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CONSTRAINTS ON COSMOLOGICAL PARAMETERS FROM MAXIMA-1

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ABSTRACT

We set new constraints on a seven-dimensional space of cosmological parameters within the class of inflationary adiabatic models. We use the angular power spectrum of the cosmic microwave background measured over a wide range of ℓ in the first flight of the MAXIMA balloon-borne experiment (MAXIMA-1) and the low ℓ results from COBE/DMR. We find constraints on the total energy density of the universe, $\Omega = 1.0^{+0.15}_{-0.30}$, the physical density of baryons, $\Omega_{\rm b}h^2 = 0.03 \pm 0.01$, the physical density of cold dark matter, $\Omega_{\rm cdm}h^2 = 0.2^{+0.2}_{-0.1}$, and the spectral index of primordial scalar fluctuations, $n_s = 1.08 \pm 0.1$, all at the 95% confidence level. By combining our results with measurements of high-redshift supernovae we constrain the value of the cosmological constant and the fractional amount of pressureless matter in the universe to $0.45 < \Omega_\Lambda < 0.75$ and $0.25 < \Omega_{\rm m} < 0.50$, at the 95% confidence level. Our results are consistent with a flat universe and the shape parameter deduced from large scale structure, and in marginal agreement with the baryon density from big bang nucleosynthesis.

Subject headings: cosmic microwave background — cosmology: observations — large-scale structure of universe

1. INTRODUCTION

The angular power spectrum of the cosmic microwave background (CMB) temperature anisotropy depends strongly on the values of most cosmological parameters and on the physical processes in the early universe; it is thus a powerful tool to constrain cosmological models (see e.g., Kamionkowski & Kosowsky 1999). Several authors have used CMB data from a number of experiments to constrain cosmological parameters (see e.g., Lange et al. 2000, Tegmark & Zaldarriaga 2000, and references therein).

In this letter we make use of the angular power spectrum measured in the first flight of the MAXIMA balloon-borne experiment, MAXIMA-1 (described in a companion paper by Hanany et al. 2000). This power spectrum covers a range $36 \le \ell \le 785$, which is the largest coverage in multipole space from a single experiment to date. We include in our analysis the 4-year COBE/DMR angular power spectrum (Górski et al. 1996), which spans the range $2 \le \ell \le 34$, to normalize the models at large angular scales. We determine constraints on a seven-dimensional space of cosmological parameters within the class of inflationary adiabatic models.

This letter is structured as follows. In Section 2 we describe and justify the cosmological parameters space we have explored and the technique we used to perform the maximum likelihood analysis. In Section 3 we apply the method to the MAXIMA-1 and COBE/DMR data, to set constraints on the suite of parameters. We also combine our constraints with those from the high-redshift supernovae measurements (Perlmutter et al. 1999; Riess et al. 1998) to set bounds on the fractional density in a cosmological constant, Ω_Λ, and pressureless matter, $\Omega_{\rm m}$. In Section 4 we summarize our results and discuss their implications for fundamental models of structure formation.

2. DATASET, METHODS AND PARAMETER SPACE

The MAXIMA-1 power spectrum is estimated in 10 bins spanning the range $36 \le \ell \le 785$ (Hanany et al. 2000). In each bin, the spectrum is assigned a flat shape, $\ell(\ell+1)C_\ell/2\pi = \mathcal{C}_B$, whose amplitude is found by maximizing the likelihood of the data using a quadratic estimator technique (Bond, Jaffe & Knox 1998) as implemented in the MADCAP software package (Bor-

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rill 1999). We find the most likely values of the cosmological parameters by maximizing the likelihood of the data. Following Bond, Jaffe & Knox (2000) we use a likelihood which is Gaussian in the quantity $\ln(\mathcal{C}_B + x_B)$, with x_B related to the noise properties of the experiment.

In this letter we only consider inflationary adiabatic models. There are two main reasons. First, the poor performance of alternative theories in reconciling measurements of clustering on galactic scales with measurements of CMB fluctuations on horizon scales has made inflation the favored contender as a fundamental theory of structure formation. Second, the angular power spectra for inflationary models are easy to calculate for given cosmological parameters, especially since the advent of fast Einstein-Boltzmann solvers such as CMBFAST (Seljak & Zaldarriaga 1996) or CAMB (Lewis, Challinor & Lasenby 2000).

