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

R. STOMPOR[1,2,3], M. ABROE[4], P. ADE[5], A. BALBI[6], D. BARBOSA[7,8], J. BOCK[9,10], J. BORRILL[11], A. BOSCALERI[12], P. DE BERNARDIS[13], P. G. FERREIRA[14,8], S. HANANY[4], V. HRISTOV[10], A. H. JAFFE[1,15], A. T. LEE[16,7,1], E. PASCALE[12], B. RABII[16,2], P. L. RICHARDS[16,2], G. F. SMOOT[16,7,2], C. D. WINANT[16,2,1], J. H. P. WU[15]

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ABSTRACT

We discuss the cosmological implications of the new constraints on the power spectrum of the Cosmic Microwave Background Anisotropy derived from a new high resolution analysis of the MAXIMA-I measurement (Lee et al. 2001). The power spectrum shows excess power at $\ell \sim 860$ over the average level of power at $411 \leq \ell \leq 785$. This excess is statistically significant on the $\sim 95\%$ confidence level. Such a feature is consistent with the presence of a third acoustic peak, which is a generic prediction of inflation-based models. The height and the position of the excess power match 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-I experiments (e.g., Jaffe et al. 2001). Our results, therefore, lend support for inflationary models and more generally for the dominance of coherent perturbations in the structure formation of the Universe. At the same time, they seem to disfavor a large variety of the non-standard (but still inflation-based) models that have been proposed to improve the quality of fits to the CMB data and consistency with other cosmological observables.

Within standard inflationary models, our results combined with the *COBE*-DMR data give best fit values and 95% confidence limits for the baryon density, $\Omega_b h^2 \simeq 0.0325 \pm 0.0125$, and the total density, $\Omega = 0.9^{+0.18}_{-0.16}$. The primordial spectrum slope (n_s) and the optical depth to the last scattering surface (τ_c) are found to be degenerate and to obey the relation $n_s \simeq 0.46\tau_c + (0.99 \pm 0.14)$, for $\tau_c \leq 0.5$ (all 95% c.l.).

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

Observations of Cosmic Microwave Background (CMB) temperature anisotropy are reaching maturity. The high signal-to-noise multi-frequency data gathered by the balloon-borne BOOMERANG-LDB (de Bernardis et al. 2000) and MAXIMA-I (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 degrees down to ~ 10 arcminute scales (corresponding to a range in ℓ space from ~ 50 up to ~ 600 for BOOMERANG-LDB and from ~ 35 to ~ 800 for MAXIMA-I. The measurements firmly established the existence of a peak in the power spectrum at $\ell \sim 220$, also suggested by the data from earlier observations (e.g., Miller et al. 1999 and Mauskopf et al. 2000). Because no secondary peaks were indisputably seen, there was no unambiguous evidence for an inflation-like scenario where structure formation is driven by passive coherent fluctuations (but see also results concurrent to ours, Netterfield et al. 2001, and Halverson et al. 2001).

The level of power detected beyond the first peak, on subdegree 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-I and BOOMERANG-LDB data could be found within the inflationary family of models (e.g., Balbi et al. 2000, 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). This discrepancy has stimulated a number of theoretical speculations aimed at improving consistency of these two different cosmological observables,

[1]Center for Particle Astrophysics, University of California, Berkeley, CA, USA
[2]Space Sciences Laboratory, University of California, Berkeley, CA, USA
[3]Copernicus Astronomical Center, Warszawa, Poland
[4]School of Physics and Astronomy, University of Minnesota/Twin Cities, Minneapolis, MN, USA
[5]Queen Mary and Westfield College, London, UK
[6]Dipartimento di Fisica, Università Tor Vergata, Roma, Italy
[7]Physics Division, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA, USA
[8]CENTRA, Instituto Superior Tecnico, Lisboa, Portugal
[9]Jet Propulsion Laboratory, Pasadena, CA, USA
[10]California Institute of Technology, Pasadena, CA, USA
[11]National Energy Research Scientific Computing Center, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[12]IROE-CNR, Florence, Italy
[13]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[14]Astrophysics, University of Oxford, UK
[15]Dept. of Astronomy, University of California, Berkeley, CA, USA
[16]Dept. of Physics, University of California, Berkeley, CA, USA

notwithstanding the fact that the BBN value was found to be within the 95% confidence limits derived from the CMB measurements. A number of alternatives and/or extensions to the standard cosmologies have been suggested (e.g., Bouchet et al. 2000, Enqvist, Kurki-Suonio, & Valiviita, 2000, Peebles, Seager, & Hu, 2001). Further high resolution data are required to test these models.

