COSMOLOGICAL PARAMETER EXTRACTION FROM THE FIRST SEASON OF OBSERVATIONS WITH THE DEGREE ANGULAR SCALE INTERFEROMETER

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ABSTRACT

The Degree Angular Scale Interferometer (DASI) has measured the power spectrum of the cosmic microwave background anisotropy over the range of spherical harmonic multipoles $100 < l < 900$. We compare these data, in combination with the COBE DMR results, to a seven-dimensional grid of adiabatic cold dark matter (CDM) models. Adopting the priors $h > 0.45$ and $0.0 < \tau < 0.4$, we find that the total density of the universe $\Omega_{\text{tot}} = 1.04 \pm 0.06$ and the spectral index of the initial scalar fluctuations $n_s = 1.01 \pm 0.08$ in accordance with the predictions of inflationary theory. In addition, we find that the physical density of baryons $\Omega_b h^2 = 0.027^{+0.004}_{-0.003}$ and the physical density of cold dark matter $\Omega_{\text{cdm}} h^2 = 0.14 \pm 0.04$. This value of $\Omega_b h^2$ is consistent with that derived from measurements of the primeval deuterium abundance combined with big bang nucleosynthesis theory. Using the result of the Hubble Space Telescope (HST) Key Project, $h = 0.72 \pm 0.08$, we find that $\Omega_{\text{tot}} = 1.00 \pm 0.04$, the matter density $\Omega_m = 0.40 \pm 0.15$, and the vacuum energy density $\Omega_\Lambda = 0.60 \pm 0.15$. (All 68% confidence limits.)

Subject headings: cosmic microwave background — cosmology: observations — techniques: interferometric

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1. INTRODUCTION

The angular power spectrum of the cosmic microwave background (CMB) has much to teach us about the nature of the universe in which we live (Hu, Sugiyama, & Silk 1997). Measurements are improving rapidly (de Bernardis et al. 2000; Hanany et al. 2000; Padin et al. 2000), and for a wide variety of theoretical scenarios, the predicted spectra can be calculated accurately (Zaldarriaga & Seljak 2000). Comparison of the data and models, which is the subject of this paper, allows quantitative constraints to be placed on the parameters of the universe in which we find ourselves.

The Degree Angular Scale Interferometer (DASI), along with its sister instrument the Cosmic Background Imager (CBI; Padin et al. 2000) and the Very Small Array (VSA; Jones 1997), is one of several new compact interferometers specifically designed for observations of the CMB. This paper is the third in a set of three. Paper I (Leitch et al. 2002) gives a detailed description of the instrument, observations, and data calibration. Paper II (Halverson et al. 2002) focuses on the extraction of the angular power spectrum from the calibrated interferometric data and provides band-power estimates of the angular power spectrum of the CMB. In this paper, we combine the low-$l$ measurements made by the COBE Differential Microwave Radiometer (DMR) instrument (Bennett et al. 1996) with the new measurements from DASI to constrain the parameters of cosmological models.

The layout of this paper is as follows. The considerations which drive our selection of the model and parameter space to probe are detailed in § 2. In § 3, we review the method used to compare band-power data to theoretical spectra. The results of this comparison are described in § 4, and in § 5, we outline our conclusions.

2. MODELS, PARAMETERS, AND MODEL GRID CONSIDERATIONS

Following the discovery of the CMB and the realization that the universe went through a hot plasma epoch, it was proposed that adiabatic density perturbations in that plasma would lead to acoustic oscillations (Peebles & Yu 1970) and a series of harmonic peaks in the angular power spectrum (Doroshkevich, Zeldovich, & Sunyaev 1978). It was assumed that the initial fluctuations were scale invariant only because this is the simplest possible case. It was not until later that (New) Inflation was proposed (Guth & Pi 1982; Bardeen, Steinhardt, & Turner 1983; Hawking 1982; Starobinsky 1982)—an elegant cosmogenic mechanism which naturally produces such conditions. The simplest versions of this theory also make the firm prediction that the universe is exactly flat, i.e., has zero net spatial curvature.

