EXTENDED MOSAIC OBSERVATIONS WITH THE COSMIC BACKGROUND IMAGER

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ABSTRACT

Two years of microwave background observations with the Cosmic Background Imager (CBI) have been combined to give a sensitive, high resolution angular power spectrum over the range 400 < ℓ < 3500. This power spectrum has been referenced to a more accurate overall calibration derived from the Wilkinson Microwave Anisotropy Probe. The data cover 90 deg 2 including three pointings targeted for deep observations. The uncertainty on the ℓ > 2000 power previously seen with the CBI is reduced. Under the assumption that any signal in excess of the primary anisotropy is due to a secondary Sunyaev-Zeldovich anisotropy in distant galaxy clusters we use CBI, Arcminute Cosmology Bolometer Array Receiver, and Berkeley-Illinois-Maryland Association array data to place a constraint on the present-day rms mass fluctuation on 8h −1 Mpc scales, σ 8 . We present the results of a cosmological parameter analysis on the ℓ < 2000 primary anisotropy data which show significant improvements in the parameters as compared to WMAP alone, and we explore the role of the small-scale cosmic microwave background data in breaking parameter degeneracies.

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

1. INTRODUCTION

The Cosmic Background Imager (CBI) is a planar synthesis array designed to measure cosmic microwave background (CMB) fluctuations on arcminute scales at frequencies between 26 and 36 GHz. The CBI has been operating at its site at an altitude of 5080 m in the Chilean Andes since late 1999. Previous results have been presented by Padin et al. (2001), Mason et al. (2003), and Pearson et al. (2003). The principal observational results of these papers were: (i) the first detection of anisotropy on the mass scale of galaxy clusters—thereby laying a firm foundation for theories of galaxy formation; (ii) the clear delineation of a damping tail in the power spectrum, best seen in the mosaic analysis of Pearson et al. (iii) the first determination of key cosmological parameters from the high-ℓ range, independent of the first acoustic peak; and (iv) the possible detection, presented in the deep field analysis of Mason et al., of power on small angular scales in excess of that expected from primary anisotropies. The interpretation of these results has been discussed by Sievers et al. (2003) and Bond et al. (2004). The CBI data, by virtue of their high angular resolution, were able to place constraints on cosmological parameters which are largely independent of those derived from larger-scale experiments; for instance, 10% measurements of ΩΛ and ns using only CBI, DMR and a weak H0 prior. The small-scale data also play an important role in improving results on certain key parameters (ΩΛ, h 2 , ns, τCMB) which are less well-constrained by large-scale data.

Theoretical models predict the angular power spectrum of the CMB

\[ C_\ell = \left\langle |a_{\ell m}|^2 \right\rangle \]

where the \( a_{\ell m} \) are coefficients in a spherical harmonic expansion of temperature fluctuations in the CMB, \( \Delta T/T_{\text{CMB}} \), where \( T_{\text{CMB}} \approx 2.725 \) K is the mean temperature of the CMB, and the angle brackets denote an ensemble average. These theories also predict a series of acoustic peaks in the angular power spectrum on scales \( \lesssim 1^\circ \) (\( \ell \gtrsim 200 \)), and a decline in power towards higher \( \ell \) due to photon viscosity and the thickness of the last scattering surface. Early indications of the first acoustic peak were presented by Miller et al. (1999); definitive measurements of the first and second peaks were reported by de Bernardis et al. (2000), Lee et al. (2001), Netterfield et al. (2002), Halverson et al. (2002), Scott et al. (2003), and Grainge et al. (2003). The last of these experiments reached \( \ell \sim 1400 \). The CBI (Padin et al. 2002) has complemented these experiments by covering an overlapping range of \( \ell \) extending to \( \ell \sim 3500 \). The Arcminute Cosmology Bolometer Array Receiver (ACBAR) (Kuo et al. 2004) has recently been used to measure these experiments.
covered a similar range of $\ell$ as the CBI at higher frequency; the Berkeley-Illinois-Maryland Association array (BIMA) has also made 30 GHz measurements at $\ell \sim 5000$ which probe the secondary Sunyaev-Zeldovich effect (SZE) anisotropy (Dawson et al. 2002). These experiments—which employ a wide variety of instrumental and experimental techniques—present a strikingly consistent picture which supports inflationary expectations (see Bond et al. (2002) for a review). However the results at intermediate angular scales ($500 < \ell < 2000$) currently have comparatively poor $\ell$-space resolution, and the high-$\ell$ results are difficult to compare conclusively owing to the low signal-to-noise ratio ($\sim 2-4$). The results presented here improve the situation by: (i) expanding the coverage of the CBI mosaics for higher $\ell$ resolution, (ii) integrating further on the deep fields, and (iii) combining the deep and mosaic data for a single power spectrum estimate over the full range of $\ell$ covered by the CBI.

The CBI results presented by Mason et al. (2003) and Pearson et al. (2003) were based on data obtained between January and December of 2000. Mason et al. analyzed the data resulting from extensive integration on three chosen “deep fields” to constrain the small-scale signal; the analysis of Pearson et al. used data with shallower coverage of a larger area (“mosaics”) to obtain better Fourier-space resolution. Further observations were conducted during 2001; these were used to extend the sky coverage of the mosaics in order to attain higher resolution in $\ell$, and to go somewhat deeper on the existing deep fields. This paper presents the power spectrum resulting from the combination of the full CBI primary anisotropy dataset, which comprises data from years 2000 and 2001 on both mosaic and deep fields. Two of the mosaic fields (14 h and 20 h) include deep pointings; there is also a third deep pointing (08 h), and a third mosaic (02 h). The CBI data have been recalibrated to a more accurate power scale derived from the Wilkinson Microwave Anisotropy Probe (WMAP).

The organization of this paper is as follows. In § 2 we discuss the observations and WMAP-derived recalibration. In § 3 we present images and power spectra derived from the data and explain the methodology employed in their derivation. In § 4 we use these results to constrain cosmological parameters based on standard models for primary and secondary CMB anisotropies. We present our conclusions in § 5.

2. OBSERVATIONS AND CALIBRATION

The analysis in this paper includes data collected in the year 2001 in addition to the year 2000 data previously analyzed. In January through late March of 2001 there was an unusually severe “Bolivian winter” which prevented the collection of useful data; regular observations resumed on 2001 March 28 and continued until 2001 November 22. The weather in the austral winter of 2001 was considerably less severe than it had been in 2000, so that significantly less observing time was lost due to poor weather.