In a companion *Letter*, Lee et al. (2001), we present a new analysis of the MAXIMA-I data that extends the measured power spectrum from the previously published range $35 < \ell < 785$ up to $\ell \leq 1235$. In this *Letter* we discuss the cosmological significance of the new result.

This *Letter* is organized as follows. In section 2, we look for the signature of acoustic oscillations in our power spectrum, the existence of which is predicted by inflation-motivated scenarios. We focus on the statistical significance of the excess power at $\ell \sim 860$ in the power spectrum. In section 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 section 4 we present our conclusions and comment briefly on the viability of non-standard cosmological models in light of the new data.

2. THE EXCESS POWER AT $\ell \sim 860 \pm 75$

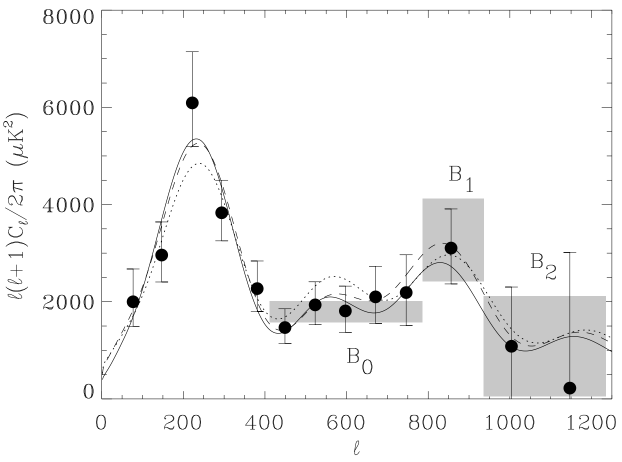

FIG. 1.— Angular power spectra of the CMB anisotropy recovered from the high resolution map of the MAXIMA-I (Lee et al. 2001). The shaded rectangles show the ranges of the bins used in our likelihood analysis in Section 2, and the 68% confidence limits on the power level in these bins. The solid line shows the best fit model to the previous low resolution results of MAXIMA-I (Hanany et al. 2000), the dashed line shows the best fit model for the new data (Lee et al. 2001), and the dotted line shows the best fit model, fulfilling the BBN constraint, found within the subfamily of all models considered here.

Lee et al. (2001) set useful constraints on the CMB anisotropy power spectrum up to $\ell \sim 1200$, corresponding to angular scales down to 5 arcminutes. This power, given as $\ell(\ell+1)C_\ell/2\pi$ in Figure 1, is consistent with a straight line for $\ell \gtrsim 410$. The appropriate χ^2 is $\simeq 5.2$ for 7 degrees of freedom[17]. The data, however, suggest the presence of excess power at $\ell \sim 860$. Qualitatively, the power level seems to increase from a value of $\sim 2000\mu$K^2 at $\ell \sim 410-785$, reaching a maximum of $\sim 3200\mu$K^2 at $\ell \sim 860$, and rapidly falling to become consistent with zero power at $\ell \sim 1000-1200$. Statistical and systematic errors and correlations between the spectral bands obscure the statistical significance of the results. We therefore employ a likelihood approach to statistically investigate the high ℓ features of the MAXIMA-I power spectrum.

We work within a three dimensional parameter space, shown as the shaded regions in Fig. 1. The initial parameters are the bin powers $\mathcal{C}_0$, $\mathcal{C}_1$ and $\mathcal{C}_2$, for bins, B_0, $411 \leq \ell \leq 785$, B_1, $786 \leq \ell \leq 925$, and, B_2, $926 \leq \ell \leq 1235$. The justification and consequences of such a choice of parameters on the interpretation of the likelihood results are discussed at the end of this section.

