COSMOLOGICAL IMPLICATIONS OF THE MAXIMA-1 HIGH-RESOLUTION COSMIC MICROWAVE BACKGROUND ANISOTROPY MEASUREMENT

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ABSTRACT

We discuss the cosmological implications of the new constraints on the power spectrum of the cosmic microwave background (CMB) anisotropy derived from a new high-resolution analysis of the MAXIMA-1 measurement. The power spectrum indicates excess power at $l \sim 860$ over the average level of power at $411 \leq l \leq 785$. This excess is statistically significant at the $95\%$ confidence level. Its position coincides with that of the third acoustic peak, as predicted by generic inflationary models selected to fit the first acoustic peak as observed in the data. The height of the excess power agrees with the predictions of a family of inflationary models with cosmological parameters that are fixed to fit the CMB data previously provided by BOOMERANG-LDB and MAXIMA-1 experiments. Our results therefore lend support for inflationary models and more generally for the dominance of adiabatic coherent perturbations in the structure formation of the universe. At the same time, they seem to disfavor a large variety of the nonstandard (but inflation-based) models that have been proposed to improve the quality of fits to the CMB data and the consistency with other cosmological observables. Within standard inflationary models, our results combined with the COBE/Differential Microwave Radiometer data give best-fit values and 95% confidence limits for the baryon density, $\Omega_b h^2 = 0.033 \pm 0.013$, and the total density, $\Omega = 0.31^{+0.06}_{-0.16}$. The primordial spectrum slope ($n_s$) and the optical depth to the last scattering surface ($\tau$) are found to be degenerate and to obey the relation $n_s = (0.99 \pm 0.14) + 0.46\tau$, for $\tau \leq 0.5$ (all at $95\%$ confidence levels).

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

Observations of the cosmic microwave background (CMB) temperature anisotropy are reaching maturity. The high signal-to-noise ratio multifrequency data gathered by BOOMERANG-LDB (the long-duration balloon flight of Balloon Observations Of Millimetric Extragalactic Radiation And Geomagnetics; de Bernardis et al. 2000) and MAXIMA-1 (the first flight of the Millimeter-wave Anisotropy eXperiment Imaging Array; Hanany et al. 2000) experiments set stringent constraints on the shape of the power spectrum in the broad range of angular scales ranging from $5^\circ$ down to $10^\circ$ scales (corresponding to a range in $l$-space from $\sim 50$ up to $\sim 600$ for BOOMERANG-LDB and from $\sim 35$ to $\sim 800$ for MAXIMA-1). The measurements firmly established the existence of a peak in the power spectrum at $l \sim 220$, which was also suggested by the data from earlier observations (e.g., Miller et al. 1999; Maukspof et al. 2000). Because no secondary peaks were indisputably seen, there was no unambiguous evidence for an inflation-like scenario in which structure formation is driven by passive adiabatic coherent fluctuations (but also see the results concurrent with ours—Netterfield et al. 2001 and Halverson et al. 2001).

The level of power detected beyond the first peak, on sub-degree scales, was found to be somewhat lower than that generally expected for inflation-based “concordance” models of pre-2000 (e.g., Ostriker & Steinhardt 1995; Krauss & Turner 1995). Although very good fits to the MAXIMA-1 and BOOMERANG-LDB data could be found within the inflationary family of models (e.g., Jaffe et al. 2001), the most favored values of the baryon density were shown to be higher than that inferred from the standard arguments based on the cosmological (big bang) nucleosynthesis (BBN), although the latter was found to be within the 95% (97%) confidence limits derived from the MAXIMA-1 (MAXIMA-1 + BOOMERANG-LDB) measurement. Notwithstanding this fact, a number of alternatives/extensions to the standard cosmologies were suggested (e.g., Bouchet et al. 2000; Enqvist, Kurki-Suonio, & Valiviita 2000; Peebles, Seager, & Hu 2000). Further high-resolution data are required to test these models.

The companion Letter by Lee et al. (2001) presents a new analysis of the MAXIMA-1 data that extends the measured power spectrum from the previously published range $35 <
power, given as in Figure 1, is consistent with anticipated within a family of generic inflation-based models. In fact a feature at , a third acoustic peak, is

In this Letter, we discuss the cosmological significance of the new result.