In 2001 we concentrated primarily on extending the mosaic coverage in three fields in order to obtain higher resolution in $\ell$. We also made a small number of observations in the deep fields discussed by Mason et al. (2003). The original field selection is discussed by Mason et al. (2003) and Pearson et al. (2003). Since our switching strategy employs pairs of fields separated in the east-west direction, contiguous extensions were easiest in the north-south direction. The extensions to these fields were selected to minimize point source contamination. In two cases (the 02 h and 14 h fields) this procedure resulted in extensions to the north, and in one case (20 h) an extension to the south. The images for the combined 2000+2001 mosaic observations are shown in Figure 1 and the sensitivity maps are shown in Figure 2. The total areas covered are 32.5, 3.5, 26.2, and 27.1 deg$^2$ for the 02 h, 08 h, 14 h, and 20 h fields respectively.

The CBI two-year data were calibrated in the same manner as the first-year data (Mason et al. 2003), except that the overall calibration scale has been adjusted in light of the recent WMAP observations of Jupiter (Page et al. 2003). The flux density scale for the first-year data was determined from the absolute calibration measurements by Mason et al. (1999) which gave a temperature for Jupiter at 32 GHz of $T_J = 152 \pm 5$ K (note that all planetary temperatures discussed in this paper are the Rayleigh-Jeans brightness temperature of the planet minus the Rayleigh-Jeans temperature of the CMB at the same frequency). Page et al. (2003) have determined $T_J(32 \text{ GHz}) = 146.6 \pm 2.0$ K from measurements relative to the CMB dipole. Figure 3 shows measurements of Jupiter with the CBI on the old (Mason et al. 1999) calibration scale, as well as the WMAP measurements. The slopes of the CBI and WMAP spectra are in agreement to better than 1σ, and the 32 GHz values are also within 1σ; these results support the original CBI amplitude and spectral slope calibrations. Since the WMAP and Mason et al. measurements are independent we adopt a weighted mean of the two and base the CBI calibration on $T_J(32 \text{ GHz}) = 147.3 \pm 1.8$ K. This 3% reduction in the CBI flux density scale corresponds to an overall scaling down of the CBI power spectrum by 6% in power. This scaling is consistent with the original 3.5% flux density scale uncertainty (7% in power). The new CBI calibration has an uncertainty of 1.3% in flux density (2.6% in power).

3. DATA ANALYSIS

The basic methods of CBI data analysis and spectrum extraction are described fully by Mason et al. (2003), Pearson et al. (2003), and Myers et al. (2003). The primary differences in this analysis are: an improved estimate of the thermal noise, which has allowed us to bring the mosaic data to bear on the “high-$\ell$ excess” evident in the deep data; new data cuts needed to deal with point sources in the mosaic extensions; and a revised $\ell$-binning appropriate to the expanded sky coverage and variable noise level of the new data. These aspects of the analysis, and the resulting power spectrum, are described in the following subsections.

3.1. Thermal Noise Estimates

We estimate the thermal noise variance for each uv data point in each scan of the CBI dataset by the mean squared-deviation about the mean, and subsequently use a weighted average to combine the estimates from different scans. It is necessary to make a small correction to
Fig. 1.— The extended mosaic images from the combined 2000+2001 observations. The angular resolution of these observations is $\sim 5'$ (FWHM).
Fig. 2.— The sensitivity across the extended mosaic images from the combined 2000+2001 observations. The deep pointings within the 14 and 20 h mosaic fields are evident in the bottom-right and upper-left of the third and fourth panels, respectively. Blue boxes indicate the approximate regions covered in the earlier CBI mosaic analysis of Pearson et al. (2003).
the estimated variance for each $(u, v)$ data point due to the finite number of samples which enter the estimate. Mason et al. 2003 present simple analytic arguments placing this correction at 8% in variance, and estimate a 2% uncertainty in the variance. We have since improved our estimate of the CBI thermal noise variance resulting in a variance correction factor of $1.05 \pm 0.01$. This is $1.5\sigma$ from the factor $(1.08 \pm 0.02)$ applied to the year 2000 data; the overestimate of noise in Mason et al. will have caused a slight underestimate---by $42 \mu K^2$---of the excess power level at high $\ell$ in the original CBI deep result Mason et al. 2003.

We calculated the noise variance correction in several ways: a first-order analytic calculation of the noise distribution; a numerical (FFT-based) integration of the distribution; and analysis of simulated data. The simulations use the actual CBI data as a starting point, replacing each 8.4 second integration with a point of zero mean and drawn from a Gaussian distribution with a dispersion derived from the estimated statistical weight of the data point. This method accounts for variations in the statistical weight from baseline to baseline and variations in the number of data points per scan due, for instance, to rejected data. This gives a result of $1.044 \pm 0.002$ (statistical error). The FFT calculation agrees within the 0.2% uncertainty in the variance. The first-order analytic calculation is lower by 0.6% but should be considered to be only a crude check. Details of the noise variance estimate are presented by Sievers 2003.

The simulations were analyzed entirely in the visibility domain. As a further check on the variance correction calculations, we gridded the visibility data following the procedure used in analyzing the real CBI data. Montes Carlo calculations of the $\chi^2$ of the gridded estimators (using the inverse of the full noise matrix) yield a noise correction factor of $1.050 \pm 0.004$ (statistical error). This is why we adopt a value of 1.05, since it is the gridded estimators that are used in the power spectrum estimation. We conservatively adopt a 1% uncertainty in the variance correction although the level of agreement between different methods of estimating this is $\sim 0.5\%$.

The importance of the improved accuracy of the thermal noise calculation is illustrated by considering the year 2000 CBI data at $\ell > 2000$. Referenced to the current calibration and noise scale, the year 2000 mosaic data presented by Pearson et al. (2003) yield a band-power of $206 \pm 178 \mu K^2$. We considered combining these data with the year 2000 CBI deep field data Mason et al. 2003. The thermal noise variance in this last bin for the year 2000 mosaic, however, is $4307 \mu K^2$, which yields a $86 \mu K^2$ systematic uncertainty due to the thermal noise variance correction alone given the previous 2% uncertainty in the noise variance. The thermal noise variance in the year 2000 deep field data is $1293 \mu K^2$, resulting in a $26 \mu K^2$ uncertainty due to the noise estimate; this was substantially less than the greatest systematic uncertainty, the residual point source correction at $50 \mu K^2$. It was clear that the mosaic data would contribute little to our understanding of the signal at $\ell > 2000$. In contrast, the thermal noise variance for the 2000+2001 mosaic+deep data in the last ($\ell > 1960$) bin is $2054 \mu K^2$, which with our present 1% knowledge of the noise variance results in a contribution to the systematic error budget slightly lower than that from noise in the year 2000 deep data, and subdominant to the residual point source contribution.