The likelihood for the three-dimensional parameter space is computed assuming the offset lognormal approximation of Bond, Jaffe & Knox (2000) to the probability distribution of the bin powers, denoted hereafter $\mathcal{L}(\mathcal{C}_0, \mathcal{C}_1, \mathcal{C}_2)$. The likelihood also depends on "nuisance" parameters describing the contribution of systematic effects such as the total calibration uncertainty, the beam and pointing error. We model all of these as fully correlated between bins and Gaussian-distributed with a dispersion depending on ℓ as given in Lee et al. (2001). We marginalize over these parameters by explicit 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 $\ell \sim 860$, and at what confidence level. This question is clearly relative in nature, i.e., independent of the overall normalization of the spectrum. Consequently, we introduce two new parameters, $\mathcal{R}_{01}$ and $\mathcal{R}_{21}$, which are given by the ratio of power between bins $\mathcal{R}_{ij} \equiv \mathcal{C}_i/\mathcal{C}_j$. As a third parameter, describing the overall normalization, we choose the bin power amplitude defined above: $\mathcal{C}_1$. We marginalize over this parameter in the course of the analysis, leaving only a two dimensional problem,

$$\mathcal{L}(\mathcal{R}_{01}, \mathcal{R}_{21}) \propto \int d\mathcal{C}_1\, \mathcal{C}_1^2\, \mathcal{L}\left[\mathcal{C}_0(R_{01}, \mathcal{C}_1), \mathcal{C}_1, \mathcal{C}_2(R_{21}, \mathcal{C}_1)\right]. \quad (1)$$

The results are shown in Figure 2. The upper left panel shows the contours of the two dimensional likelihood $\mathcal{L}(\mathcal{R}_{01}, \mathcal{R}_{21})$ as a function of the ratios $\mathcal{R}_{01}$ and $\mathcal{R}_{21}$. The contours show 68, 95, 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. It is clear that models without excess power can not be rejected at a confidence level higher than "1σ" ($\sim$ 68%).

It is also apparent, however, that most of the models, allowed by the data, have power in the leftmost bin, B_0, that is lower than that in the central bin, B_1. Thus in the 2-dimensional parameter space $\{\mathcal{R}_{01}, \mathcal{R}_{21}\}$, the condition for a power excess in the bin B_1 (i.e., $\mathcal{R}_{01} < 1$ and $\mathcal{R}_{21} < 1$) is violated by the high power admissible in the high ℓ bin (B_2), due to the significant statistical and systematic uncertainty of our spectrum constraints there.

Although we fall short of unambiguously detecting excess power in the middle bin (B_1) with respect to *both* neighbors at a sufficiently high confidence level, the level of power in that bin is still significantly larger than that in the lower-ℓ bin (B_0). This point is addressed in the lower panels of Figure 2, showing the one-dimensional likelihoods computed through an explicit marginalization over the other parameter. We find that $\mathcal{R}_{01}$ is lower than 1 at the confidence level $\sim$ 95%[18], yielding a "2σ"

[17] Here and below, we define χ^2 assuming a Gaussian distribution rather than the approximately offset-lognormal form used in the explicit likelihood calculations.

[18] All the confidence intervals that we quote have an uncertainty of 1% due to numerical inaccuracies.

detection of the power rise at $\ell \sim 860$ over the intermediate-ℓ-range covered by the B_0 bin.

It may appear that this high confidence level is largely due to the leftmost point of the spectrum (at $\ell \sim 435$) included in our (clearly arbitrary) definition of B_0. However, excluding that point lowers the confidence level only to $\sim 93\%$.