This Letter is organized as follows. In § 2, we look for the signature of acoustic oscillations in our power spectrum, the existence of which is predicted by inflation-based scenarios. In § 3, we discuss the cosmological implications of such a feature and derive constraints on some of the cosmological parameters within the family of standard inflationary cosmological models. Finally, in § 4, we present our conclusions and comment briefly on the viability of nonstandard cosmological models in light of the new data.

2. THE EXCESS POWER AT \( l \sim 860 \pm 75 \)

Lee et al. (2001) set useful constraints on the CMB anisotropy power spectrum up to \( l \sim 1200 \), corresponding to angular scales down to 5°. In terms of the simple \( \chi^2 \) statistics, this power, given as \( \ell (\ell + 1) C_{\ell} / 2\pi \) in Figure 1, is consistent with a straight horizontal line for \( \ell \approx 410 \) yielding a value of \( \chi^2 = 5.2 \) for 7 degrees of freedom. However, not only does such a model have no physical justification, but the data also qualitatively suggest the presence of high power at \( l \sim 860 \), in excess of the power levels at \( l \sim 410 - 785 \) and \( l \sim 1000 - 1200 \). In fact a feature at \( l \sim 850 \), a third acoustic peak, is anticipated within a family of generic inflation-based models which are selected to reproduce a first peak at a position \( l \sim 220 \) as seen in the data. A statistically significant detection of such a feature would provide important additional support to this family of models. Statistical and systematic errors and correlations between the spectral bands obscure the statistical significance of the results. We therefore employ a likelihood approach to assess the statistical importance of the feature at \( l \sim 860 \) in the MAXIMA-1 power spectrum.

We work within a three-dimensional parameter space. The initial parameters are the bin powers \( C_0, C_1, \) and \( C_2 \) for bins \( B_0 (411 \leq l \leq 785) \), \( B_1 (786 \leq l \leq 925) \), and \( B_2 (926 \leq l \leq 1235) \), as shown by the shaded regions in Figure 1. Those parameters are chosen to facilitate the search for the feature at \( l \sim 850 \). Such a family of spectrum models includes a flat spectrum as a special case, and in the Bayesian spirit, our analysis seeks to determine how well such a model represents our data.

The likelihood for the three-dimensional parameter space is computed by assuming the offset lognormal approximation of Bond, Jaffe, & Knox (2000) to the probability distribution of the bin powers, denoted hereafter as \( L (C_0, C_1, C_2) \). The likelihood also depends on “nuisance” parameters that describe the contribution of systematic effects such as the total calibration uncertainty and the beam and pointing error. We model all of these as fully correlated between bins and Gaussian-distributed with a dispersion that depends on \( l \) as given in Lee et al. (2001).

We marginalize over these parameters by numerical integration.

The question we first ask is whether the power in the two side bins (\( B_0 \) and \( B_2 \)) is lower than the power in the middle bin centered at \( l \sim 860 \), and at what confidence level. For that reason, we introduce two new parameters, \( R_{01} \) and \( R_{21} \), that are given by the ratio of power between bins \( R_{01} \equiv C_1 / C_0 \). As a third parameter, describing the overall normalization, we choose the bin power amplitude defined above: \( C_1 \). We adopt flat priors in the bin powers and marginalize over the parameter \( C_1 \), leaving only a two-dimensional problem.

\[
L(R_{01}, R_{21}) \propto \int dC_0 C_1^2 L(C_0(R_{01}, C_1), C_1, C_2(R_{21}, C_1)).
\]  

where \( C_1^2 \) is a Jacobian. The results are shown in Figure 2. The left panel shows the contours of the two-dimensional likelihood \( L (R_{01}, R_{21}) \) as a function of the ratios \( R_{01} \) and \( R_{21} \). The contours show 68%, 95%, and 99% confidence levels computed assuming flat priors for both parameters. The shaded area indicates the region of parameter space favoring excess power in the middle bin relative to its neighbors. Models without excess power cannot be rejected at a confidence level higher than “1 o” (~68%).