We consider a seven-dimensional space of parameters. This includes the amplitude of fluctuations at $\ell = 10$, C_{10}, the fractional densities of baryons, $\Omega_{\rm b}$, and cosmological constant, Ω_Λ, the total energy density of the universe, $\Omega \equiv \Omega_{\rm m} + \Omega_\Lambda$ (where the fractional density of pressureless matter is $\Omega_{\rm m} \equiv \Omega_{\rm b} + \Omega_{\rm cdm}$ and $\Omega_{\rm cdm}$ is the fractional density of cold dark matter) 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 = 0.1, 0.3, 0.5, 0.7, 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2, 1.3, 1.5; $\Omega_{\rm b}$ = 0.01, 0.03, 0.05, 0.07, 0.09, 0.12, 0.20, 0.28; Ω_Λ = 0.0, 0.1, $\cdots$, 0.8, 0.9; n_s = 0.60, 0.64, $\cdots$, 1.36, 1.40; τ_c = 0, 0.025, 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.5. For the seventh parameter we have either used the Hubble parameter, H_0 = 40, 45, $\cdots$, 85, 90 km s^{-1}Mpc^{-1}, or the physical baryon density, $\Omega_{\rm b}h^2$ = 0.003125, 00625, 0.0125, 0.0175, 0.02, 0.025, 0.030, 0.035, 0.04, 0.05, 0.075, 0.1, 0.15, 0.2 (where $h \equiv H_0/(100$ km s^{-1}Mpc^{-1})). This approach allows us to check the importance of the parameters ranges, which are effectively used as a uniform prior in our analysis. When we use H_0 as the free parameter we get relatively fine but restricted coverage of H_0 and $\Omega_{\rm b}h^2$. When we use $\Omega_{\rm b}h^2$ we consider a much more extended set of priors. To ensure that we are sampling the set of parameters with enough resolution, we include models corresponding to values of the parameters that are not on the grid by quadratically interpolating between power spectra. We have not allowed for the presence of massive neutrinos, since their effect on the angular power spectrum of the CMB would be negligible for the dataset used here (Dodelson, Gates & Stebbins 1996).

We evaluate the likelihood for a subset of parameters by maximizing it over all the remaining parameters. This approach, already adopted in previous analyses of this kind (Tegmark & Zaldarriaga 2000; Melchiorri et al. 1999), replaces the time-consuming integration that is required to marginalize over the unwanted parameters. In all our estimates we marginalize over the overall MAXIMA-1 calibration uncertainty (Hanany et al. 2000), assuming a Gaussian prior; we have also marginalized over the beam uncertainty reported in Hanany et al. (2000) but have found that it has a negligible effect on our results.

3. CONSTRAINTS

The position of the first peak in the angular power spectrum of adiabatic models can be used to constrain the geometry of the universe (Doroshkevich, Zel'dovich & Sunyaev 1978). Features in the radiation pattern at recombination are set by the maximum distance sound waves have traveled at that time. The diameter-distance relation allows us to relate the physical scale of these features to the angle they subtend on the sky and strongly depends on the curvature of the universe, which is determined by the total energy density of the universe $\Omega \equiv \Omega_{\rm m} + \Omega_\Lambda$. Other cosmological parameters have much less effect on this relation.

