A MEASUREMENT OF Ω FROM THE NORTH AMERICAN TEST FLIGHT OF Boomerang

A. Melchiorri[1,2,9], P.A.R. Ade[3], P. de Bernardis[1], J.J. Bock[4,5], J. Borrill[6,7], A. Boscaleri[8], B.P. Crill[4], G. De Troia[1], P. Farese[10], P. G. Ferreira[9,11,12], K. Ganga[4,13], G. de Gasperis[2], M. Giacometti[1], V.V. Hristov[4], A. H. Jaffe[6], A.E. Lange[4], S. Masi[1], P.D. Mauskopf[14], L. Miglio[1,15], C.B. Netterfield[15], E. Pascale[8], F. Piacentini[1], G. Romeo[16], J.E. Ruhl[10] and N. Vittorio[2]

[1] Dipartimento di Fisica, Universita' La Sapienza, Roma, Italy
[2] Dipartimento di Fisica, Universita' Tor Vergata, Roma, Italy
[3] Queen Mary and Westfield College, London, UK
[4] California Institute of Technology, Pasadena, CA, USA
[5] Jet Propulsion Laboratory, Pasadena, CA, USA
[6] Center for Particle Astrophysics, University of California, Berkeley, CA, USA
[7] National Energy Research Scientific Computing Center, LBNL, Berkeley, CA, USA
[8] IROE-CNR, Firenze, Italy
[9] Dept. de Physique Theorique, Universite de Geneve, Switzerland
[10] Dept. of Physics, Univ. of California, Santa Barbara, CA, USA
[11] CENTRA, IST, Lisbon, Portugal
[12] Theory Division, CERN, Geneva, Switzerland
[13] Physique Corpusculaire et Cosmologie, College de France, 11 place Marcelin Berthelot, 75231 Paris Cedex 05, France
[14] Dept. of Physics and Astronomy, University of Massachussets, Amherst, MA, USA
[15] Depts. of Physics and Astronomy, University of Toronto, Canada
[16] Istituto Nazionale di Geofisica, Roma, Italy

ABSTRACT

We use the angular power spectrum of the Cosmic Microwave Background, measured during the North American test flight of the Boomerang experiment, to constrain the geometry of the universe. Within the class of Cold Dark Matter models, we find that the overall fractional energy density of the universe, Ω, is constrained to be $0.85 \leq \Omega \leq 1.25$ at the 68% confidence level. Combined with the COBE measurement and the high redshift supernovae data we obtain new constraints on the fractional matter density and the cosmological constant.

Subject headings: cosmology: Cosmic Microwave Background, anisotropy, measurements, power spectrum

1. INTRODUCTION

The dramatic improvement in the quality of astronomical data in the past few years has presented cosmologists with the possibility of measuring the large scale properties of our universe with unprecedented precision (e.g. Kamionkowski & Kosowsky 1999). The sensitivity of the angular power spectrum of the Cosmic Microwave Background (CMB) to cosmological parameters has lead to analyses of existing datasets with increasing sophistication in an attempt to measure such fundamental quantities as the energy density of the universe and the cosmological constant. This activity has lead to improved methods of Maximum Likelihood Estimation (Bond, Jaffe & Knox 1998, hereafter BJK98, Bartlett et al 1999), attempts at enlarging the range of possible parameters (Lineweaver 1998, Tegmark 1999, Melchiorri et al. 1999), and the incorporation of systematic uncertainties in the experiments (Dodelson & Knox, from now on DK99, Ganga et al. 1997).

Within the class of adiabatic inflationary models there is now strong evidence from the CMB that the universe is flat. The most extensive range of parameters has been considered by Tegmark (1999) where the author found that a flat universe was consistent with CMB data at the 68% confidence level. A more thorough analysis was performed in DK99, incorporating the non-Gaussianity of the likelihood function, possible calibration uncertainties and the

most recent data: again, the 68% likelihood contours comfortably encompass the Einsten-de Sitter Universe. All these previous analyses were restricted to the class of open and flat models.