3.2. Treatment of the Discrete Source Foreground

The treatment of the discrete source foreground is similar to that adopted in the earlier CBI analyses of Mason et al. (2003) and Pearson et al. 2003. All sources above 3.4 mJy in the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998) were included in a constraint matrix and projected out of the data Bond, Jaffe, & Knox 1993, Halverson et al. 2002. This is roughly equivalent to completely downweighting the synthesized beam corresponding to each of these sources and effectively eliminates 25% of our data. We correct for sources below the 3.4 mJy cutoff in NVSS statistically. The statistical correction reduces the power in the high-$\ell$ bin by $\sim 20\%$ (see Figure 4). We have also obtained independent 30 GHz measurements of the bright sources in the CBI fields with the OVRO 40-m telescope. For presentation purposes we subtract these flux densities from the maps with reasonable results, although some residuals are visible. The constraint matrices eliminate the impact of any errors in the source subtraction, and the power spectrum results are unchanged even if no OVRO subtraction is performed.

Although the extensions were chosen to minimize point source contamination, the larger size of the expanded mosaics and the requirement that the extensions be contiguous with the already highly-optimized original CBI mosaic fields resulted in a handful of sources brighter than those present in the year 2000 CBI mosaic data Pearson et al. 2003. In particular the 02h extension contains the Seyfert galaxy NGC 1068 ($S_{30 \, \text{GHz}} \sim 0.4 \text{Jy}$) which we found was not effectively removed by the constraint matrix. To deal with this we excluded CBI pointings around this source (as well as one other bright source in the 02h field, and one in each of the 14h field and 20h...
fields) until the maximum signal-to-noise ratio on any discrete source in the total mosaic areas—before subtraction or projection—was less than some threshold $X$. In our final analysis we have adopted $X = 50$, eliminating 9 out of 263 CBI pointings. To check this we analyzed the data with a more stringent SNR cutoff of $X = 25$ and found no significant change in the power spectrum.

3.3. Power Spectrum Analysis

The dataset combines very deep pointings (and thus low noise levels) on a few small areas with substantially shallower coverage of wider areas. The signal at low-$\ell$ is stronger and the features in the power spectrum are expected to be more distinct, so we seek to use the wider coverage for maximum $\ell$ resolution on large angular scales. Most of the statistical weight in the dataset at small scales comes from the deep integrations, and since the sky coverage of these is quite limited the $\ell$ resolution is lower. In this regime the signal-to-noise ratio is lower and we seek to compensate by combining many Fourier modes. In order to present a single unified power spectrum which makes use of information from all the data over the full range of angular scales we adopt bins which are narrowest at low $\ell$ ($\delta\ell = 100$), and increase in steps towards a single high $\ell$ bin above $\ell \sim 2000$. The bin widths were chosen to yield maximum $\ell$ resolution while keeping typical bin-to-bin anti-correlations to less than $\sim 30\%$. We have chosen two distinct binnings of the data which we call the “even” and “odd” binnings. These binnings are not independent but are helpful in determining whether particular features are artifacts of the bin choice. Subsequent statistical analyses—including primary anisotropy parameter estimation and the $\sigma_8$ analysis of secondary anisotropy—employ only one binning (the “even” binning).

The updated CBI power spectrum is shown in Figure 4 and tabulated in Table 1. Results are presented in terms of bandpower ($\Delta T^2 = T^2_{\text{CMB}}(\ell + 1)C_\ell / 2\pi$), which is assumed to be flat within each bin; also shown are the values of the noise power spectrum $X_B$. This table presents both “even” and “odd” binnings of the CBI data. Window functions for the two binnings are presented in Figures 5 and 6. The procedures for calculating window functions and noise power spectra are defined by [Myers et al. 2003].

The possible detection of power in excess of the expected primary anisotropy at high-$\ell$ by Mason et al. (2003) has stirred considerable interest (e.g., Komatsu & Seltz 2002; Oh, Cooray, & Kamionkowski 2003; Subramanian, Seshadri, & Barrow 2003; Griffiths, Kunz, & Silk 2003), and the results we present in this paper improve the bandpower constraint. Binning all the 2000+2001 data above $\ell = 1960$ together, we find a bandpower of $355 \pm 103 \mu K^2$ (random error only). By way of comparison, the Mason et al. result, referenced to the current CBI calibration scale and noise correction, is $511 \pm 156 \mu K^2$; the new result is thus $25\%$ lower but within $\sim 1\sigma$ of the Mason et al. result, although the datasets are not independent. Table 2 presents the $\ell > 2000$ bandpower constraints from these and three other combinations of the full CBI dataset, all referenced to the current calibration scale and with our best noise variance estimates. For purposes of comparison this table shows only the random errors derived from the Fisher matrix at the best fit point (which includes couplings to other bins); in addition there is a common overall uncertainty of $48 \mu K^2$ from the discrete source correction.

In order to constrain the excess more accurately we have explicitly mapped the likelihood in the last bin, allowing for the following systematic errors in the analysis: uncertainty in the statistical source correction ($48 \mu K^2$); uncertainty in the thermal noise power spectrum ($20 \mu K^2$); and the $56 \mu K^2$ dispersion in the high-$\ell$ bandpower caused by the uncertainty in the bandpower of the neighboring bin. We determine confidence intervals on $\Delta T^2$ of $233-492\mu K^2 (68\%)$ and $110-630\mu K^2 (95\%)$. From the 68% confidence limit we can state our result as $355^{+137}_{-122} \mu K^2$. This result is consistent with but lower than that derived from the earlier analysis of CBI deep fields; and while the detection of power remains statistically significant, the detection of power in excess of the band-averaged power expected from the primary anisotropy ($\sim 80-90 \mu K^2$) is marginal. A slightly more significant detection is obtained by combining CBI, ACBAR, and BIMA data, and we present the results of such an analysis in § 4.1.

We have also computed the value of the high $\ell$ bin for several statistically independent splits of the total (2000+2001 deep plus mosaic) dataset. In all cases the power spectra are consistent. The most sensitive of these splits was a division of the dataset into two halves by field (02h plus 08h, and 14h plus 20h), in which case the high $\ell$ bandpowers were within $1.3\sigma$ of each other and consistent with the best value of $355 \mu K^2$.

4. INTERPRETATION

4.1. Basic Cosmological Parameters from the Primary Anisotropy

We use a modified version of the publicly available Markov Chain Monte Carlo (MCMC) package COSMOMC (Lewis & Bridle 2002) to obtain cosmological parameter fits to the CMB data. The code has been tested extensively against our fixed resolution grid based method, which we applied to the first year CBI data in the papers by Sievers et al. (2003) and Bond et al. (2004). Bond, Contaldi & Pogosyan (2003) show that the agreement between the two methods is good when identical data and priors are used. Advantages of the MCMC method include a reduced number of model spectrum computations required to accurately sample the multi–dimensional likelihood surfaces and automatic rather than built-in adaptivity of the parameter sets sampled.