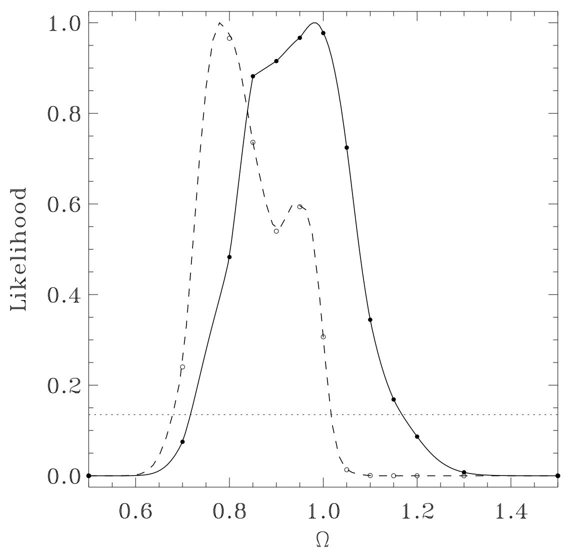

FIG. 1.— Likelihood function of the total energy density of the universe Ω. The solid line was obtained by maximizing over all other parameters over the ranges described in the text, while the dashed line was obtained by constraining $\Omega_{\rm b}h^2 = 0.0190 \pm 0.0024$ and $H_0 = 65 \pm 7$ km s^{-1} Mpc^{-1}. The intersections with the horizontal line give the bounds for 95% confidence.

Figure 1 shows the likelihood of the total energy density of the universe, Ω. We obtain the solid line if we maximize over all the remaining parameters; we get the dashed line if we impose the big bang nucleosynthesis (BBN) constraint $\Omega_{\rm b}h^2 = 0.0190 \pm 0.0024$ (Burles et al. 1999; see also, Tytler et al. 2000), and restrict $H_0 = 65 \pm 7$ km s^{-1} Mpc^{-1} (Freedman 1999). From the solid line we see that $0.7 < \Omega < 1.15$ at the 95% confidence level.

We identified the other tightly constrained parameters from a principal component analysis of the likelihood function (Efstathiou & Bond 1999). In Figure 2 we plot the likelihoods for three well-constrained parameters, the physical baryon density, $\Omega_{\rm b}h^2$, the physical cold dark matter density, $\Omega_{\rm cdm}h^2$, and the spectral index of primordial scalar fluctuations, n_s. The likelihood for each parameter was obtained by maximizing over all the remaining parameters.

We find $0.02 < \Omega_{\rm b}h^2 < 0.04$, $0.1 < \Omega_{\rm cdm}h^2 < 0.4$, and $0.98 < n_s < 1.18$, all at the 95% confidence level. The constraint on $\Omega_{\rm b}h^2$ is independent of the one coming from BBN (Burles et al. 1999) and agrees with it at about the 2σ level. However, the most likely value of $\Omega_{\rm b}h^2$ emerging from our dataset is noticeably higher than the one from BBN. Imposing the BBN prior to our dataset has the effect of moving the best fit region towards open models (see Figure 1). The constraint on n_s indicates that the combined MAXIMA-1 and COBE/DMR data are consistent with a scale invariant spectrum, with a smaller variance than that estimated using previous datasets (see e.g., Lange et al.

2000, Tegmark & Zaldarriaga 2000). This result should however be interpreted with some caution, because it is sensitive to assumptions on the treatment of calibration uncertainties and depends in part on the absence of tensor modes in our analysis.

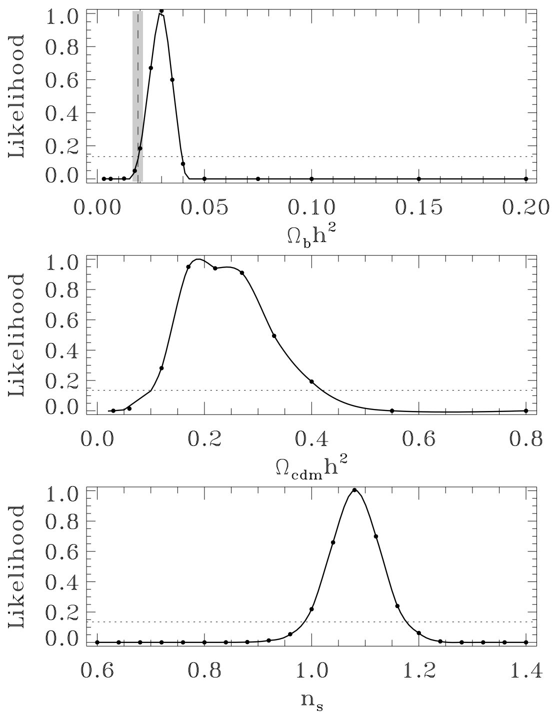

FIG. 2.— Likelihoods of three cosmological parameters: from top to bottom, the physical baryon density, $\Omega_b h^2$, the physical cold dark matter density, $\Omega_{cdm} h^2$, and the scalar spectral index, n_s. For each of these parameters, the likelihood was maximized over all the remaining parameters. The vertical band in the top panel represents the BBN constraint $\Omega_b h^2 = 0.0190 \pm 0.0024$ (Burles et al. 1999). The intersections with the horizontal line give the bounds for 95% confidence.

