Evidence for a Flat Universe from the North American Flight of BOOMERANG

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Abstract

BOOMERANG is a millimeter- and submillimeter-wave telescope designed to observe the Cosmic Microwave Background from a stratospheric balloon above Antarctica. In August 1997, a test version of the payload flew in Texas, mapping 200 square degrees of the sky at 90 and 150 GHz at 26' and 17' resolution respectively. A measurement of the power spectrum of this map shows a localized peak of amplitude 75 μK at $\ell = 200$, evidence supporting the adiabatically seeded cold dark matter paradigm of structure formation. Within the context of these models, a maximum likelihood analysis shows evidence for a flat universe with $0.85 < \Omega < 1.25$ at the 68% confidence level.

1 Introduction

Recent measurements of the angular power spectrum of fluctuations in the Cosmic Microwave Background have put strong constraints on the angular scale and amplitude of a peak at degree scales. Here we present results from a 6 hour overnight test flight of the BOOMERANG experiment from Palestine, Texas which constrains the power spectrum further and thereby puts limits on the geometry of the universe. For further details see Mauskopf et al. 1999 and Melchiorri et al. 1999.

2 Instrument

BOOMERANG is a balloon-borne millimeter- and submillimeter-wave telescope designed for Long Duration Balloon (LDB) flights above Antarctica to observe the Cosmic Microwave Background. BOOMERANG uses silicon nitride micromesh bolometric detectors housed in a custom long duration liquid helium cryostat. The detectors are cooled to 0.3K with a Helium-3 sorption fridge and are coupled to an ambient temperature 1.3 meter off-axis primary mirror via conical feed horn structures and two cold (4K) re-imaging mirrors.

The optical signal is modulated on the sky by scanning the telescope in azimuth. Electronic modulation and synchronous demodulation of the bolometer signals provides the low frequency stability necessary for observations with total power radiometers.

The test receiver consists of 150 GHz and 90 GHz channels with 16.5' and 26' resolution. A "dark" bolometer is kept shielded from light external to the receiver in order to measure fluctuations of the detectors' thermal environment. The results presented here come primarily from a single 150 GHz detector which achieved an in-flight NET_{CMB} of 250 $\mu K/\sqrt{Hz}$. As a systematic test, data from a 90 GHz detector with NET_{CMB} of 400 $\mu K/\sqrt{Hz}$ was also analyzed.

3 Observations

The instrument was launched on August 30, 1997 and spent 6 hours at an average float altitude of 38.5 km. 4.5 hours were spent observing the CMB in 40 degree peak-to-peak azimuth scans centered on the South at an elevation angle of 45 degrees. The scans were smooth triangle waves with a peak scan speed of 2.1 azimuth degrees per second. As the earth rotated, the scans mapped out a wide strip of sky from -73 < RA < 23 and -20 < DEC < -16.

Observations of Jupiter, which was mapped twice during the flight, provided a measurement of the solid angle of the beam and a responsivity calibration. The precision of the calibration at 150 GHz and 90 GHz is 8.1% and 8.5%.

4 Power Spectrum Estimation

To produce a map and a power spectrum, the calibrated data are processed using the MADCAP software package (Borrill 1999) on the Cray T3E-900 at NERSC and the Cray T3E-1200 at CINECA. MADCAP produces a maximum likelihood map and pixel-pixel correlation matrix of 23,561, 1/3 beam sized (6') pixels from the time-ordered 150 GHz data, the noise correlation function, and the telescope pointing information. The maximum likelihood power spectrum is estimated from the map in eight bins between 25 < ℓ < 1125. and is shown in figure 1.

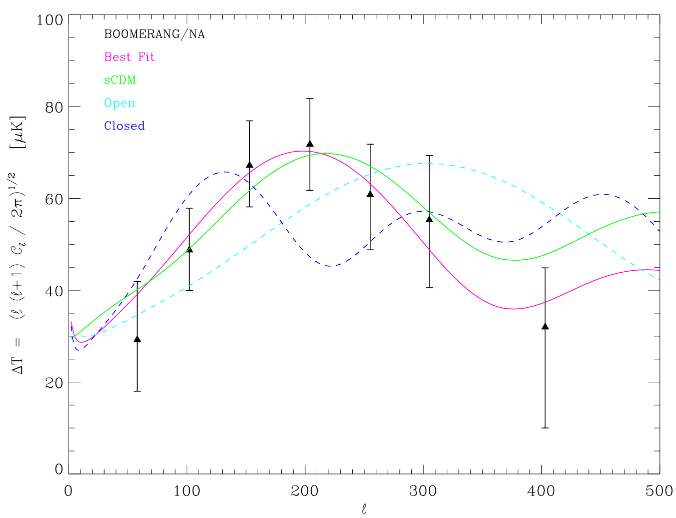

Figure 1: the angular power spectrum of the CMB as measured by BOOMERANG / NA. Superposed is the best-fit model of Melchiorri et al., a standard cold dark matter spectrum, and open and closed models.

5 Systematics Checks

The scan strategy and the analysis allow a variety of tests for systematic effects to be performed on the data. First, we analyze coarsely pixelized maps made from combinations of data which we expect to produce a null result: 1) the difference between left-going and right-going scans which are adjacent in time, and 2) the dark bolometer. The amplitude of a flat power spectrum for 25 < ℓ < 475 for the left-right difference is $\ell(\ell+1)C_\ell/2\pi$ = -400±200 μK^2 and -100±100 μK^2 for the dark channel. The negative power in the left-right difference is due to the effects of noise which is correlated from scan to scan and both results are consistent with zero.