Our typical run involves the calculation of 8 Markov chains over the following basic set of cosmological parameters: $\omega_\mathrm{b} \equiv \Omega_\mathrm{b} h^2$, the physical density of baryons; $\omega_\mathrm{c} \equiv \Omega_\mathrm{c} h^2$, the physical density of cold dark matter; $\Omega_\Lambda$, the energy density in the form of a cosmological constant; $n_s$, the spectral index of the scalar perturbations; $A_s$, an amplitude parameter for the scalar perturbations; and $\tau_C$, the optical depth to the surface of last scattering.

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14 The error quoted from the Fisher matrix at the best fit point, $\pm 103 \mu K^2$, includes this contribution, and it is only added in separately here because the likelihood mapping procedure keeps other bins fixed.

15 http://cosmologist.info/cosmomc/
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Fig. 4.— The 2000+2001 CBI Spectrum. The “even” binning is shown in red and the “odd” binning in light blue. Orange stars indicate the thermal noise variance; green triangles indicate the statistical source correction which has been subtracted from the power spectrum. The solid black line is the WMAP ΛCDM model with a pure power-law primordial spectrum (model spectrum is file wmap_lcdm_pl_model_yr1_v1.txt, available on the WMAP website http://lambda.gsfc.nasa.gov).

Table 1

| Bin     | Even Binning | Odd Binning |
|---------|--------------|-------------|
| ℓ-Range | Bandpower (μK²) | X_B (μK²) | ℓ-Range | Bandpower (μK²) | X_B (μK²) |
| 0–300   | 7091 ± 1882  | 3176        | 0–250  | 7860 ± 4151  | 8196        |
| 300–400 | 2059 ± 717   | 489         | 250–350| 4727 ± 1157  | 796         |
| 400–500 | 1688 ± 457   | 377         | 350–450| 961 ± 454    | 397         |
| 500–600 | 2415 ± 545   | 449         | 450–550| 2369 ± 504   | 390         |
| 600–700 | 1562 ± 391   | 423         | 550–650| 2081 ± 480   | 455         |
| 700–800 | 2201 ± 490   | 577         | 650–750| 1494 ± 400   | 469         |
| 800–900 | 2056 ± 436   | 631         | 750–850| 2346 ± 476   | 582         |
| 900–1000| 1138 ± 396   | 743         | 850–950| 2117 ± 482   | 770         |
| 1000–1140| 797 ± 275  | 674         | 950–1070| 305 ± 239    | 626         |
| 1140–1280| 780 ± 263  | 726         | 1070–1210| 1266 ± 300   | 694         |
| 1280–1420| 586 ± 278  | 933         | 1210–1350| 423 ± 269    | 820         |
| 1420–1560| 1166 ± 361 | 1064        | 1350–1490| 1020 ± 333   | 1040        |
| 1560–1700| 196 ± 223   | 941         | 1490–1660| 714 ± 279    | 960         |
| 1760–1960| −4 ± 263   | 386         | 1660–1860| −98 ± 201    | 834         |
| 1960+   | 355 ± 103   | 2184        | 1860–2060| 243 ± 229    | 457         |

Each chain is run on a separate 2-CPU node of the CIT A McKenzie Beowulf cluster for a typical run-time of approximately 9 hours when the proposal densities are estimated using a previously computed covariance matrix for the same set of parameters. The chains are run until the largest eigenvalue returned by the Gelman-Rubin convergence test reaches 0.1. We run the chains at a temperature setting of 1.2 in order to sample more densely the tails of the distributions; the samples are adjusted for this when analyzing the chains.

All of our parameter analysis imposes a “weak-h” prior comprising limits on the Hubble parameter (45 km s⁻¹ Mpc⁻¹ < H₀ < 90 km s⁻¹ Mpc⁻¹) and the age of the universe (t₀ > 10 Gyr). We primarily consider flat models (Ω_tot = 1) in this work, and unless otherwise stated a flat prior has been imposed. Within the context of flat models the weak-h prior influences the results very little. We include all of the bandpowers shown...
Fig. 5.— The 2000+2001 CBI window functions (“even” binning).

Fig. 6.— The 2000+2001 CBI window functions (“odd” binning).

| Dataset             | Bandpower ($\mu$K²) |
|---------------------|---------------------|
| 2000+2001 Deep+Mosaic | 355 ± 103           |
| 2000+2001 Deep      | 393 ± 134           |
| 2000 Deep           | 514 ± 158           |
| 2000 Deep+Mosaic    | 457 ± 122           |
| 2000 Mosaic         | 206 ± 178           |

**Table 2: Comparison of high-\(\ell\) results for different subsets of CBI data**

*Note.* — Results for the high-\(\ell\) bin on the WMAP power scale, with current noise correction applied. For further discussion see text.

In Table 2, we compare the constraints obtained when including only the WMAP measurements with those obtained when also including the new CBI bandpowers and a compilation of “ALL” present CMB data ¹⁶ for the weak-\(h\) prior case. We include both total intensity and TE spectra from WMAP in our analysis. For Boomerang and ACBAR, recalibrations and their uncertainties were applied using the power spectrum based method described in Bond, Contaldi & Pogosyan (2003), which obtains maximum likelihood calibration parameters as a by-product of the optimal, combined power spectrum calculation with multiple experiment results. Detailed results for the fits are summarized in Table 1 of Bond, Contaldi & Pogosyan (2003). We note that this method gives calibrations in agreement with

¹⁶ WMAP (Bennett et al. 2003); VSA (Dickinson et al. 2003); DASI (Halverson et al. 2002); ACBAR (Kuo et al. 2004); MAXIMA (Lee et al. 2001); and BOOMERANG (Ruhl et al. 2003).

In Table 2, except for the highest and lowest \(\ell\) band. The highest band is excluded due to possible contamination by secondary anisotropies; the first band is poorly constrained and provides no useful information.
TABLE 3
Cosmological Constraints from the "WMAP only", "CBI + WMAP", and "CBI + All" for an assumed $\Omega_{\text{tot}} = 1.0$.

| Parameter | WMAP only | CBI + WMAP | CBI + ALL |
|-----------|-----------|------------|-----------|
| $\Omega_b h^2$ | 0.0242$^{+0.0016}_{-0.0016}$ | 0.0225$^{+0.0011}_{-0.0011}$ | 0.0225$^{+0.0009}_{-0.0009}$ |
| $\Omega_c h^2$ | 0.123$^{+0.017}_{-0.018}$ | 0.107$^{+0.012}_{-0.013}$ | 0.111$^{+0.010}_{-0.009}$ |
| $\Omega_{\Lambda}$ | 0.71$^{+0.08}_{-0.08}$ | 0.75$^{+0.05}_{-0.05}$ | 0.74$^{+0.05}_{-0.05}$ |
| $\tau_C$ | 0.18$^{+0.03}_{-0.06}$ | 0.13$^{+0.02}_{-0.04}$ | 0.11$^{+0.02}_{-0.04}$ |
| $n_s$ | 1.01$^{+0.05}_{-0.05}$ | 0.96$^{+0.03}_{-0.03}$ | 0.95$^{+0.02}_{-0.02}$ |
| $10^{10} A_S$ | 27.7$^{+5.5}_{-5.1}$ | 22.2$^{+2.8}_{-2.9}$ | 21.9$^{+2.4}_{-2.3}$ |
| $H_0$ | 72.1$^{+6.4}_{-3.1}$ | 73.4$^{+4.6}_{-4.7}$ | 71.9$^{+5.9}_{-3.9}$ |
| Age (Gyr) | 13.3$^{+0.3}_{-0.3}$ | 13.7$^{+0.2}_{-0.3}$ | 13.7$^{+0.2}_{-0.3}$ |
| $\Omega_m$ | 0.29$^{+0.08}_{-0.05}$ | 0.25$^{+0.05}_{-0.05}$ | 0.26$^{+0.04}_{-0.05}$ |
| $\sigma_8$ | 0.96$^{+0.14}_{-0.15}$ | 0.78$^{+0.08}_{-0.08}$ | 0.80$^{+0.06}_{-0.06}$ |