Although Inflation sets the stage at the beginning of the plasma epoch, it has nothing to say about the contents of the universe. Over the last several decades, a wealth of evidence has accumulated for the existence of some form of gravitating matter which does not interact with ordinary baryonic material; the so-called cold dark matter (CDM). Conflicting theoretical expectations and experimental measurements led to the proposal that a third component is present—an intrinsic vacuum energy. This three-component model is the scenario we have chosen to consider.
The density required to produce zero net spatial curvature is referred to as the critical density $\rho_c = 3H_0^2/(8\pi G)$, where $H_0$ is the Hubble constant ($H_0 \equiv 100h$ km s$^{-1}$ Mpc$^{-1}$). It is convenient to measure the present day density of a component of the universe in units of $\rho_c$, denoting this $\Omega_i$: the density of baryonic matter $\Omega_b$, the density of CDM $\Omega_{\text{cdm}}$, and the equivalent density in vacuum energy $\Omega_{\Lambda}$. Thus, the density of matter is given by $\Omega_m \equiv \Omega_b + \Omega_{\text{cdm}}$ and the total density is given by $\Omega_{\text{tot}} \equiv \Omega_m + \Omega_{\Lambda}$. Since $\Omega_i = \rho_i/\rho_c$, note that $\Omega_b h^2$ is a physical density independent of the value of the Hubble constant.

To generate theoretical CMB anisotropy power spectra, we have used version 3.2 of the freely available CMBFAST program (Zaldarriaga & Seljak 2000). This is the most widely used code of its type, and versions 3 and greater can deal with open, flat, and closed universes. CMBFAST calculates how the initial power spectrum of density perturbations is modulated through the acoustic oscillations during the plasma phase, by the effects of recombination, and by reionization as the CMB photons stream through the universe to the present. The program sets up transfer functions, taking as input $\Omega_b$, $\Omega_{\text{cdm}}$, and $\Omega_{\Lambda}$, as well as $H_0$, the optical depth due to reionization ($\tau_i$), and some other parameters. It can then translate initial perturbation spectra into the mean angular power spectra of the CMB anisotropy which would be observed in such a universe today. Inflation predicts that the initial spectrum is a simple power law with slope close to, but not exactly, unity.

In any given comparison of data to a multidimensional model, we may have external information about the values of some or all of the parameters. This may come from theoretical prejudice or from other experimental results. It may also be that the data set in hand is unable to simultaneously constrain all of the possible model parameters to the precision which we desire. In such cases, we can choose to invoke our external knowledge and fold additional information about the preferred parameter values into the likelihood distribution. Often this occurs because a parameter which could potentially be free is fixed at a specific value (an implicit prior). Or we may multiply the likelihood distribution by some function which expresses the values of the parameters which we prefer (an explicit prior). The choice of measure, e.g., whether a variable is taken to be linear or logarithmic, is also an implicit prior, although such distinctions become less important as a variable becomes increasingly well constrained.

There is no a priori reason to suppose that the marginal likelihoods of the cosmological parameters are Gaussian. Thus, the curvature of the likelihood surface at the peak does not fully characterize the distribution. To set accurate constraints, it is therefore necessary to explore the complete likelihood space by testing the data against a large grid of models. If the introduction of priors is to be avoided, the grid must be expanded until one can be confident that it encompasses essentially all of the total likelihood.

Unfortunately, it turns out that even within the paradigm of adiabatic CDM models, the anisotropy power spectrum of the CMB does not fully constrain the parameters of the universe. For example, it is well known that $\Omega_m$ and $\Omega_{\Lambda}$ are highly degenerate. It is always necessary to invoke external information in any constraint-setting analysis. The clear articulation of these priors, both implicit and explicit, is critically important, as has previously been noted (Jaffe et al. 2001).

We have chosen to consider a seven-dimensional model space. The parameters which we include are the physical densities of baryonic matter ($\Omega_b h^2 \equiv \omega_b$) and CDM ($\Omega_{\text{cdm}} h^2 \equiv \omega_{\text{cdm}}$), as well as the spectral slope of the initial scalar fluctuations ($n_s$) and the overall normalization of the power spectrum as measured by the amplitude at the 10th multipole $C_{10} \equiv l(l+1)C_{10}/2\pi$. Noting that the degeneracy in the $(\Omega_m, \Omega_{\Lambda})$ plane is along a line of constant total density, we may opt to rotate the basis vectors by 45° and grid over the sum and difference of these parameters: $\Omega_m + \Omega_{\Lambda} = \Omega_{\text{tot}}$ and $\Omega_m - \Omega_{\Lambda} = \Omega_\Lambda$. This reduces the size of the model grid required to box in the region of significant likelihood. The 7th parameter is the optical depth due to reionization ($\tau_i$). Note that for each point in $(\Omega_\Lambda, \Omega_{\text{tot}}, \omega_b, \omega_{\text{cdm}})$ space there is an implied value of the Hubble constant ($h = [2(\omega_b + \omega_{\text{cdm}})/(\Omega_{\text{tot}} + \Omega_\Lambda)]^{1/2}$), so we can calculate the $(\Omega_b, \Omega_{\text{cdm}}, \Omega_\Lambda, h)$ values for input to CMBFAST.