In this *letter* we present further evidence for a flat universe from the CMB. Using the methods for parameter estimation described in BJK98, we perform a search in cosmological parameter space for the allowed range of values for the fractional density of matter, Ω_M, and cosmological constant, Ω_Λ, given the recent estimate of the angular power spectrum from the 1997 test flight of the Boomerang experiment (see the companion paper Mauskopf et al. 1999). We obtain our primary constraints from this data set *alone* and find compelling evidence, *within the family of adiabatic inflationary models* for a flat universe. In section 2 we briefly describe the Boomerang experiment, the data analysis undertaken and the characteristics of the angular power spectrum obtained. In section 3 we spell out the parameter space we have explored, the method we use and the constraints we obtain on the fractional energy density of the universe, $\Omega = \Omega_M + \Omega_\Lambda$. Finally in section 4 we discuss our findings and combine it with other cosmological data to obtain a new constraint on the cosmological constant.

2. THE DATA

The data we use here are from a North American test flight of BOOMERANG (BOOMERANG/NA), a balloon-borne telescope designed to map CMB anisotropies from a long-duration, balloon-borne (LDB) flight above the Antarctic. A detailed description of the instrument can be found in Masi et al. 1999. A description of the data and observations, with a discussion of calibrations, systematic effects and signal reconstruction can be found in Mauskopf et al. 1999. This test flight produced maps of the CMB with more than 200 square degrees of sky coverage at frequencies of 90 and 150 GHz with resolutions of 26 arcmins FWHM and 16.6 arcmins FWHM respectively.

The size of the BOOMERANG/NA 150 GHz map (23,561, $6'$ pixels) required new methods of analysis able to incorporate the effects of correlated noise and new implementations capable of processing large data sets. The pixelized map and angular power spectrum were produced using the MADCAP software package of Borrill (1999a, 1999b) (see http://cfpa.berkeley.edu/~borrill/cmb/madcap.html) on the Cray T3E-900 at NERSC and the Cray T3E-1200 at CINECA.
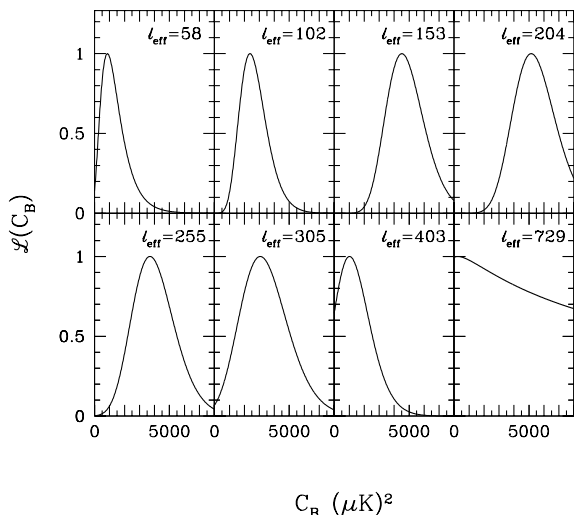

FIG. 1.— The Likelihood function of each of the eight band powers, $\ell_{\text{eff}} = (58, 102, 153, 204, 255, 305, 403, 729)$, reported in Mauskopf et al. 1999 computed using the offset lognormal ansatz of BJK98.

The angular power spectrum, C_ℓ, resulting from the analysis of the 150 GHz map was estimated in eight bins spanning ℓ with seven bin's centered between $\ell = 50$ to $\ell = 400$ and one bin at $\ell = 800$.

The bin correlation matrix is diagonalized as in BJK98 resulting in eight orthogonalized (independent) bins. We present the likelihood for each orthogonalized band power in Figure 1, using the offset lognormal ansatz proposed in BJK98. As described in Mauskopf et al. 1999 the data show strong evidence for an acoustic peak with an amplitude of $\sim 70\mu K_{CMB}$ centered at $\ell \sim 200$.