One of the intriguing developments arising in contemporary observational cosmology is the possible existence of a smooth, negative-pressure component, for example a cosmological constant, driving an accelerated expansion of the universe (Perlmutter et al. 1999; Riess et al. 1998). While CMB data are quite powerful in constraining the total energy density of the universe, a precise independent determination of Ω_m and Ω_Λ is limited by the presence of the geometrical degeneracy discussed in Efstathiou & Bond (1999) (which can be broken if a gravitational lensing imprint on the CMB is detected, see e.g., Stompor & Efstathiou 1999). We can however find the locus of models in the Ω_m—Ω_Λ plane which are favored by the combined MAXIMA-1 and COBE/DMR data. We do so in Figure 3, where once again we maximize over all the remaining parameters. The fact that the MAXIMA-1 dataset extends to large values of ℓ helps to narrow the contours along the degeneracy direction $\Omega_m + \Omega_\Lambda$ = constant. Although a large portion of the Ω_m—Ω_Λ plane is ruled out, one clearly needs additional data to strongly break the degeneracy. We then overlay our results on the likelihood contours from the high-redshift supernovae data of Perlmutter et al. (1999) and Riess et al. (1998) and calculate the combined likelihood. The resulting constraints are: $0.45 < \Omega_\Lambda < 0.75$ and $0.25 < \Omega_m < 0.50$, at the 95% confidence level.

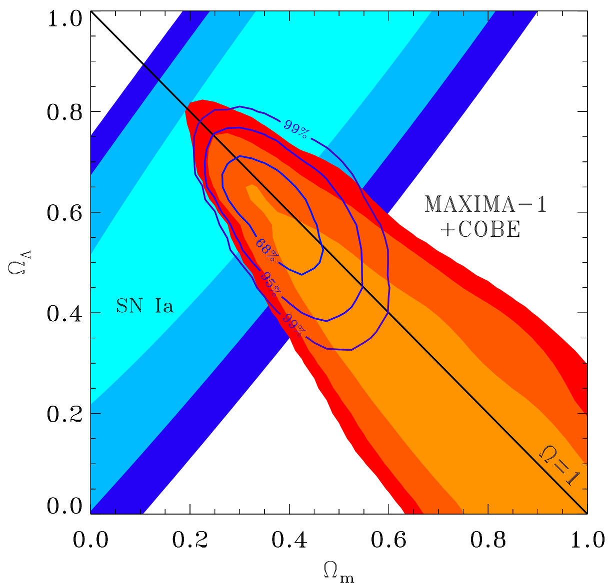

FIG. 3.— Constraints in the Ω_m–Ω_Λ plane from the combined MAXIMA-1 and COBE/DMR datasets. The likelihood at each point in the plane is taken by maximizing over the remaining five parameters. The borders of the shaded regions correspond to 0.32, 0.05 and 0.01 of the peak value of the likelihood. These are overlaid on the bounds obtained from high redshift supernovae data (Perlmutter et al. 1999; Riess et al. 1998). The closed contours are the confidence levels from the combined likelihood. The diagonal line corresponds to flat models.

4. CONCLUSIONS

Using the broad ℓ-space coverage of the MAXIMA-1 and COBE/DMR data we set constraints on a number of cosmological parameters within the class of inflationary adiabatic models. We find: $\Omega = 1.0^{+0.15}_{-0.30}$, $\Omega_b h^2 = 0.03 \pm 0.01$, $\Omega_{cdm} h^2 = 0.2^{+0.2}_{-0.1}$ and $n_s = 1.08 \pm 0.1$ at the 95% confidence level. The constraints we have obtained on Ω are consistent with those of other recent analyses (Melchiorri et al. 1999; Dodelson & Knox 1999; Tegmark & Zaldarriaga 2000; Lange et al. 2000) and provide further support to a flat universe. Combining our constraints with those coming from measurements of supernovae at high redshift strongly favors a non-zero cosmological constant, $\Omega_\Lambda = 0.60 \pm 0.15$, and a pressureless matter density parameter $\Omega_m = 0.375 \pm 0.125$, both at the 95% confidence level.