We assume, as is the theoretical prejudice, that the contribution of tensor mode perturbations is very small (as compared to scalar) and ignore their effect (Lyth 1997). Tensor modes primarily contribute power at low $l$ numbers, so if a large fraction of the power seen by DMR was caused by this effect, the scalar spectrum would need to be strongly tilted up to provide the observed power at smaller angular scales. However, we know that $n_s$ cannot be much greater than 1, as this would conflict with results from large-scale structure studies. Our constraints should, however, be taken with an understanding of our assumption regarding tensor modes.

In principle, some of the dark matter could be in the form of relativistic neutrinos (hot as opposed to cold dark matter). However, the change that this would make to the CMB power spectrum is negligible compared to the uncertainties of the DASI data (Dodelson, Gates, & Stebbins 1996). We therefore assume that all the dark matter is cold and set $\Omega_\Lambda = 0$, although it should then be understood that the $\Omega_{\text{cdm}} h^2$ value we find may, in principle, contain some hot dark matter.

Papers fitting the BOOMERANG-98 and MAXIMA-1 band-power data (Balbi et al. 2000; Lange et al. 2001; Jaffe et al. 2001) considered seven-dimensional grids rather similar to our own. Other studies have examined model grids with as many as 11 dimensions (Tegmark, Zaldarriaga, & Hamilton 2001), including an explicit density in neutrinos and tensor mode perturbations, generally finding both effects to be small.

Taking the philosophy that simplicity is a virtue, we have not made use of $l$-space or $k$-space splitting to accelerate the calculation of the model grid (Tegmark et al. 2001). In addition, we have generated a simple regular grid rather than attempting to concentrate the coverage in the maximum likelihood region. Finally, we have not treated the normalization parameter $C_{10}$ as continuous, preferring to explicitly grid over this parameter as well. This is computationally somewhat slower, but it makes the marginalization simpler and involves no assumption about the form of the variation of $\chi^2$ versus this parameter. Using the notation lower edge: step value: upper edge (number of values), our grid is as follows: $\Omega_{\Lambda} = -1.0 : 0.2 : 3.4$ (23), $\Omega_m = 0.7 : 0.05 : 1.3$ (13), $\Omega_{\text{cdm}} h^2 = 0.0100 : 0.0025 : 0.0400$ (13), $\Omega_{\text{cdm}} h^2 = 0.00 : 0.05 : 0.5$ (11), $\tau_i = 0.0 : 0.1 : 0.4$ (5), $n_s = 0.75 : 0.05 : 1.25$ (11), and $C_{10} = 300 : 50$ : 1300 (21). Excluding the small, physically unreasonable corner of parameter space where
\( \Omega_m \leq 0 \), we make 205, 205 runs of CMBFAST, generating 205, 205 \( \times 11 = 2,257,255 \) theoretical spectra and calculating 2,257,255 \( \times 21 = 47,402,355 \) values of \( \chi^2 \) against the data.

For theoretical and phenomenological discussions of how the various peak amplitudes and spacings of the power spectrum are related to the model parameters, see Hu et al. (1997) and Hu et al. (2001). In this paper, we choose to compare data and models without explicitly considering such connections.

3. COMPARISON OF DATA AND MODELS

Consider a set of observed band powers \( D_i \) in units of \( \mu K^2 \) together with their covariance matrix \( P_{ij} \). If the overall fractional calibration uncertainty of the experiment is \( s \), we can add this to the covariance matrix as follows:

\[
N_{ij} = P_{ij} + s^2 D_i D_j .
\]

For the purposes of the present analysis, we assume \( s = 0.08 \), which includes both temperature scale and beam uncertainties. (The fractional error on the band powers is 8\%, corresponding to 4\% in temperature units. See Paper II.)