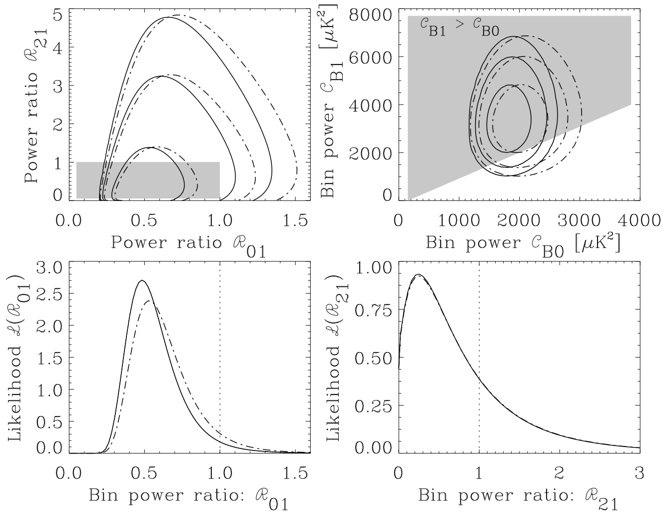

FIG. 2.— Upper panels: The 2-dimensional likelihoods as a function of the bin power ratios (left panel) and bin powers (right panel). The contours correspond to 68, 95 & 99% confidence levels computed through integration over the regions enclosed within given contours. The shaded areas show the half planes, which correspond to the existence of the "excess power" in the bin centered at $\ell \sim 860$. Bottom panels: The 1-dimensional likelihoods for bin power ratios: $\mathcal{R}_{01}$ (left) and $\mathcal{R}_{21}$ (right panel). Different lines are used for the two definitions of B_0. The solid lines are for $411 \leq \ell \leq 785$ and the dashed lines for $486 \leq \ell \leq 785$. The two lines coincide in the bottom right panel.

Because of the large uncertainties of the Lee et al. results beyond $\ell \simeq 900$ the statistical confidence that the power declines beyond the bin B_1 is only $\sim 80\%$ (see Figure 2). However, the recent CBI result (Padin et al. 2001) constrains the power to $882^{+663}_{-428}\mu K^2$ at $\ell \simeq 1190^{+261}_{-234}$, providing extra and independent support to the presence of such a decline. The high power level, we see in the MAXIMA-I data at $\ell \sim 860$, therefore can not extend far beyond the right edge of the bin B_1 ($\simeq 925$). The amplitude of this excess power is restricted by our data to $C_1 = 3273^{+1750}_{-1580}\mu K^2$ at 95% c.l. including both statistical and systematic errors.

Our definition of bin ranges is clearly somewhat arbitrary and not free of theoretical prejudices. In the most popular family of models based on the inflationary paradigm, one expects to find a second peak in the region of $410 \leq \ell \leq 785$. While a single flat band power provides an excellent fit to all the points within bin B_0 with $\chi^2 \sim 1.5$ and 0.26 for 4 (wider bin) and 3 (narrower) degrees of freedom[19], 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 B_0, this bin is expected to be only a factor $\lesssim 2$ wider than a typical feature of the power spectrum ($\Delta\ell \sim 150$) of the standard inflationary model. If such a peak structure is present in that range, $R_{01} < 1$ means that the bin power at $\ell \sim 860$ is higher than the level of power in some subsection of the $410 \leq \ell \leq 786$ range. Then our analysis above demonstrates that this happens at a confidence level of *at least* 95% and that value is our confidence level of detecting a high-ℓ ($\ell \gtrsim 410$) feature in the power spectrum. We get back to this issue at the end of the next section, assuming a particular family of theoretical models.

3. COSMOLOGICAL PARAMETERS

3.1. *Parameter space*

Figure 1 demonstrates that an inflationary model with parameters as determined by fitting to the MAXIMA-I 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*-DMR result. The total χ^2 is $\simeq 32$ for 41 data points (MAXIMA-I plus DMR) and $\chi^2 \simeq 8$ for the 13 points of MAXIMA-I only. Thus, our new data is consistent with the predictions made on the basis of the relatively narrow class of inflation-motivated models assumed in the previous papers. Within this class of models, the observed power excess in the bin at $\ell \sim 860$ can be interpreted as evidence for acoustic oscillations of the ionized plasma prior to cosmological reionization and therefore for the presence of coherent primordial fluctuations (e.g., Peebles & Yu 1970).

Hereafter, we focus on the family of inflationary models chosen in Balbi et al. (2000) with the aim of showing the changes introduced by the extra constraints at high ℓ, rather than exhaustively re-exploring the parameter space. We therefore 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, $\Omega_{cdm}h^2$, and the cosmological constant, Ω_Λ, the total energy density of the universe, $\Omega \equiv \Omega_b + \Omega_{cdm} + \Omega_\Lambda$, the spectral index of primordial scalar fluctuations, n_s, and the optical depth of reionization, τ_c. We use the following ranges and sampling: C_{10} is continuous; Ω = 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; $\Omega_{cdm}h^2$ = 0.03, 0.06, 0.12, 0.17, 0.22, 0.27, 0.33, 0.40, 0.55, 0.8; Ω_Λ = 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; τ_c = 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 elsewhere (Balbi et al. 2000). Note, however, that our current data base of models is somewhat different than in that paper in parameters, size, and gridding. Models were computed using a version of CMBFAST by Tegmark, M., Zaldarriaga, M., & Hamilton, A., (2001), originally by Seljak & Zaldarriaga (1996).