Note. — We included weak external priors on the Hubble parameter ($45 \text{ km s}^{-1} \text{ Mpc}^{-1} < H_0 < 90 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and the age of the universe ($t_0 > 10 \text{ Gyr}$). The flatness prior has the strongest effect on the parameters by breaking the geometrical degeneracy and allowing us to derive tight constraints on $H_0$ and $\Omega_m$.

TABLE 4
Cosmological Constraints from "CBI + All" data plus LSS constraints

| Parameter | CBI + ALL + 2df | CBI + ALL + LSS |
|-----------|-----------------|-----------------|
| $\Omega_b h^2$ | 0.0224$^{+0.0008}_{-0.0008}$ | 0.0225$^{+0.0009}_{-0.0009}$ |
| $\Omega_c h^2$ | 0.117$^{+0.007}_{-0.006}$ | 0.118$^{+0.007}_{-0.007}$ |
| $\Omega_{\Lambda}$ | 0.71$^{+0.03}_{-0.03}$ | 0.71$^{+0.03}_{-0.04}$ |
| $\tau_C$ | 0.10$^{+0.02}_{-0.02}$ | 0.11$^{+0.02}_{-0.02}$ |
| $n_s$ | 0.95$^{+0.02}_{-0.02}$ | 0.95$^{+0.02}_{-0.02}$ |
| $10^{10} A_S$ | 21.6$^{+2.1}_{-2.0}$ | 22.3$^{+2.1}_{-2.2}$ |
| $H_0$ | 69.6$^{+2.5}_{-2.5}$ | 69.6$^{+2.8}_{-2.9}$ |
| Age (Gyr) | 13.7$^{+0.2}_{-0.2}$ | 13.7$^{+0.2}_{-0.2}$ |
| $\Omega_m$ | 0.29$^{+0.03}_{-0.03}$ | 0.29$^{+0.04}_{-0.03}$ |
| $\sigma_8$ | 0.83$^{+0.05}_{-0.05}$ | 0.83$^{+0.05}_{-0.05}$ |

Note. — The priors are the same as in Table 3. In addition we have added a LSS prior in the form of constraints on the combination $\sigma_8(\Omega_0)^{0.56}$ and the shape parameter $\Gamma_{\text{eff}}$, or using the 2dGfRS power spectrum results.

TABLE 5
Cosmological Constraints including a Running Spectral Index

| Parameter | WMAP + LSS | CBI + WMAP + LSS | CBI + ALL + LSS |
|-----------|------------|-----------------|-----------------|
| $\Omega_b h^2$ | 0.0240$^{+0.0025}_{-0.0025}$ | 0.0222$^{+0.0019}_{-0.0017}$ | 0.0218$^{+0.0013}_{-0.0014}$ |
| $\Omega_c h^2$ | 0.116$^{+0.013}_{-0.013}$ | 0.120$^{+0.013}_{-0.012}$ | 0.124$^{+0.011}_{-0.011}$ |
| $\Omega_{\Lambda}$ | 0.74$^{+0.08}_{-0.08}$ | 0.69$^{+0.08}_{-0.08}$ | 0.67$^{+0.07}_{-0.07}$ |
| $\tau_C$ | 0.32$^{+0.08}_{-0.07}$ | 0.24$^{+0.05}_{-0.05}$ | 0.21$^{+0.04}_{-0.04}$ |
| $n_s$ | 0.00$^{+0.08}_{-0.06}$ | 0.09$^{+0.06}_{-0.06}$ | 0.08$^{+0.05}_{-0.05}$ |
| $\alpha_s$ | -0.061$^{+0.037}_{-0.037}$ | -0.085$^{+0.031}_{-0.030}$ | -0.087$^{+0.028}_{-0.028}$ |
| $10^{10} A_S$ | 36.1$^{+10.0}_{-10.0}$ | 29.4$^{+7.1}_{-6.4}$ | 28.1$^{+5.3}_{-5.2}$ |
| $H_0$ | 75.7$^{+6.4}_{-5.1}$ | 68.9$^{+4.4}_{-5.0}$ | 67.0$^{+4.0}_{-5.2}$ |
| Age (Gyr) | 13.2$^{+0.5}_{-0.4}$ | 13.7$^{+0.3}_{-0.4}$ | 13.8$^{+0.2}_{-0.3}$ |
| $\Omega_m$ | 0.26$^{+0.08}_{-0.08}$ | 0.31$^{+0.08}_{-0.07}$ | 0.33$^{+0.07}_{-0.07}$ |
| $\sigma_8$ | 1.4$^{+0.1}_{-0.1}$ | 0.92$^{+0.08}_{-0.08}$ | 0.91$^{+0.07}_{-0.07}$ |

Note. — Cosmological Constraints including a running spectral index $\alpha_s = d\alpha_s/d\ln k$ obtained from the CMB and our conservative LSS prior. We find all combinations prefer a negative value for $\alpha_s$ with significances above the 2σ level for the combinations CBI + WMAP and CBI + ALL.
those obtained from the WMAP/CBI cross-calibration via Jupiter, and a map-based comparison of Boomerang and
WMAP gives a very similar recalibration and error for Boomerang to those used here (E. Hivon 2003, pri-
ivate communication). The original reported calibrations of DASI, Maxima, and VSA were used. Although the
optimal spectrum procedure also produces best fit values with errors for the beam parameters of each experiment,
we have used the reported beams and their uncertainties in each case for the parameter estimates given in this
paper.

The “CBI + ALL” parameters and their errors in Table 3 can be compared with the “March 2003” values
given in Table 5 of Bond, Contaldi & Pogosyan (2003). These were evaluated using the MCMC method with the
calibrations for CBI used here, but no recalibration with decreased errors for Boomerang and ACBAR. The results
are quite similar.