Now consider a model power spectrum \( D'_i \). The expectation value of the data given the model is obtained through the "band-power" window function \( W_{B_i/l} \) (Knox 1999),

\[
F_i = \sum_j W_{B_i} D_j .
\]

The band-power window functions \( W_{B_i/l} \) are calculated from the band-power Fisher matrix, \( F \), and the Fisher matrix \( F^{ij} \) of the bands, \( b_i \), subdivided into individual multipole moments,

\[
W_{B_i} = \sum_l (F^{-1})_{il} \sum_j F^{jil} ,
\]

(adapted from Knox 1999 for Fisher matrices with significant off-diagonal elements). The sum of each row of the array \( W_{B_i/l} \) is unity, so equation (2) simply represents a set of weighted means. Note that any experiment with less than full-sky coverage will always have non-top hat band-power window functions. In practice, we calculate equation (3) by subdividing each band into four subbands and interpolate the results. The functions for the DASI band powers are plotted in Figure 1 and are available at our Web site. In practice, the effect of using the correct window function versus simply choosing the \( D_i \) at the nominal band center is extremely modest.

The uncertainties of the \( D_i \) are non-Gaussian, so it would not be correct to calculate \( \chi^2 \) at this point. However, it is possible to make a transformation such that the uncertainties become Gaussian to a very good approximation (Bond, Jaffe, & Knox 2000). An additional set of quantities \( x_i \) need to be calculated from the data which represent the component of the total uncertainty which is due to instrument noise. We can then transform each of the variables as follows:

\[
\begin{align*}
D'_i & = \ln (D_i + x_i) , \\
D''_i & = \ln (D_i + x_i) , \\
M_{ij} & = N_{ij}^{-1} (D_i + x_i) (D_j + x_j) ,
\end{align*}
\]

and calculate \( \chi^2 \) as usual,

\[
\chi^2 = (D'_i - D''_i) M_{ij}^{-1} (D'_j - D''_j) .
\]

The inverse covariance matrix elements \( M_{ij}^{-1} \) will be approximately independent of the band powers \( D_i \). This is true even with the added calibration uncertainty term in equation (1), under the assumption that the band-power uncertainty is sample variance dominated, i.e., \( s_i \gg 1 \) (as is the case with almost all the DASI band powers) or that the fractional calibration uncertainty is small compared to the total uncertainty in the band power, \( s^{2} < N_{ij}^{-1} \), which is the case for DMR. Use of this transformation is very important as it allows us to use \( \chi^2 \), and therefore not only to find the best fitting model, but to determine an absolute goodness of fit.

The ability of smaller angular scale \( (l > 100) \) CMB data to set constraints on model parameters is much improved when the large angular scale \( (l \leq 25) \) information from the DMR instrument is included. We use the DASI band powers described and tabulated in Paper II together with the 24 DMR band powers provided in the RADPACK distribution (Available from the Web site of L. Knox 2000; see also Bond et al. 2000), concatenating the \( D_i \) and \( x_i \) vectors and forming a block diagonal covariance matrix. Note that while the effect of the transformation described above is modest for the DASI points, it is very important for those from DMR (due to the large sample variance at the lower \( l \) values).

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1 The Web address is http://astro.uchicago.edu/dasi.

2 The Web address is http://bubba.ucdavis.edu/~knox/.
Fig. 2.—DASI first-season angular power spectrum in nine bands (filled circles). DMR information is shown compressed to the single lowest l point. Solid line is the best fitting model which falls on our grid, while the dashed shows the concordance model \((\Omega_m, \Omega_{dm}, \Omega_k, \tau, n_s, h) = (0.05, 0.35, 0.60, 0.1, 0.0, 0.65)\). Error bars plotted here are strictly for illustrative purposes only. The \(\chi^2\) calculation is made using the full covariance matrix, and after the transformation described in § 3. Thus, “Chi-by-eye” can be misleading. [See the electronic edition of the Journal for a color version of this figure.]