3.2. *Results*

We compute the likelihood on the grid for models using an offset lognormal approximation (Bond, Jaffe, & Knox 2000), including both statistical and systematic errors in a manner analogous to Section 2. We neglect a sub-dominant (Lee et al. 2001) pointing uncertainty, amounting only to up 10% of the total error. 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 value of the Hubble constant $0.4 \leq h \leq 0.9$, the matter density (defined as $\Omega_m \equiv \Omega_b + \Omega_{cdm}$) $\Omega_m > 0.1$ and the age of the Universe > 10Gyr. We marginalize over the calibration and beam uncertainty in order to account for remaining systematic uncertainties

[19]In fact one may worry that the χ^2 values are too low and the spectral points do not scatter enough. However, due to the strongly asymmetric shape of the χ^2 distribution with so few degrees of freedom; they are very close to the maxima of those distributions.

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, $\Omega = 0.9^{+0.18}_{-0.16}$, baryon density, $\Omega_b h^2 = 0.0325 \pm 0.0125$ and power spectrum normalization $C_{10} = 690^{+200}_{-125}\mu K^2$. Our 95% confidence limit on the cold dark matter density is $\Omega_{cdm}h^2 = 0.17^{+0.16}_{-0.07}$. However, this result is mostly determined by the priors defining the database parameter range, as discussed in Jaffe et al. (2001).

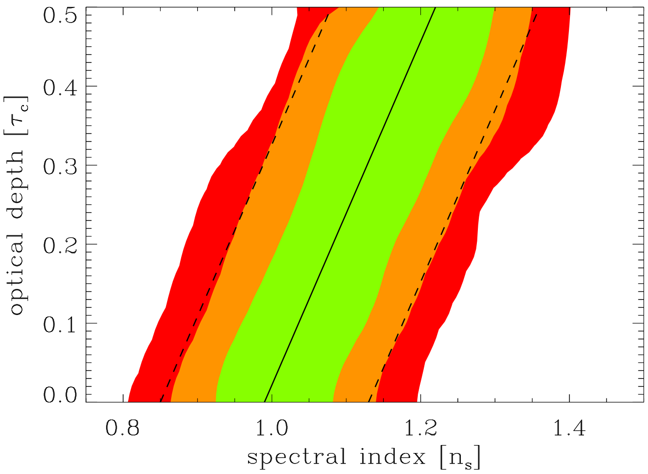

FIG. 3.— A spectral index – optical depth contour plot obtained for the MAXIMA-I data combined together with that of the *COBE*-DMR. Shaded contours show 68, ,95 & 99% likelihood-ratio confidence levels. Lines show an approximate relation between n_s and τ_c fitted to this result. Central values are shown by the solid line and 95% bounds by the dashed lines.

We find a strong degeneracy between the optical depth to the last scattering surface, τ_c, and the primordial power spectrum index, n_s (Fig. 3). In this case, the degeneracy restricts the parameters to a subspace allowing us to derive a combined constraint: $n_s \simeq 0.46\tau_c + (0.99 \pm 0.14)$ (95% c.l.), for $\tau_c \leq 0.5$. We note that we recover the 95% upper limit ($\lesssim 0.4$) on τ_c, derived by Griffiths et al. (1999), if we constrain the spectral index to be ≤ 1.2 as was assumed by those authors. Independent of the value of the optical depth, we can put a very firm $\gtrsim 99\%$ lower limit on the spectral index $n_s \geq 0.8$. Assuming no reionization ($\tau_c = 0$), 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% c.l. upper limit $\tau_c \lesssim 0.26$.

The best fit model parameters $(\Omega_b, \Omega_{cdm}, \Omega_\Lambda, \tau_c, n_s, h) = (0.07, 0.68, 0.1, 0.0, 1.025, 0.63)$ are characterized by the high matter and low vacuum energy content (see also Balbi et al. 2000). However, due to strong degeneracy between Ω_m and Ω_Λ (e.g., Zaldarriaga, Spergel, & Seljak 1998) we can easily find models comfortably fulfilling both MAXIMA-I+DMR and supernovae constraints (see Figure 4). The χ^2 of the best fit model is 30 for all 41 points used in the fittings, and 4 for the 13 points of MAXIMA-I only.