Our analysis was restricted to inflationary adiabatic models. Several hints suggest that this may indeed be the right paradigm. The presence of a localized peak in our data in the region $150 < \ell < 250$ is in itself an evidence in favor of inflationary adiabatic models; alternative theories either predict a broader peak at higher ℓ or a broad shelf at $\ell < 200$ (see e.g., Knox & Page 1999). Furthermore, from a goodness-of-fit analysis (with the caveat that our data are not perfectly well-described by a Gaussian likelihood) we find that the class of models we have considered are perfectly consistent with the data. Our best fit has χ^2=41 using the 38 data points of the combined MAXIMA-1/COBE dataset (χ^2=7 using only the 10 data points from MAXIMA-1). Within inflationary models, the

Standard CDM model and the Open CDM model with $\Omega = 0.3$ both provide a poor fit to our data, having, respectively, χ^2=67 (25) and χ^2=224 (159). The Λ-CDM 'concordance model' (Ostriker & Steinhardt 1995; Krauss & Turner 1995) has χ^2=50 (9). These results are summarized in Figure 4, where we plot the MAXIMA-1 data overlaid with various cosmological models.

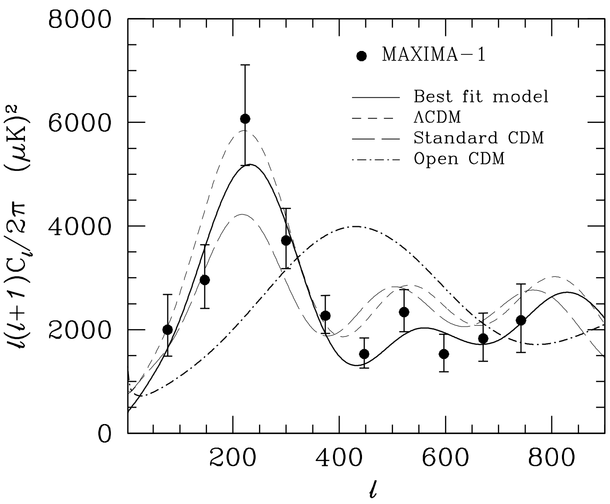

FIG. 4.— Angular power spectrum from MAXIMA-1 (Hanany et al. 2000). The solid line is the best fit model of our analysis, having $(\Omega_b, \Omega_{cdm}, \Omega_\Lambda, n_s, h) = (0.1, 0.6, 0.3, 1.08, 0.53)$. The long-dashed line is the Standard CDM model (0.05,0.95,0,1,0.5). The short-dashed line is the Λ-CDM model with (0.05,0.35,0.6,1,0.65). The dot-dashed line is the Open CDM model with $\Omega = 0.3$.

Finally, the agreement of our results with those obtained from other observations lends further credence to the possibility that we are considering the correct family of cosmological models. First, we find an independent constraint on the physical baryon density of the universe: $0.02 < \Omega_b h^2 < 0.04$, which, although favoring higher values than the BBN estimate of Burles et al. (1999), agrees with it within 2σ. Second, we are able to constrain the amount of cold dark matter in the universe: $\Omega_{cdm}h^2 = 0.2^{+0.2}_{-0.1}$. If we combine this value with our constraint on $\Omega_b h^2$ and the MAXIMA-1/COBE/SN Ia best fit value of $\Omega_m \simeq 0.375$ derived from Figure 3, we find that the "shape" parameter (commonly used in analysis of large scale structure; see e.g., Sugiyama 1995) is $\Gamma \equiv \Omega_m h \exp(-\Omega_b - \Omega_b/\Omega_m) = 0.24 \pm 0.1$. Together with our best estimate of $n_S = 1.08 \pm 0.1$, this is consistent with the value $\Gamma = 0.23 - 0.28(1 - 1/n_S)$ which emerges from a completely independent analysis of galaxy catalogs (Viana & Liddle 1999; Liddle et al. 1995; Peacock & Dodds 1994).