It is also apparent, however, that most of the models preferred by the data have power in the leftmost bin, \( B_0 \), that is lower than that in the central bin, \( B_1 \). This point is addressed in the right panel of Figure 2, which shows the one-dimensional likelihoods computed through an explicit marginalization over the other pa-
spectrum, and the optical depth of reionization, \( \tau \). We use the following ranges and sampling: \( C_{10} \) is continuous; \( \Omega = 0.3, 0.5, 0.6, 0.7, 0.75, ..., 1.2, 1.3, 1.5; \( \Omega_b h^2 = 0.00325, 0.00625, 0.01, 0.015, 0.02, 0.0225, ..., 0.04, 0.045, 0.05, 0.075, 0.1; \( \Omega_m h^2 = 0.03, 0.06, 0.12, 0.17, 0.22, 0.27, 0.33, 0.40, 0.55, 0.8; \( \Omega = 0.0, 0.1, 0.2, 1.0; \( n_s = 0.6, 0.7, 0.75, 0.8, 0.85, 0.875, ..., 1.2, 1.25, ..., 1.5; \( \tau = 0, 0.025, 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.5. \) The justification of the presented choice of the parameter space can be found in Balbi et al. (2000). Models were computed using a version of CMBFAST by Tegmark, Zaldarriaga, & Hamilton (2001; originally by Seljak & Zaldarriaga 1996).

3.2. Results

We compute the likelihood on the grid for models using an offset lognormal approximation (Bond et al. 2000), including both statistical and systematic errors in a manner analogous to § 2. We neglect a subdominant pointing uncertainty (Lee et al. 2001). The likelihood for a subset of parameters is evaluated by an explicit marginalization over all the remaining parameters, using a top-hat prior in parameters used to define our database. In addition, we impose top-hat priors for the values of the Hubble constant (0.4 \( \lesssim h \lesssim 0.9 \)), the matter density (\( \Omega_m = \Omega_b + \Omega_{\text{cdm}} > 0.1 \)), and the age of the universe (>10 Gyr). We marginalize over the calibration and beam uncertainty in order to account for the remaining systematic uncertainties in our results. To provide an extra large angular scale constraint, we combine our data with the results from the COBE/DMR satellite as provided by Górski et al. (1996).

Within the chosen family of inflationary models, we put stringent 95\% confidence level constraints on the total density (\( \Omega = 0.9^{+0.18}_{-0.16} \)), the baryon density (\( \Omega_b h^2 = 0.033 \pm 0.013 \)), and the power spectrum normalization (\( C_{10} = 690^{+200}_{-120} \mu K^2 \)). Our 95\% confidence limit on the cold dark matter density is \( \Omega_{\text{cdm}} h^2 = 0.17^{+0.16}_{-0.07} \). However, this result is mostly determined by the priors defining the database parameter range, as discussed in Jaffe et al. (2001). We find a strong degeneracy between the optical depth to the last scattering surface, \( \tau \), and the primordial power spectrum index, \( n_s \). In this case, the degeneracy restricts the parameters to a subspace, allowing us to derive a combined constraint: \( n_s = (0.99 \pm 0.14) + 0.46 \tau \) (at a 95\% confidence level), for \( \tau \leq 0.5 \). We note that we recover the 95\% upper limit (\( n_s \approx 0.4 \)) on \( \tau \), derived by Griffiths, Barbosa, & Liddle (1999), if we constrain the spectral index to be \( \leq 1.2 \), as was assumed by those authors. Independent of the value of the optical depth, we can put a very firm \( \approx 99\% \) lower limit on the spectral index, \( n_s \geq 0.8 \). Assuming no reionization (\( \tau = 0 \)), we can get both lower and upper limits on the spectral index reading \( n_s = 0.99 \pm 0.14 \). Alternatively, fixing \( n_s \) at unity gives us a 95\% confidence level upper limit (\( \tau \approx 0.26 \)).

The \( \chi^2 \) of the best-fit model is 30 for all 41 points used in the fittings and 4 for the 13 points of MAXIMA-1 only. The best-fit model parameters (\( \Omega, \Omega_{\text{cdm}}, \Omega_b, \tau, n_s, h = 0.07, 0.68, 0.1, 0.0, 1.025, 0.63 \)) are characterized by high matter and a low vacuum energy content (see also Balbi et al. 2000). However, due to the strong degeneracy between \( \Omega_m \) and \( \Omega_b \) (e.g., Zaldarriaga, Spergel, & Seljak 1997), we can easily find models comfortably fulfilling both MAXIMA-1 + DMR and supernova (SN) constraints (see Fig. 3). These data sets constrain jointly the matter and vacuum energy densities to be \( \Omega_m, \Omega_b = (0.32^{+0.14}_{-0.11}, 0.65^{+0.15}_{-0.16}) \) (at a 95\% confidence level).