The constraint on $\Omega_b h^2$ mentioned above is compatible with the best determination to date of the baryon density based on measurements of primordial deuterium and calculations of standard Big Bang nucleosythesis (Burles, Nollett, & Turner, 2001, Tytler et al. 2000), $\Omega_b h^2 = 0.020 \pm 0.002$. The consistency of the data with BBN becomes even more apparent by constraining our parameter estimation on the BBN value of $\Omega_b h^2$, which we approximate by fixing $\Omega_b h^2$ at the grid value nearest to the BBN prediction (i.e., $\Omega_b h^2 = 0.02$). The best fit model has parameters $(\Omega_b, \Omega_{cdm}, \Omega_\Lambda, \tau_c, n_s, h) = (0.07, 0.78, 0.0, 0.0, 1.0, 0.53)$ with a $\chi^2 \simeq 7$ for the 13 MAXIMA-I points only. This extremely 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, showing that even in that case, the best fit model has a higher third than second peak.

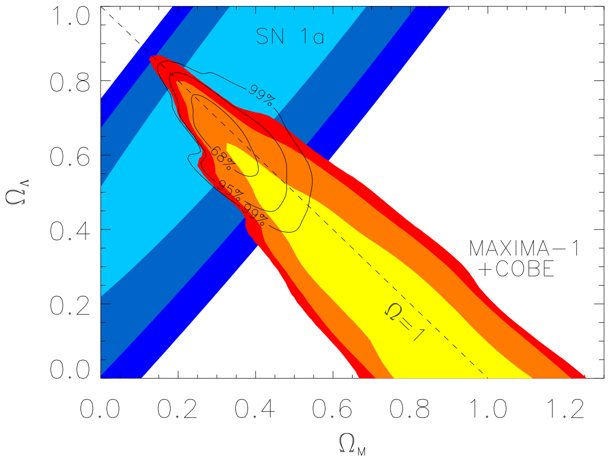

FIG. 4.— Constraints in the Ω_m–Ω_Λ plane from the combined MAXIMA-I and *COBE*-DMR datasets. The shown contours correspond to 68, 95, & 99% likelihood-ratio confidence levels. The bounds obtained from high redshift supernovae data (Perlmutter et al. 1999; Riess et al. 1998) are also overlaid as well as the confidence levels of the joint likelihood.

We also compute constraints on the ratio of bin powers, $\mathcal{R}_{01}$, as imposed by the MAXIMA-I data within the discussed family of models. We find that the most likely value of that ratio is $0.68^{+0.27}_{-0.13}$ at the 95% confidence level, consistent with (though on average higher than) our "model-independent" results in Section 2 (see Figure 2).

4. IMPLICATIONS FOR COSMOLOGICAL MODELS

Inflation-based models provide us with an abundance of excellent fits to the MAXIMA-I extended power spectrum. These include the best fit models found by the analysis of the first data sets of BOOMERANG-LDB and MAXIMA-I (Jaffe et al. 2001, Balbi et al. 2000). Constraints on cosmological parameters using DMR and MAXIMA-I confirm the near flatness of the Universe and, when combined with recent supernova data (Riess et al. 1998, Perlmutter, et al. 1998), support the need for the non-zero 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 indicate an increase in the power spectrum between $\ell \sim 410-785$ and $\ell \sim 786-925$, which, within the considered family of inflationary models, requires the ratio of the corresponding bin powers to be $\mathcal{R}_{01} = 0.68^{+0.27}_{-0.13}$.

The 95% confidence lower limit on the power at $\ell \sim 860$

is $\simeq 1700 \mu K^2$, only slightly lower than the average power in the $410 \leq \ell \leq 785$ region of our spectrum. We have shown that such a constraint can be easily fulfilled by these inflationary models. However, it imposes strong requirements on some non-standard models which were proposed to better accommodate the first results of the BOOMERANG-LDB and MAXIMA-I 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 tend to also have lower power at the high ℓ end and therefore to disagree with our new constraint at $\ell \sim 860$. These disfavored models include: the mixture of inflation and topological defect models (Bouchet et al. 2000, Contaldi 2000), hybrid adiabatic plus isocurvature initial condition models (Stompor, Banday, & Górski, 1996, Enqvist, et al. 2000), broken power-law primordial spectra models (Griffiths, Silk, & Zaroubi, 2000, Barriga et al. 2001), or models with a delayed recombination (Peebles, et al. 2001).

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