as much SZE power as at 150 GHz and we expect the foregrounds to be dominated by radio sources rather than dusty galaxies. The plotted theory spectra are for 150 GHz only.

### TABLE 1

<table>
<thead>
<tr>
<th>$\ell$ range</th>
<th>$\ell_{\text{eff}}$</th>
<th>Cluster masked</th>
<th>Cluster + Sources masked</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$q$ ($\mu K^2$)</td>
<td>$\sigma$ ($\mu K^2$)</td>
</tr>
<tr>
<td>3000-4000</td>
<td>3532</td>
<td>-74</td>
<td>94</td>
</tr>
<tr>
<td>4000-6000</td>
<td>4957</td>
<td>26</td>
<td>73</td>
</tr>
<tr>
<td>6000-8000</td>
<td>6968</td>
<td>-58</td>
<td>132</td>
</tr>
<tr>
<td>8000-10000</td>
<td>8844</td>
<td>546</td>
<td>280</td>
</tr>
</tbody>
</table>

Note. — Band multipole range and weighted value $\ell_{\text{eff}}$, band powers $q$, and uncertainty $\sigma$ from the analysis of the XMM-LSS field with two masks. The first two columns (Cluster masked) show the results when the central X-ray detected cluster in the field is masked to 6′ diameter. The second set of columns (Cluster + Sources masked) masks twenty-seven $> 3 \sigma$ sources detected in the map to 1.5′ diameter as well as the cluster. More details on the masks can be found in §4.2.
background at frequencies of 600 GHz to 1.2 THz (Viero et al. 2009). BLAST measured a Poisson contribution from star-forming galaxies with an amplitude of 2.63 \pm 0.1 \times 10^3 \text{ Jy}^2 \text{ sr}^{-1} at 600 GHz. A clustering term is detected as well on angular scales larger than those probed by APEX-SZ. Expressing the frequency dependence of the source fluxes as \( S(\nu) \propto \nu^\alpha \), we can derive an effective spectral index, \( \alpha \), by comparing the power measured by BLAST at 600 GHz to the point source power likelihood function of the APEX-SZ maps at 150 GHz. This index will depend on the spectral of the individual galaxies and their redshift distribution. We find that a spectral index of \( \alpha = 2.64 \pm 0.2 \) scales the BLAST power to match the best-fit \( C_\ell = 1.1^{+0.9}_{-0.6} \times 10^{-5} \text{ \mu K}^2 (1.7^{+1.4}_{-1.3} \text{ Jy}^2 \text{ sr}^{-1}) \) of the APEX-SZ data. This inferred spectral index agrees well with previous estimates for sub-mm bright galaxies. Knox et al. (2004) examined nearby galaxy data and found \( S_{\nu} \propto \nu^{2.05} \pm 0.3 \), in an alternative approach, Greve et al. (2004) compared the flux of sources in overlapping regions observed by MAMBO (1.2 mm) and SCUBA (850 \mu m) and found the fluxes scaled as \( S_{\nu} \propto \nu^{2.65} \). The point source power in the APEX-SZ data set at 150 GHz is consistent with being entirely due to a population of dusty submm-bright galaxies such as those observed by BLAST.

We also consider radio sources as a potential foreground in the APEX-SZ maps. Granato et al. (2004) and de Zotti et al. (2005) have modeled the number counts of several classes of radio sources at tens of GHz. We derive \( C_\ell^{\text{radio}} \) from their modeled number counts at 150 GHz. The radio source power is dependent on the brightest objects and is expected to scale approximately linearly with the source cut threshold. At the 2 mJy source cut threshold of APEX-SZ, \( C_\ell^{\text{radio}} \) should be \( \lesssim 5\% \) of the dusty galaxy contribution.

<table>
<thead>
<tr>
<th>Zero SZE power: ( C_\ell^{\text{PS}} ) ( (10^{-5} \text{ \mu K}^2) )</th>
<th>Cluster masked</th>
<th>Cluster + Sources masked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed ( \sigma_s = 0.8 ): ( C_\ell^{\text{PS}} ) ( (10^{-5} \text{ \mu K}^2) )</td>
<td>1.0^{+0.9}_{-0.6}</td>
<td>1.2^{+1.0}_{-0.8}</td>
</tr>
<tr>
<td>Unconstrained ( \sigma_s ): ( C_\ell^{\text{PS}} ) ( (10^{-5} \text{ \mu K}^2) )</td>
<td>0.9^{+0.9}_{-0.6}</td>
<td>1.1^{+0.9}_{-0.8}</td>
</tr>
<tr>
<td>( \sigma_s ) (95% CL)</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>( \sigma_s ) (NG) (95% CL)</td>
<td>1.18</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Flat excess:

<table>
<thead>
<tr>
<th>( D_\nu ) (\text{\mu K}^2)</th>
<th>33^{+37}_{-24}</th>
<th>36^{+39}_{-26}</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL</td>
<td>97</td>
<td>105</td>
</tr>
</tbody>
</table>