3. MEASURING CURVATURE

The BOOMERANG/NA angular power spectrum covers a range of ℓ corresponding to the horizon size at decou-

pling. The amplitude and shape of the power spectrum is primarily sensitive to the overall curvature of the universe, Ω (Doroskevich, Zeldovich, & Sunyaev 1978); other parameters such as the scalar spectral index, n_S, the fractional energy density in baryons, Ω_B, the cosmological constant, Ω_Λ, and the Hubble constant, $H_0 \equiv 100h$ km sec^{-1}, will also affect the height of the peak and therefore some "cosmic confusion" will arise if we attempt individual constraints on each of the parameters (Bond et al 1994). In our analysis we shall restrict ourselves to the family of adiabatic, CDM models. This involves considerable theoretical predjudice in the set of parameters we choose to vary although, as the presence of an acoustic peak at $\ell \sim 200$ becomes more certain, the assumption that structure was seeded by primordial adiabatic perturbations becomes more compelling (Liddle 1995; however, counterexamples exist, Turok 1997, Durrer & Sakellariadou 1997, Hu 1999).

We should, in principle, consider an 11-dimensional space of parameters; sensible priors due to previous constraints and the spectral coverage of the BOOMERANG/NA angular power spectrum reduce the space to 6 dimensions. In particular, we assume $\tau_c = 0$ (lacking convincing evidence for high redshift reionization), we assume a negligeable contribution of gravitational waves (as predicted in the *standard* scenario), and we discard the weak effect due to massive neutrinos. The remaining parameters to vary are Ω_{CDM}, Ω_Λ, Ω_B, h, n_S and the amplitude of fluctuations, C_{10}, in units of C_{10}^{COBE}. The combination $\Omega_B h^2$ is constrained by primordial nucleosynthesis arguments: $0.013 \leq \Omega_B h^2 \leq 0.025$, while we set $0.5 \leq h \leq 0.8$. For the spectral index of the primordial scalar fluctuations we make the choice $0.8 \leq n_S \leq 1.3$ and we let a 20% variation in C_{10}. As our main goal is to obtain constraints in the $(\Omega_M = \Omega_{CDM} + \Omega_B, \Omega_\Lambda)$ plane, we let these parameters vary in the range $[0.05, 2] \times [0, 1]$. Proceeding as in DK99, we attribute a likelihood to a point on this plane by finding the remaining four, "nuisance", parameters that maximize it. The reasons for applying this method are twofold. First, if the likelihood were a multivariate Gaussian in all the parameters, maximizing with regards to the nuisance parameters corresponds to marginalizing over them. Second, if we define our 68%, 95% and 99% contours where the likelihood falls to 0.32, 0.05 and 0.01 of its peak value (as would be the case for a two dimensional Multivariate Gaussian), then the constraints we obtain are conservative relative to any other hypersurface we may choose in parameter space in the sense that they rule out a smaller range of parameter space than other usual choices.

The likelihood function for the estimated band powers is non-Gaussian but one can apply the "radical compression" method proposed by BJK98; the likelihood function is well approximated by an offset lognormal distribution whose parameters can be easily calculated from the output of MADCAP. The theory C_ℓs are generated using CMB-FAST (Seljak & Zaldarriaga 1996) and the recent implementation for closed models CAMB (Lewis, Challinor & Lasenby 1999). We search for the maximum along a 4 dimensional grid of models, using the fact that variations in C_{10} and n_s are less CPU time consuming. We searched also for the multidimensional maxima of the likelihood adopting a *Downhill Simplex Method* (Press et al. 1989), obtaining consistent results.
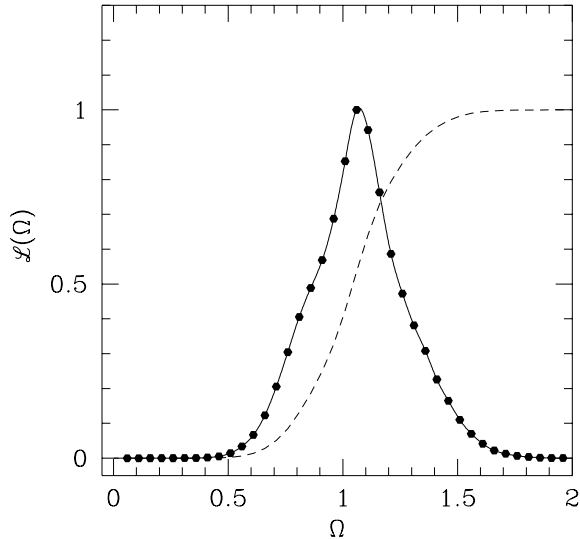
FIG. 2.— The Likelihood function of $\Omega = \Omega_M + \Omega_\Lambda$ normalized to unity at the peak after marginalizing along the $\Omega_M - \Omega_\Lambda$ direction. The dashed line is the cumulative likelihood.