Our main results for the flat plus weak-h case are summarized in Figure 4 showing marginalized one-
dimensional distributions for the basic six parameters to-
gether with three other derived parameters: the Hubble parameter $H_0$ in units of km s$^{-1}$Mpc$^{-1}$, the total age $t_0$ of the universe in Gyr, and the total energy density of matter $\Omega_m$ in units of the critical energy density. We show three curves for each parameter corresponding to the “WMAP only”, “CBI + WMAP”, and “CBI + ALL” cases. They show how the inclusion of high-$\ell$ bandpowers is crucial to excluding significant tails in the distributions that remain because of the limited $\ell$-range of the WMAP results.

Of particular significance is the effect of including the CBI band powers on the correlated trio $n_s$, $\tau_C$, and $\omega_b$. The “WMAP only” case shows long tails towards high values for the three parameters which are only excluded when the CBI or the “CBI + ALL” combinations are included. We do not include a cutoff on the value of $\tau_C$ as was done by Spergel et al. (2003). Their cutoff has a rather strong effect also on the tails of the distribution in $n_s$ and $\omega_b$. We rely only on the addition of extra data. This can be seen in Figure 8 which shows the marginalized distribution in the $n_s$-$\omega_b$ plane for the “WMAP only”, “CBI + WMAP”, and “CBI + ALL” cases.

The results of the CMB+LSS parameter analyses are presented in Table 4. We consider two cases to illustrate the impact of large scale structure observations on the cosmological parameter distributions: (i) the Two Degree Galaxy Redshift Survey (2dFGRS) results of Percival et al. (2003), and (ii) a more conservative LSS prior that straddles most weak lensing and cluster results for the amplitude $s_8$ (Bond, Contaldi & Pogosyan 2003, and references therein), but a weaker version of the 2dFGRS and SDSS (Tegmark et al. 2004) results for the shape of the matter power spectrum than the direct application of the 2dFGRS data gives. Explicitly the prior on the amplitude is $\sigma_8 n_m^{0.56} = 0.47 \pm 0.02, -0.11$ distributed as a Gaussian (first error) convolved with a uniform (top-hat) distribution (second error), both in $\ln(\sigma_8 n_m^{0.56})$. The prior on the effective shape parameter is $\Gamma_{\text{eff}} = 0.21 \pm 0.03, -0.08$. Again the small-scale CMB results substantially improve the constraints in comparison to what is obtained with only the larger angular scale CMB data. Figure 11 shows the $\tau_C-\sigma_8$ plane, illustrating the exclusion of the high values along the line of near-degeneracy which results when CBI and ACBAR data are added to WMAP+LSS.

All of the above analysis assumes $\Omega_{tot} = 1$. It is well known that revoking this assumption yields substantially worse parameter estimates when CMB data are analyzed in isolation (e.g., Efstathiou & Bond 1994; Spergel et al. 2003; Bond, Contaldi & Pogosyan 2003; Tegmark et al. 2004, and references therein). The main parameters affected are $\Omega_m$, $\Omega_L$, and $H_0$; typically low Hubble parameters and larger ages $t_0$ are favored in this case. For CBI+ALL we find a factor of $2 - 3$ degradation in the precision of the constraints on $\Omega_L$ and $\Omega_m$. The best value for the curvature in this scenario is $\Omega_k = -0.052^{+0.037}_{-0.036}$. Results on $\Omega_b h^2$, $\Omega_c h^2$, $\tau_C$, and $n_s$ are not significantly affected. Thus CMB data alone yield a robust determination of the non-baryonic dark matter density, and a determination of the total baryon content of the universe consistent with those derived from deuterium absorption measurements (Kirkman et al. 2003), as well as limits from other light-element methods (e.g. Bania, Rood, & Balser 2002, and references therein).

4.2. Running of the scalar spectral index

Inflation models rarely give pure power laws, with $n_s(k)$ constant, even over the limited ranges of wavevector $k$ that the CMB+LSS data probe. In most models, the breaking is rather gentle, with small corrections having been entertained since the early eighties. Much more radical forms for $n_s(k)$ are possible. The gentle form most often adopted involves a running index described by a logarithmic correction:

$$n_s(k) = \frac{dn}{dk} = n_s(k_0) + \alpha_s \ln \left( \frac{k}{k_0} \right),$$

where $\alpha_s = dn_s/d\ln k$. Here $P(k)$ is the primordial post-inflation power spectrum for scalar curvature perturba-
tions and $k_0$ is a pivoting scale above which $n_s(k)$ is expanded. The effect is that for negative $\alpha_s$ the slope is flattened below $k_0$ and steepened above $k_0$, i.e., power is suppressed on scales both greater than and less than $k_0$.

There has been much focus recently on whether the data require such a running index, motivated by the incorporation of Lyman-α absorption data in the WMAP analyses of Spergel et al. (2003) and explored further by, e.g., Bridle et al. (2003), Bastero-Gil, Freese, & Mersini-Houghton (2003), and Mukherjee & Wang (2003). Bond, Contaldi & Pogosyan (2003) have shown that the CMB data marginally favor a non–vanishing negative running term. The effect is driven by the requirement to reconcile an apparent lack of power on the largest scales observed by WMAP with observations on arcminute scales such as those reported in this work. In this regard, CBI adds a significant lever arm beyond WMAP to higher $\ell$, and the CBI/WMAP cross-calibration presented here therefore helps to furt

[17] This explains the mechanism for degraded estimates of other parameters: increased uncertainty in $H_0$ coupled with fixed values of $\Omega_b h^2$ and $\Omega_c h^2$ leads to the increased uncertainty in $\Omega_m$, also causing an increased uncertainty in $\Omega_L$. 

Extended Mosaic Observations with the CBI

Fig. 7.— Marginalized likelihood curves for a range of individual cosmological parameters, each shown for three CMB datasets: “WMAP only” (blue/dotted); “CBI + WMAP” (red/dashed); and “CBI + ALL” (green/solid). In all cases a flat plus weak-$\alpha$ prior is used.

$\alpha_s = dn_s/d\ln k$, with the LSS prior applied for the three cases. We have not limited $\alpha_s$ by any theoretical prior prejudices, but have just allowed it to vary over the range $-0.2 < \alpha_s < 0.2$. The final 1-d marginalized distributions for a number of combinations of data and priors are shown in Figure 10. Analyzing the WMAP data alone, we find $\alpha_s = -0.077^{+0.044}_{-0.086}$. Including LSS constraints reduces the uncertainties somewhat, yielding $\alpha_s = -0.085^{+0.031}_{-0.030}$. Estimates for the optical depth $\tau_C$ and linear amplitude $\sigma_8$ are generally higher and those for the spectral index at the chosen pivot scale $n_s(k_0 = 0.05\text{Mpc}^{-1})$ are lowered. Figure 11 shows the $\sigma_8-\alpha_s$ marginalized distribution, for three data combinations. We note that $\alpha_s$ is significantly correlated with other cosmological parameters, in particular with $n_s(k_0)$, $\tau_C$, and $\sigma_8$, so applying further priors to $\alpha_s$ motivated by inflation theory would affect these results, but it is useful to see what the data imply without such impositions.