4. RESULTS

Figure 2 shows the DASI band powers together with the DMR data condensed to a single point for display. The \(\chi^2\) of the best-fit model which falls on our grid is 29.5 for the 9 DASI plus 24 DMR band powers. Assuming a full 7 degrees of freedom are lost to the fit, this is at the 71% point of the cumulative distribution function. The parameters of this model are \((\Omega_m, \Omega_k, h^2, \Omega_{cdm}h^2, \tau, n_s, \theta_{10}) = (0.725, 0.325, 0.0200, 0.15, 0.0, 0.95, 800)\), equivalent to \((\Omega_b, \Omega_{cdm}, \Omega_k, \tau, n_s, h) = (0.09, 0.64, 0.33, 0.0, 0.95, 0.48)\). However, no particular importance should be ascribed to these—the concordance model (Ostriker & Steinhardt 1995; Krauss & Turner 1995) that is shown has a \(\chi^2\) of 30.8 (76%) and is also rather a good fit. The message of Figure 2 is simply that there are models within the grid which fit acceptably well, and that we are therefore justified in proceeding to marginalized parameter constraints. We convert \(\chi^2\) to likelihood, \(L = e^{-\chi^2/2}\).

The extreme degeneracy of CMB data in the \((\Omega_m, \Omega_k)\) plane has already been mentioned. This inability to choose between models with the same \(\Omega_{tot}\) is in fact weakly broken at very low-\(l\) numbers by the Sachs-Wolfe effect (Efstathiou & Bond 1999). The likelihood contours diverge from the \(\Omega_{tot} = 1\) line as \(\Omega_k\) becomes much greater than 1 and the allowed region broadens. Consequently, the marginal likelihood curve of \(\Omega_{tot}\) acquires a high side tail as models with progressively greater \(\Omega_k\) are included. These high \(\Omega_k\) models have very low values of \(h\) and are known to be invalid from a wide range of non-CMB data. This being the case, it is clearly not sensible to allow them to influence our results.

We are therefore prompted to introduce additional external information. We could simply restrict \(\Omega_m\) and \(\Omega_k\) to some “reasonable” range; for example requiring \(\Omega_k > 0\) and \(\Omega_m < 1\). Instead, we choose to introduce a prior on \(h\), since this strongly breaks the degeneracy and is a quantity which is believed to have been measured to 10% precision (Freedman et al. 2000). We use two \(h\) priors; a weak \(h > 0.45\) and a strong \(h = 0.72 \pm 0.08\), assuming a Gaussian distribution. For the weak prior, adding the additional restriction \(h < 0.90\) has almost no effect, as the excluded models already have very small likelihoods. To apply the prior, we simply calculate the \(h\) value at each grid point, assign it the relevant likelihood, and multiply the two grids together.

Figure 3 shows how the marginal likelihood distributions of the model parameters change as we move from the implicit prior of \((\Omega_k \leq 3.4, \Omega_{tot} \leq 1.3)\) to weak and then strong prior cases. Note that most of the curves fall to a small fraction of their peak value before the edge of the grid is reached. For all parameters where this is not the case, one must introduce external priors such that it becomes so, and/or acknowledge the implicit top-hat prior which the range of that grid parameter represents. Only then can the constraint on any of the parameters be accepted. All such priors must then be quoted with the constraints. In fact, we see that \((\Omega_b h^2, \Omega_{cdm} h^2, n_s, \theta_{10})\) are almost completely unaffected by the choice of prior on \(h\); this indicates that correlations between these parameters and \((\Omega_k, \Omega_{tot})\) are modest and is a fortunate result.

We turn now to \(\tau\), which as is evident in Figure 3, is a very poorly constrained parameter. The effect of reionization is to suppress power at small angular scales and tilt the spectrum down. However, this can be compensated by adjusting \(n_s\) upward, making these two parameters largely degenerate. Worse still, unlike the \(h\) prior discussed above, we have very weak experimental guidance as to the value of \(\tau\); we know only that reionization occurred at \(z \geq 6\), roughly equivalent to \(\tau > 0.03\). From theoretical ideas regarding early structure formation and energy emission, it seems essentially impossible that \(\tau > 0.4\). (See Haiman & Knox 1999, for a recent review of our knowledge regarding reionization.) The theoretical prejudice for \(n_s \approx 1\) is strong, but since this is a fundamental parameter of the cosmology which we are trying to measure, we are very reluctant to place a prior on it.