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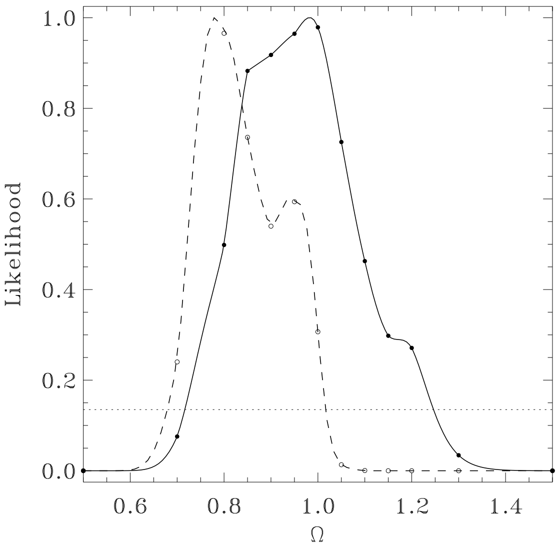
ERRATUM

In the Letter "Constraints on Cosmological Parameters from MAXIMA-1" by A. Balbi et al. (ApJ 545, L1 [2001]), an error was found in the results: while it is claimed in the Letter that the optical depth of reionization, τ_c, took values bewteen 0 and 0.5, an error in the computer code led to the results being based on $\tau_c = 0$. We have regenerated the database of models with the correct (published) values of τ_c, namely, τ_c = 0, 0.025, 0.05, 0.075, 0.1, 0.15, 0.2, 0.3, 0.5. The best-fit model quoted in the Letter remains unchanged. However, we have found that the 95% confidence level constraints on the total energy density of the universe, the physical density of baryons and the scalar spectral index of primordial fluctuations change to: $\Omega = 1.0^{+0.25}_{-0.30}$, $\Omega_{\rm b}h^2 = 0.030^{+0.018}_{-0.010}$ and $n_s = 1.08^{+0.32}_{-0.08}$, respectively. The likelihoods for the remaining parameters are effectively unchanged. In Figures 1 and 2, we present the figures which should replace Figures 1 and 2 of the original Letter.



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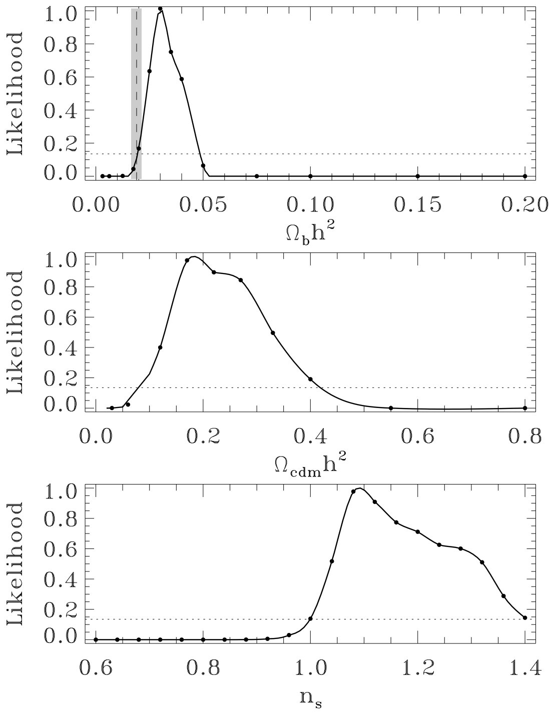

FIG. 2.— Likelihoods of three cosmological parameters: from top to bottom, the physical baryon density, $\Omega_{\rm b}h^2$, the physical cold dark matter density, $\Omega_{\rm cdm}h^2$, and the scalar spectral index, n_s. For each of these parameters, the likelihood was maximized over all the remaining parameters. The vertical band in the top panel represents the BBN constraint $\Omega_{\rm b}h^2 = 0.0190 \pm 0.0024$ (Burles et al. 1999). The intersections with the horizontal line give the bounds for 95% confidence.