In Figure 2, we plot the likelihood of Ω normalized to 1 at the peak where, again, we have maximized along the $\Omega_M - \Omega_\Lambda$ direction. The likelihood shows a sharp peak near $\Omega = 1$ and this result is insensitive to the tradeoff between Ω_M and Ω_Λ. (see Figure 3 and explanation in following paragraphs). This is an extreme manifestation of the "cosmic degeneracy" problem (because we are focusing on just the first peak): we are able to obtain robust constraints on Ω without strong constraints on Ω_M and Ω_Λ individually.

Within the range of models we are considering, we find that 68% of integrated likelihood corresponds to $0.85 \leq \Omega \leq 1.25$ ($0.65 \leq \Omega \leq 1.45$ at 95%). The best fit is a marginally closed model with $\Omega_{CDM} = 0.26$, $\Omega_B = 0.05$, $\Omega_\Lambda = 0.75$, $n_S = 0.95$, $h = 0.70$, $C_{10} = 0.9$. An almost equivalent good fit is given by $\Omega_{CDM} = 0.39$, $\Omega_B = 0.07$, $\Omega_\Lambda = 0.65$, $n_S = 0.90$, $h = 0.55$, $C_{10} = 1.0$.

In Figure 3 (top panel) we estimate the likelihood of the data for a 20×20 grid in $(\Omega_M, \Omega_\Lambda)$ by applying the maximization/marginalization algorithm described above. The effect of marginalizing is, as expected, to expand the contours along the $\Omega =$ constant lines but has little effect in the perpendicular direction and we are able to rule out a substantial region of parameter space.

For $\Omega_M \sim 1$ models, the position of the peak is solely dependent on the angular-diameter distance, with a good approximation being $\ell_{peak} \propto \Omega^{-\frac{1}{2}}$; this approximation breaks down when $\Omega_M \to 0$ where the early time integrated Sachs-Wolfe effect becomes important and ℓ_{peak} is far more sensitive to Ω (White & Scott 1996). This effect leads to a convergence of contour levels as $\Omega_M \to 0$ in Figure 3.
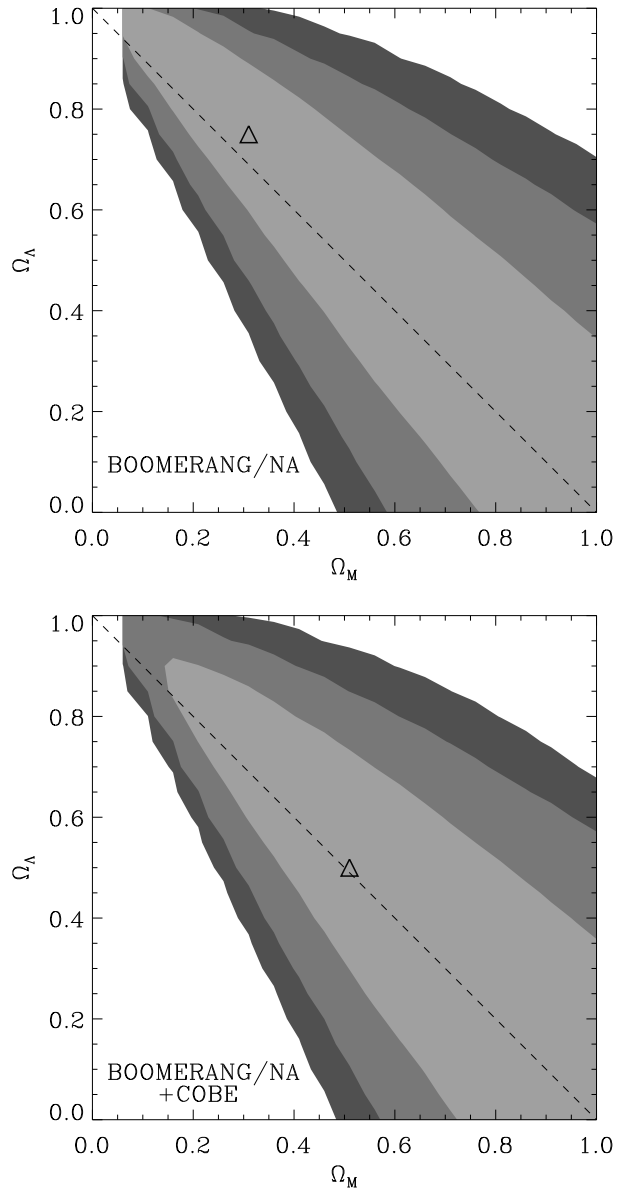