The constraint on \( \Omega_b h^2 \) mentioned above is compatible with the best determination to date of the baryon density based on parameter. We find that \( R_{10} = 0.49^{+0.46}_{-0.21} \), and hence it is lower than 1 at the confidence level of \( \sim 95\% \) (compared with the value of \( R_{10} \) computed in the next section), yielding a "2 σ" detection of the power rise at \( l \approx 860 \) over the intermediate-\( l \) range covered by the \( B_0 \) bin. This result remains unchanged if we allow for the presence of the (uncorrelated) point-source–like component with the amplitude as expected for the 150 GHz band of MAXIMA-1, even in the most pessimistic cases (Lee et al. 2001).

It may appear that this high confidence level is largely due to the leftmost point of the spectrum (at \( l \approx 435 \)) included in our (clearly arbitrary) definition of \( B_0 \). However, excluding that point lowers the confidence level to only \( \sim 93\% \). Because of the large uncertainties of the Lee et al. results beyond \( l \approx 900 \), the statistical confidence that the power declines beyond the bin \( B_1 \) is only \( \sim 80\% \). However, the recent Cosmic Background Imager result (Padin et al. 2001) constrains the power to \( 882^{+463}_{-428} \mu K^2 \) at \( l = 1190^{+354}_{-284} \), providing extra and independent support for the presence of such a decline. Therefore, the high power level that we see in the MAXIMA-1 data at \( l \approx 860 \) cannot extend far beyond the right edge of the bin \( B_1 \) (\( l = 925 \)). The amplitude of this excess power is restricted by our data to \( C_1 \approx 3273^{+1750}_{-1500} \mu K^2 \) at a 95\% confidence level, including both statistical and systematic errors.

In the usual family of inflation-based models, one also expects to find a second peak in the region of \( 410 \lesssim l \lesssim 785 \). While a single flat band power provides an excellent fit to all the points within bin \( B_0 \) with \( \chi^2 \approx 1.5 \) and 0.26 for 4 (wider bin) and 3 (narrower) degrees of freedom, \( 18 \) respectively, the presence of a second peak in that region is still comfortably admissible by the data (Fig. 1). With our choice of the range of \( R_{10} \), this bin is expected to be only a factor of \( \approx 2 \) wider than a typical feature of the power spectrum (\( \Delta l \approx 150 \)) of the standard inflationary model. If such a peak structure is present in that range, \( R_{10} < 1 \) means that the bin power at \( l \approx 860 \) is higher than the level of power in some subjection of the \( 410 \lesssim l \lesssim 786 \) range. Then our analysis above demonstrates that this happens at a confidence level of \( \approx 95\% \) and that value is our confidence level for detecting a feature in the power spectrum at \( l \approx 860 \).

3. COSMOLOGICAL PARAMETERS

3.1. Parameter Space

Figure 1 illustrates that an inflationary model with parameters as determined by fitting to the MAXIMA-1 power spectrum published by Hanany et al. (2000) provides a very good fit over the entire current range of our new data together with the COBE/Differential Microwave Radiometer (DMR) result. The total \( \chi^2 \) is \( \approx 32 \) for 41 data points (MAXIMA-1 + DMR) and \( \chi^2 = 8 \) for the 13 points of MAXIMA-1 only. Thus, our new data are consistent with the predictions made on the basis of the relatively narrow class of inflation-based models assumed in the previous papers. Such a class of models can be seen as a particular subset of the family of models considered in the previous section.