4.3. Constraints on $\sigma_8$ from the High $\ell$ Excess Power

Intrinsic CMB anisotropies on small angular scales are expected to be significantly suppressed by photon viscosity and the finite thickness of the last scattering region. Data from the CBI were the first to show this damping tail by mapping a drop of more than a factor of ten in power between $\ell = 400$ and $\ell = 2000$. This damping has subsequently also been observed by both ACBAR and the VSA.

A number of effects are expected to produce secondary anisotropies which peak at high $\ell$. These include the Vishniac effect (Vishniac 1987), gravitational lensing (Blanchard & Schneider 1987), patchy reionization (Aghanim et al. 1996), the Sunyaev-Zeldovich effect in galaxy clusters at moderate redshifts $z \lesssim 5$ (e.g., Bond & Myers 1996, Cooray 2001), and Sunyaev-
Zeldovich fluctuations from the first stars at high redshifts \((z \sim 20)\) (Oh, Cooray, & Kamionkowski 2003).

We previously considered the possible implications of the SZE in galaxy clusters at moderate redshifts (Bond et al. 2004), and here we discuss this effect in the light of the new results presented above. We have estimated \(\sigma_8\) by fitting jointly for a primary CMB spectrum and template SZE spectra. The technique is detailed in Goldstein et al. (2003) where a combination of high-\(\ell\) bandpowers (Mason et al. 2003; Kuo et al. 2004; Dawson et al. 2002) was used in a two parameter fit of “primary” and “secondary” spectrum amplitude parameters. The SZE contribution to the power spectrum is highly dependent on the amplitude of the mass fluctuations, characterised by \(\sigma_8\) (e.g., Komatsu & Kitavama 1999; Seljak et al. 2003; Bond et al. 2004). Since the SZE power spectrum has a weak dependence on \(\Omega_0\) in addition to a strong \(\sigma_8\) dependence, it is useful to use an amplitude parameter \(\sigma_{SZ}^8\) to describe the scaling of the secondary SZE power spectrum. Assuming that the power spectrum \(C_{\ell}^{SZ}\) scales as \((\Omega_0 h)^2\sigma_{SZ}^8\), we define \(\sigma_{SZ}^8 \equiv (\Omega_0 h/0.035)^2/\sigma_8\). It should be noted that secondary anisotropies, unlike intrinsic anisotropies, are not expected to have a Gaussian distribution. Although the detections in these bands are marginal, the strong dependence of the SZE power spectrum on the linear amplitude of the matter power spectrum already implies some constraints on the value of \(\sigma_8\). The primary spectrum amplitude parameter encompasses the linear amplitude of perturbations as well as the effects of \(n_s\) and \(\tau_C\) on the expected high-\(\ell\) bandpower. Goldstein et al. (2003) present an extensive discussion of the fitting procedure.

The method approximates the effect of the non-Gaussian secondary anisotropy power spectra by multiplying the expected sample variance in each band by a factor \(f_{NG}\) of between 1 and 4. The bin covariances...
are increased by the same factor. While this approach is simplistic, it is supported by numerical simulations which have shown the variance of simulated power spectra to be greater than the Gaussian case by a factor of approximately 3 for the ℓ-range considered (Cooray 2001; White, Hernquist, & Springel 2002; Komatsu & Seljak 2002; Zhang, Pen, & Wang 2002). Future work may require a more accurate treatment of non-Gaussianity. However we note that even large changes (fNG = 1–4) have a minimal impact on the results. There are also theoretical uncertainties of a factor of ∼2 in the theoretical SZE power spectrum predictions. These theoretical uncertainties translate into ∼10% in σ8 and are also a limiting factor.

For this work we used the last two bands of the power spectrum in the “even” binning of Table 1 for the CBI results, the last three bands of the ACBAR results (Kuo et al. 2004), and the two band result from the BIMA array (Dawson et al. 2002). As a template primary spectrum we used the best-fit ΛCDM model with power law initial spectrum to the WMAP data18. We assign a Gaussian prior with an rms of 10% around the best-fit amplitude for the primary spectrum while keeping all other parameters fixed, and marginalize over the primary amplitude parameter when deriving the final confidence intervals for σ8SZ. We have also included, for the CBI bandpowers, uncertainties due to the residual discrete source and thermal noise corrections. By considering the χ2 of the CBI+ACBAR+BIMA to a model comprising primary anisotropy and zero SZE signal, and with fNG = 1, we associate a statistical significance of 98% with the detection of an SZE foreground at ℓ > 2000. The BIMA+CBI data alone give a 92% significance.

In Table 4 we show the constraints on σ8SZ obtained from the fits to CBI + BIMA, and to CBI + BIMA + ACBAR. The distributions have long tails extending to low values of σ8SZ and are effectively unbounded from below (see Figure 12). In the context of our calculation this is entirely due to Gaussian statistics and the results of changing variables to bandpower1/7 (in effect). We therefore define the confidence intervals as centered around the maximum in the distribution with the 1-σ bounds given by a drop of a factor of e−1/2 on either side.

We note that the results we derive for σ8SZ are rather similar to those obtained using the one-year deep CBI field in conjunction with BIMA and ACBAR, as reported by Goldstein et al. (2003). We have repeated this analysis of the CBI one-year deep field results using the cross-calibration with WMAP, and find similar results. This is because the deep field component of our combined two-year data dominates the high ℓ power, and this is not changed much when the extra deep field 2001 data are added. What is important to note is that the much larger spatial coverage afforded by the full mosaic dataset (and thereby lesser sample variance) does not much diminish the amplitude of σ8SZ.

5. CONCLUSIONS

The CBI power spectrum is compared with WMAP and ACBAR results in Figure 13. These results, together with those from a host of other ground- and balloon-based experiments in recent years, are consistent with the key predictions of structure formation and inflationary theories: The universe is close to flat; the initial spectrum of perturbations is nearly scale invariant; oscillations and damping in the power spectrum evince the expected signatures of sub-horizon scale causal processes; initial conditions are Gaussian, and are consistent with adiabatic fluctuations; and the magnitude of fluctuations from the largest scales down to galaxy cluster scales is consistent with what is needed to produce locally observed structures through gravitational collapse. For discussion of these points see Bond et al. (2002), Peiris et al. (2003), and references therein. The concordance of observational results with theoretical expectations has permitted cosmological parameters to be determined with precision. In this work we obtain: Ωm h2 = 0.0225±0.0009, Ωb h2 = 0.111±0.009, ΩΛ = 0.74±0.05, τC = 0.113±0.02, nS = 0.95±0.02, t0 = 13.7±0.2 Gyr, and Ωm = 0.26±0.05 from a selection of current primary anisotropy data including CBI, WMAP, ACBAR, and Boomerang, and using the flat plus weak-h prior (see Table 8). Similar results are obtained when large-scale structure priors are incorporated (Table 4). As discussed in § 4 a flat prior (i.e., assumption that Ωtot = 1) is imposed on most of our parameter analysis; while supported by observational data this does impose a strong constraint, and some parameter estimates would be less accurate without it. A marginal detection of a running scalar spectral index remains, and is consistent with that presented by Spergel et al. (2003).