To check that our measured power is indeed CMB anisotropy, we compare the 150 GHz power spectrum to that of the 90 GHz channel. Flat band powers for a single bin (25 < ℓ < 475) of $\ell(\ell+1)C_\ell/2\pi$ = 3100±500 μK^2 and 2500±700 μK^2 are found for 150 GHz and 90 GHz respectively.

The mapped region lies over a wide range of galactic latitude, from b=-15 to b=-80. To test for the presence of galactic foregrounds in the map, the data is divided into two halves: low galactic latitude (-15 < b < -45) and high galactic latitude (-45 < b < -80). These two halves are analyzed separately, and a consistent flat band power from 25 < ℓ < 475 of $\ell(\ell+1)C_\ell/2\pi$ = 3580±700 μK^2 and 2980±700 μK^2 are found for the low galactic latitude and high galactic latitude halves, respectively.

6 Measuring Curvature

The BOOMERANG / NA data cover a range of ℓ space corresponding to the horizon size at last scattering.The angular scale of a peak at degree angular scales in the angular power spectrum at $\ell = 200$ is primarily sensitive to the angle / distance relationship to last scattering and can be used to constrain the total energy density of the universe, $\Omega = \Omega_M + \Omega_\Lambda$.

We perform a maximum likelihood search in cosmological parameter space following the methods of Bond, Jaffe, and Knox (1998). We restrict our search to the family of adiabatic inflationary cosmological models and vary only the parameters $\Omega_{CDM}, \Omega_\Lambda, \Omega_B, h, n_s$, and C_{10}. We search a grid in the plane ($\Omega_M = \Omega_{CDM} + \Omega_B$,$\Omega_\Lambda$)over the range [0.05,2]and [0,1]. As in Dodelson and Knox, at each point on the grid, we maximize the likelihood with respect to the four remaining parameters. Using constraints from other cosmological measurements, we restrict the parameters to lie within $0.8 \le n_S \le 1.3$, $0.5 \le h \le 0.8$, $0.9 \le C_{10}/C_{10}^{COBE} \le 1.1$, and $0.013 \le \Omega_B h^2 \le 0.025$.

Using BOOMERANG / NA data alone, we obtain the results in figure 2.

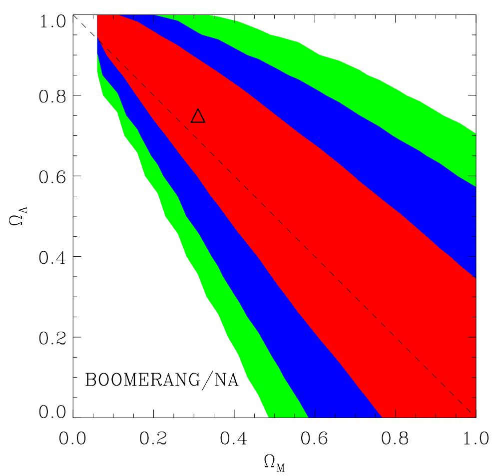

Figure 2: likelihood contours for the BOOMERANG / NA power spectrum alone. Colors represent contours corresponding to 0.32, 0.05, and 0.01 of the peak likelihood. The triangle represents the maximum likelihood model. 68% of the integrated likelihood corresponds to $0.85 \le \Omega \le 1.25$. The best fit model gives

7 Discussion

Within the class of models considered, we have obtained a strong constraint on Ω using BOOMERANG / NA data alone.

The constraints can be improved further by including data from other experiments. Figure 3 shows the results of the analysis including the COBE power spectrum measurement, and Figure 4 shows the results of the analysis including the results of Perlmutter et al. 1998. We find 1σ constraints $0.2 \le \Omega_M \le 0.45$ and $0.6 \le \Omega_\Lambda \le 0.85$.

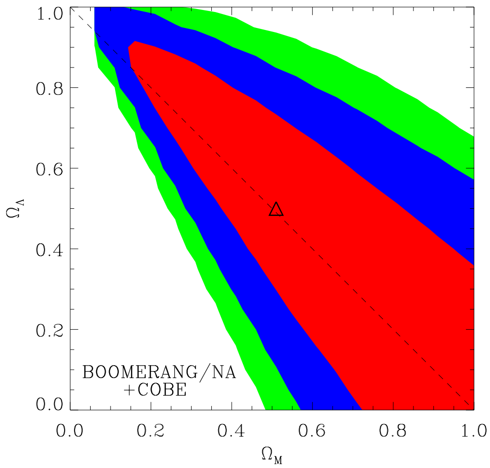

Figure 3: likelihood contours as in figure 2, including the COBE data with the BOOMERANG / NA power spectrum.

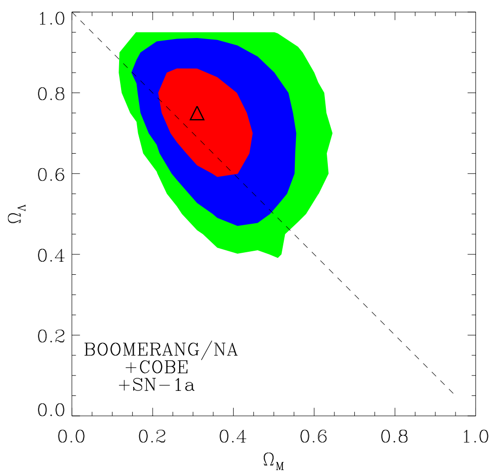

Figure 4: likelihood contours including high redshift supernovae data.

8 References

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