Note. — The constraint on point source power \( C_\ell^{\text{PS}} \), and the 95\% CL upper limit on \( \sigma_s \) derived from the APEX-SZ data set are tabulated for different assumptions about the SZE power and masks. The expected primary CMB anisotropy power has been subtracted from the measured band powers. We show the upper limit on \( \sigma_s \) with (NG) and without (G) accounting for the non-Gaussian distribution of the SZE. Accounting for the non-Gaussianity in the expected SZE sky weakens the upper limit considerably. The first column (Cluster masked) shows the results when the massive, X-ray detected cluster in the field is masked to 6’ diameter. The second column (Cluster + Sources masked) excludes the >3\( \sigma \) sources detected in the map as well as the cluster. More details on the masks can be found in §4.2. The measured point source power is in excellent agreement with the predicted amplitude of \( 1.1 \times 10^{-5} \text{ \mu K}^2 (1.7 \text{ Jy}^2 \text{ sr}^{-1}) \) for the sum of the radio and dusty galaxy models in all cases. We also show the results under the assumption that the power at high-\( \ell \) above the primary CMB anisotropies can be modeled as a flat band-power. The 95\% CL upper limit on a flat excess of <105 \text{ \mu K}^2 includes the beam and calibration uncertainties but does not include non-Gaussian contributions to cosmic variance.
number density of 19 sources/deg$^2$ falls between these two source densities as we would expect. The source number counts in the APEX-SZ maps appear consistent with the numbers expected for dusty galaxies.

6. CONCLUSIONS

Observations with the APEX-SZ instrument have been used to constrain the power in excess of the primary CMB temperature anisotropies at 150 GHz. This power is expected to be dominated by emission from sub-mm bright, dusty galaxies and the APEX-SZ band powers are consistent with this hypothesis. We find excellent agreement between the point source power in the APEX-SZ maps and model predictions based on observations at other frequencies. We estimate that the flux of these sub-mm bright galaxies scales with frequency as $S_\nu \sim \nu^{2.64}$ by comparing the power measured by BLAST at 600 GHz to the best-fit point source power in the APEX-SZ maps at 150 GHz. Determining the contribution of these foreground sources not only constrains models for the population of dusty galaxies, but is important for planning current and future observations of secondary CMB anisotropies at these wavelengths.

We also place upper limits on $\sigma_8$ from fits to the amplitude of the SZE power spectrum while marginalizing over a Poisson point source contribution. We assume a template for the SZE power spectrum derived from simulations by Shaw et al. (2009) with the amplitude of the SZE power spectrum scaling as $\sigma_8^2$. We find an upper limit of $\sigma_8 < 1.18$ at 95% confidence. This result is similar to the constraints from the CBI and BIMA interferometers operating at 30 GHz. The limits from SZA, QUA, or ACBAR would likely be slightly lower, but they did not express their results in terms of upper limits on $\sigma_8$. At these frequencies and angular scales, the previous best limit comes from Sayers et al. (2009), who used observations with the Bolocam instrument to constrain $\sigma_8 < 1.57$ at 90% confidence.

A third of the APEX-SZ instrument was recently upgraded to more sensitive detectors with improved optical efficiencies. In the next year, the remainder of the focal plane will be upgraded resulting in significant improvements to the instrument’s mapping speed. The instrument will continue observing in the next several years with a focus on developing a catalog of clusters with SZE, X-ray and optical observations across the Southern hemisphere.

7. ACKNOWLEDGMENTS

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[Fig. 2.— (solid and lower x-axis) Marginalized likelihood function for $\sigma_8$ for a flat prior on $\sigma_8$ after accounting for non-Gaussianity. (dashed and upper x-axis) Marginalized likelihood function for $C^{\nu^2}_t$. These curves are for the Cluster+Sources mask.]

![Likelihood function](image-url)
Fig. 3.— The 1-σ and 2-σ contours on the 2D likelihood surface for σ₈ and the point source amplitude for the Cluster+Sources mask applied to the APEX-SZ map. The contours include the effects of non-Gaussianity in the SZE. A flat prior on σ₈ has been assumed.

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REFERENCES


Cooray, A. 2001, Phys. Rev. D, 64, 063514


05CH11231. Nils Halverson acknowledges support from an Alfred P. Sloan Research Fellowship.
Author/s:
Reichardt, CL; Zahn, O; Ade, PAR; Basu, K; Bender, AN; Bertoldi, F; Cho, H-M; Chon, G; Dobbs, M; Ferrusca, D; Halverson, NW; Holzapfel, WL; Horellou, C; Johansson, D; Johnson, BR; Kennedy, J; Kneissl, R; Lanting, T; Lee, AT; Lueker, M; Mehl, J; Menten, KM; Nord, M; Pacaud, F; Richards, PL; Schaaf, R; Schwan, D; Spieler, H; Weiss, A; Westbrook, B

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