We have opted to accept the top-hat prior implicit in our model grid, i.e., that the likelihood of \(\tau\), falling between 0.0 and 0.4 is uniform. In Table 1, we list the spline interpolated median, 1 \(\sigma\), and 2 \(\sigma\) points of the integral constraint curves. The modal (maximum likelihood) value is also given. All of the constraints quoted in this paper are 68% confidence intervals about the median. Although one can argue that the mode is perhaps more natural, in practice it makes little difference.

Referring to Figure 3, we see that the \(\Omega_k\) constraint is almost wholly driven by the prior on \(h\); for this reason we have not included it in Table 1. However, if one is prepared to accept the strong prior \(h = 0.72 \pm 0.08\), then our data indicate that \(\Omega_{tot} = 1.00 \pm 0.04\), \(\Omega_m = 0.40 \pm 0.15\), and \(\Omega_k = 0.60 \pm 0.15\).
Figure 4 illustrates the effect of setting $\tau_c = 0.0$ (which the data weakly prefers). As already mentioned the primary degeneracy is with $n_s$ which shifts to $n_s = 0.97^{+0.05}_{-0.04}$.

The selection of the particular set of nine band powers which we have used in this analysis is quite arbitrary. We have tested increasing the number of bins, and as expected, the variance and covariance of the points increases to compensate and the constraint curves remain the same. Shifting the bins in $l$ also leaves the results unchanged; for instance, the alternate binning shown in Paper II leads to results which are indistinguishable from those presented here.

### TABLE 1

| Parameter | 2.5%  | 16%   | 50%   | 84%   | 97.5%  | Mode  |
|-----------|-------|-------|-------|-------|--------|-------|
| $\Omega_{\text{tot}}$ | 0.927 | 0.986 | 1.044 | 1.103 | 1.150  | 1.047 |
| $\Omega_b h^2$  | 0.0156| 0.0187| 0.0220| 0.0255| 0.0292 | 0.0220|
| $\Omega_{\text{cdm}} h^2$ | 0.075 | 0.100 | 0.137 | 0.175 | 0.225  | 0.135 |
| $n_s$       | 0.901 | 0.949 | 1.010 | 1.092 | 1.166  | 0.993 |
| $C_{10}$    | 558   | 642   | 741   | 852   | 973    | 728   |

**Note.**—These constraints are from a seven-dimensional grid, assuming the weak prior $h > 0.45$ and $0.0 \leq \tau_c \leq 0.4$. The indicated points on the cumulative distribution function are given, as well as the maximum likelihood value.
5. CONCLUSION

We have compared the DASI+DMR data to adiabatic CDM models with initial power-law perturbation spectra. The best-fitting model has an acceptable $\chi^2$ value, indicating that for data of the present quality, models within this class are a plausible representation of the underlying physics. Adopting the conservative priors $h > 0.45$ and $0 \leq \tau_c \leq 0.4$, we find $\Omega_{\text{tot}} = 1.04 \pm 0.06$ and $n_s = 1.01^{+0.08}_{-0.06}$, consistent with the predictions of inflation. Moving to more aggressive priors on $h$ and $\tau_c$ tightens the constraints on $\Omega_{\text{tot}}$ and $n_s$, respectively, but they remain consistent with the theory. We find that $\Omega_b h^2 = 0.022^{+0.004}_{-0.003}$ and $\Omega_{\text{cdm}} h^2 = 0.14 \pm 0.04$, adding to the already very strong evidence for nonbaryonic dark matter. These constraints are only weakly affected by the choice of $h$ and $\tau_c$ priors. Setting a strong $h$ prior breaks the $(\Omega_m, \Omega_b)$ degeneracy such that we constrain $\Omega_m = 0.40 \pm 0.15$ and $\Omega_b = 0.60 \pm 0.15$, consistent with other recent results.

The current best value for $\Omega_c h^2$ derived from the well-developed theory of big bang nucleosynthesis (BBN), combined with measurements of the primeval deuterium abundance, is $\Omega_c h^2 = 0.020 \pm 0.002$ (95% confidence; Burles, Nollett, & Turner 2001). The $\chi^2$ of the difference between this and our own value is at the 42% point of the cumulative distribution function (assuming Gaussian errors on both); the values are hence consistent. Previous CMB analyses have seen little power in the second peak region and have determined $\Omega_b h^2$ values higher than, and inconsistent with, BBN at the $\approx 3 \sigma$ level (Lange et al. 2001; Jaffe et al. 2001).

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