Here we consider a seven-dimensional space of parameters. The parameters include the amplitude of fluctuations at \( l = 10, C_{10}, \) the physical baryon density, \( \Omega_b h^2 \), the physical density of cold dark matter, \( \Omega_{\text{cdm}} h^2 \), the cosmological constant, \( \Omega_k \), the total energy density of the universe, \( \Omega = \Omega_b + \Omega_{\text{cdm}} + \Omega_k \), the spectral index of primordial scalar fluctuations, \( n_s \), and the...
measurements of primordial deuterium and calculations of standard BBN (Burles, Nollett, & Turner 2001; Tytler et al. 2000), \( \Omega_\Lambda h^2 = 0.020 \pm 0.002 \). The consistency of the data with BBN becomes even more apparent by constraining our parameter estimation on the BBN value of \( \Omega_\Lambda h^2 \), which we approximate by fixing \( \Omega_\Lambda h^2 \) at the grid value nearest to the BBN prediction (i.e., \( \Omega_\Lambda h^2 = 0.02 \)). The best-fit model then has parameters (\( \Omega_\Lambda, \Omega_c, \tau_*, n_s, h \)) = (0.07, 0.78, 0.0, 0.0, 1.0, 0.53) with \( \chi^2 \approx 7 \) for the 13 MAXIMA-1 points only. This very good fit emphasizes the compatibility of our data with other cosmological measurements. The spectrum of this model is indicated in Figure 1 with a dotted line, and it shows that even in that case, the best-fit model has a higher third than second peak, if \( l(l+1)C_l \) is plotted versus \( l \).

We also compute constraints on the ratio of bin powers, \( R_{01} \), as imposed by the MAXIMA-1 data within the discussed family of models. We find that the most likely value of that ratio is 0.68 \( \pm 0.05 \) at the 95\% confidence level, consistent with (although on average higher than) our result in § 2 (see Fig. 2).

4. IMPLICATIONS FOR COSMOLOGICAL MODELS

Inflation-based models provide us with an abundance of excellent fits to the MAXIMA-1 extended power spectrum. These include the best-fit models found by the analysis of the first data sets of BOOMERANG-LDB and MAXIMA-1 (Jaffe et al. 2001; Balbi et al. 2000). Constraints on cosmological parameters using DMR and MAXIMA-1 confirm the near flatness of the universe and, when combined with recent SN data (Riess et al. 1998; Perlmutter et al. 1999), support the need for the nonzero vacuum energy density. The most likely baryon density indicated by our data is found to be somewhat higher than the preferred BBN value, yet the latter is within the 95\% confidence range of our determination. Moreover, there are excellent fits to the data with the baryon fraction at the BBN value.

Our results constrain the power at \( l \sim 860 \) to be \( \sim 1700 \mu K^2 \) at the 95\% confidence level. They also indicate an increase in the power spectrum between \( l \sim 410 \) and \( l \sim 786 \) to 925, yielding the ratio of the corresponding bin powers equal to \( R_{01} = \frac{4.90}{0.21} \) in a general case or \( R_{01} = 0.68^{+0.07}_{-0.03} \) within the considered family of inflationary models. We have shown that such constraints can be easily fulfilled by these inflationary models. However, they impose strong requirements on some nonstandard models that were found to better accommodate the first results of the BOOMERANG-LDB and MAXIMA-1 experiments. Those models, by design, have an amplitude of power in the intermediate range of \( l \) below the typical predictions of the standard inflationary models. However, they also tend to have lower power at the high-\( l \) end, and, therefore, to match our new constraint at \( l \sim 860 \), they would require an even higher baryon abundance than the family of the models considered in § 3. These disfavored models include a mixture of inflation and topological defect models (Bouchet et al. 2000; Contaldi 2000), hybrid adiabatic plus isocurvature models (Stompor, Banday, & Górski 1996; Enqvist et al. 2000), broken power-law primordial spectra models (Griffiths, Silk, & Zaroubi 2001; Barriga et al. 2001), or models with a delayed recombination (Peebles et al. 2000). Further investigation is required to fully elucidate the status of these models.

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Fig. 3.—Constraints in the \( \Omega_\Lambda, \Omega_\Lambda \) plane from the combined MAXIMA-1 and COBE/DMR data sets. The contours shown correspond to 68\%, 95\%, and 99\% likelihood-ratio confidence levels. The bounds obtained from high-redshift SN data (Perlmutter et al. 1999; Riess et al. 1998) are also overlaid as well as the confidence levels of the joint likelihood.