FIG. 3.— The likelihood contours in the Ω_M, Ω_Λ plane, evaluated at the maxima of the remaining four "nuisance" parametes. The top panel is from the BOOMERANG/NA data, the bottom panel is from BOOMERANG/NA+COBE. The contours correspond to 0.32, 0.05 and 0.01 of the peak value of the likelihood. The small triangle indicates the best fit. The dashed line corresponds to the flat models.

4. DISCUSSION

In the previous section we have obtained a constraint on Ω using only the BOOMERANG/NA data. These new results are consistent with Lineweaver (1998), Tegmark (1999) and DK99. However, the BOOMERANG/NA data on its own does not constrain the shape and amplitude of the power spectrum at $\ell \leq 25$ and limits our ability to independently determine the parameters n_S, Ω_B, h, Ω_Λ and C_{10}. We combine the BOOMERANG/NA data with the 4-year COBE/DMR angular power spectrum to attempt to break this degeneracy. In Figure 3 (bottom panel) we

plot the likelihood contours, again maximized over the nuisance parameters for the combined BOOMERANG/NA and COBE data. The inclusion of the COBE data does not greatly affect the constraints at high Ω_M or the confidence levels on Ω, but, as expected, it helps to close of the contours at low values of Ω_M. The best fit model changes to have $\Omega_{CDM} = 0.46$, $\Omega_B = 0.05$, $\Omega_\Lambda = 0.50$, $n_S = 1.0$, $h = 0.70$, $C_{10} = 0.94$. We find that for the likelihood to be greater than 0.32 of its peak value then $\Omega_M > 0.2$, again similar to the results of DK99.

One can combine our constraints with those obtained from the luminosity-distance measurements of high-z supernovae (Perlmutter et al. 1998, Schmidt et al 1998): using the 1-σ constraint from Perlmutter et al (1998), $\Omega_M - 0.6\Omega_\Lambda = -0.2 \pm 0.1$, we find $0.2 \leq \Omega_M \leq 0.45$ and $0.6 \leq \Omega_\Lambda \leq 0.85$.

A few comments are in order about the robustness of our analysis. Firstly we have not truly marginalized over the nuisance parameters. However the constraints we obtain in this way are, if anything, more conservative. Secondly, although we are limiting ourselves to standard adiabatic models, a strong case can be made against the rival theory of topological defects: the presence of a fairly localized rise and fall in the data around ℓ of 200 indicates that the characteristic broadening due to decoherence of the either cosmic strings (Contaldi, Hindmarsh & Magueijo 1999) or textures (Pen, Seljak & Turok 1997) is strongly disfavoured.

Finally we have restricted ourselves to only four extra nuisance parameters. Again we believe this does not affect our main result (our constraints on Ω) although it may affect the low Ω_M constraints when we combine the BOOMERANG/NA data with COBE; the results from Tegmark (1998) and DK99 lead us to believe that the effect will not greatly change our results.

To summarize we have used the angular power spectrum of the BOOMERANG/NA test flight to constrain the curvature of the universe. Given that we have based our results on this data set alone, our results are completeley independent from previous analysis of the CMB. At the time of submission, this *letter* is also the first analysis of this kind to include closed models in the computation.