As discussed in § 4 the addition of CMB data from 600 < ℓ < 2000 significantly improves constraints on

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18 http://lambda.gsfc.nasa.gov
**Fig. 13.** — The CBI+WMAP+ACBAR Spectrum. The solid black line is the WMAP ΛCDM model with a pure power-law primordial spectrum (wmap_lcdm_pl_model_v1.txt). The highest-ℓ ACBAR point has been displaced slightly to lower ℓ for clarity.

**TABLE 6**

| $f_{NG}$ | $\sigma^8_{SZ}$ (CBI + BIMA) | $\sigma^8_{SZ}$ (CBI + BIMA + ACBAR) |
|----------|-----------------------------|--------------------------------------|
| 1        | $0.96^{+0.06}_{-0.07}$ 0.96  | $0.98^{+0.06}_{-0.07}$ $0.98^{+0.07}_{-0.07}$ |
| 2        | $0.96^{+0.07}_{-0.08}$ 0.96  | $0.98^{+0.06}_{-0.07}$ $0.98^{+0.07}_{-0.07}$ |
| 3        | $0.96^{+0.07}_{-0.08}$ 0.96  | $0.98^{+0.06}_{-0.07}$ $0.98^{+0.07}_{-0.07}$ |
| 4        | $0.96^{+0.07}_{-0.08}$ 0.96  | $0.98^{+0.06}_{-0.07}$ $0.98^{+0.07}_{-0.07}$ |

**Note.** — $\sigma^8_{SZ}$ values derived from the marginalized distributions obtained by fitting an SZE spectrum to the high-ℓ CMB data. The value for $f_{NG}$ is the factor used in rescaling the sample variance for each band (and inter-band correlations) to approximate varying degrees of non-Gaussianity. We find that the confidence limits do not depend strongly on the assumed $f_{NG}$.

$\Omega_b h^2$, $n_s$, the amplitude of the primary anisotropies, the age of the universe, and $\tau_C$ relative to what is obtained with only large-scale CMB data (see Figure 7). In the absence of a restrictive $\tau_C$ prior the $\ell < 600$ data leave significant degeneracies which are broken by the higher-ℓ experiments (see Figures 8 and 9). We note that the improvement between the “CBI+WMAP” and “CBI+ALL” cases comes primarily from the addition of the Boomerang data. Improvements are also seen in analyses which allow a running scalar spectral index (Figure 11). The tight constraint on the baryon density, $\Omega_b h^2 = 0.0225^{+0.0009}_{-0.0009}$ compares favorably with observationally determined BBN values of $\Omega_b h^2 = 0.0214 \pm 0.0020$ (Kirkman et al. 2003). We have also obtained an accurate measurement of $n_s$ from the CMB data only, $n_s = 0.95 \pm 0.02$. These results are robust with respect to prior assumptions, such as flatness, imposed on the analysis. By way of comparison the WMAP-only values for these parameters are $\Omega_b h^2 = 0.0243 \pm 0.0016$ and $n_s = 1.01 \pm 0.05$. The breaking of these degeneracies largely relies on the ratio of power levels on small angular scales to those on large angular scales, so the precision of these results has benefited from the accurate cross-calibration with WMAP. The CBI data also favor a negative running scalar spectral index $\alpha_s = -0.087 \pm 0.028$ (CBI+ALL+LSS), consistent with the results from WMAP combined with LSS constraints.

In Figure 14 we show the same data as plotted in Figure 13, now on a log-log plot and with additional curves which show the expected level of SZE power for the two sets of simulations discussed by Bond et al. (2004). Note that the fortuitous “agreement” between the CBI and ACBAR power levels at $\ell > 2000$ is not expected if the power has a significant component due to the Sunyaev-Zel’dovich Effect because of the different observing fre-
Fig. 14.— The CBI+WMAP+ACBAR Spectrum + high $\ell$ points from BIMA. The curves at high $\ell$ show the levels of SZ power expected in representative models using moving mesh hydrodynamics simulations (dotted) and smooth particle hydrodynamics (dashed) simulations (see text). The green and pink curves correspond to 30 GHz and 150 GHz, respectively. In these simulations $\sigma_{\text{SZ}}^8 = 0.98$, which also fits well the WMAP and CBI observations at lower $\ell$ for the case of a running spectral index (see Table 5). The highest-$\ell$ ACBAR point has been displaced slightly to lower $\ell$ for clarity.

quantities. Nevertheless, given the uncertainties in these two measurements, it can be seen that the models span a range of power at high $\ell$ which fits both the CBI and ACBAR observations.

The detection of power at $\ell > 2000$ is consistent with the results presented by Mason et al. (2003), although somewhat lower. We find a bandpower $355^{+137}_{-122} \mu K^2$ (68% confidence, including systematic contributions). By combining this result with high-$\ell$ results from BIMA and ACBAR we detect power in excess of that expected from primary anisotropy at 98% confidence. This result includes a marginalization over expected primary anisotropy power levels. Assuming the signal in excess of expected primary anisotropy is due to a secondary SZ foreground we determine $\sigma_{\text{SZ}}^8 = 0.96^{+0.06}_{-0.07}$ (68%). The lower confidence level of the detection of an excess, and also the smaller values of $\sigma_{\text{SZ}}^8$, are chiefly due to the lower high-$\ell$ bandpower we obtain and the inclusion of the uncertainty in the primary anisotropy bandpower at $\ell > 2000$. The strong dependence of the observable power on $\sigma_8$ gives rise to firm upper limits on $\sigma_8$ but a tail to low values (Figure 12). It should be borne in mind that there are systematic uncertainties in the theoretical prediction of the power spectrum due to secondary SZ anisotropies which correspond to a 10% systematic uncertainty in $\sigma_8$.

An appreciable fraction of CBI data were rejected by vetoing NVSS sources, and furthermore the uncertainty in the power level of the source population remaining after the NVSS veto is a limiting factor at $\ell > 2000$. In late 2004 a sensitive, wideband continuum receiver will be commissioned on the Green Bank Telescope (GBT) to deal with both of these issues. This will result in a more sensitive determination of the total intensity power spectrum at all $\ell$ covered by the CBI. Since the end of the observations reported here, the CBI was upgraded and dedicated to full-time polarization observations.

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