We find strong evidence against an open universe: we find that $0.65 \leq \Omega \leq 1.45$ at the 95% confidence level, significantly ruling out the current favourite open inflationary models for structure formation (Lyth & Stewart 1990, Ratra & Peebles 1995, Bucher, Goldhaber & Turok 1995). Much tighter constraints will soon be placed on these and others cosmological parameters from future data sets, including data obtained during by the Antarctic LDB flight of BOOMERANG, which mapped over 1200 square degrees of the sky with $12'$ angular resolution and higher sensitivity per pixel than the BOOMERANG/NA.

REFERENCES

Bennett, C. L. et al. 1996, ApJ, 464, 1
Bond, J.R et al 1994, Phys. Rev. Lett. 72, 13.
Bond, J. R., Jaffe A. H., & Knox L. 1998, Phys. Rev. D, 57, 2117
Bond, J. R., Jaffe, A. H., & Knox, L. 1999, ApJ, submitted, astro-ph/9808264
Bartlett, J. et al, 1999, astro-ph/9903045
Borrill, J. 1999, *The Challenge of Data Analysis for Future CMB Observations*, in "Proceedings of the 3K Cosmology: EC-TMR Conference", Rome, Italy edited by L. Maiani, F. Melchiorri, and N.Vittorio AIP Conference Proceedings, astro-ph/9903204
Borrill, J. 1999, *MADCAP: The Microwave Anisotropy Dataset Computation Analysis Package*, in "Proceedings of the Fifth European SGI/Cray MPP Workshop", astro-ph/9911389
Borrill, J. 1999, Phys Rev D, 59, 7302, astro-ph/9712121
Bucher, M., Goldhaber, A. & Turok, N. 1995 Phys.Rev.D 52, 3314.
Contaldi, C., Hindmarsh, M. & Magueijo, J. 1999 Phys.Rev.Lett. 82 679.
Dodelson, S. & Knox, L. astro-ph/9909454
Durrer, R. & Kovner, I. 1990 ApJ356 49.
Doroskevich, A.G., Zeldovich, Ya. & Sunyaev, R. 1978, Sov. Astron., 22, 523.
Durrer, R. & Sakellariadou, M. 1997, Phys. Rev. D56, 4880.
Ganga, K., Ratra, B., Gunderson, J.O. & Sugiyama, N. 1997, ApJ, 484, 7

Hu, W. 1999, Phys. Rev. D. 59 021301
Kamionkowski, M. & Kosowsky, A., 1999, To appear in *Annu. Rev. Nucl. Part. Sci.*, astro-ph/9904108
Lewis A., Challinor A., Lasenby A., astro-ph/9911176
Lineweaver, C.H. 1998, ApJ505, L69
Liddle, A. 1995 Phys.Rev. D51, 5347.
Lyth, D. & Stewart, E. 1990 Phys. Lett. B 252, 336
Masi, S. et al. 1999, *BOOMERanG: a scanning telescope for 10 arcminutes resolution CMB maps*, in "Proceedings of the 3K Cosmology : EC-TMR Conference", Rome, Italy edited by L. Maiani, F. Melchiorri, and N.Vittorio AIP Conference Proceedings 476
Mauskopf, P. et al 1999, submitted to ApJ, astro-ph/9911444
Melchiorri, A. et al 1999, ApJ, 518, 562
Pen, U., Seljak, U. & Turok, N. 1997 Phys.Rev.Lett. 79 1611
Perlmutter et al astro-ph/9812133
Press et al, 199.. *Numerical Recipes*, C.U.P., Cambridge.
Ratra, B. & Peebles, P. 1995 Phys.Rev.D 52, 1837
Schmidt et al 1998 ApJ507, 46.
Seljak, U. & Zaldarriaga, M. 1996, ApJ, 469, 437.
Tegmark M. 1999, ApJ, 514, L69
Turok, N. 1997, Phys. Rev. Lett. 77 4138 (1996).
White, M. & Scott, D. 1996 ApJ459 415.
Wright, E. 1996, astro-ph/9612006