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Results From the First Year of Observations With the Wilkinson Microwave Anisotropy Probe

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The Wilkinson Microwave Anisotropy Probe (WMAP) has produced all-sky maps in five frequency bands between 23 and 94 GHz that can be used to study the CMB. We present an overview of the results from an analysis of maps made with one year of data. The highlights are that a) the flat ΛCDM model fits the data remarkably well, an Einstein-deSitter model ($\Omega_{\text{tot}} = 1$, $\Omega_\Lambda = 0$) does not; b) from the polarization of the CMB there is evidence of the birth of the first generation of stars at $z_r \sim 20$; c) when the WMAP data are combined and compared with other cosmological probes a cosmic consistency emerges: multiple different lines of inquiry lead to the same results. The best-fit flat cosmological model to just the WMAP CMB data shows that the matter density is $\Omega_{\text{m}}h^2 = 0.14^{+0.02}_{-0.02}$, the baryon density is $\Omega_{\text{b}}h^2 = 0.024 \pm 0.001$, and $n_{\text{s}} = 0.99 \pm 0.04$. WMAP continues to operate, and so results will improve.

KEY WORDS: cosmology; cosmic microwave background; WMAP; inflation.

1. INTRODUCTION

We present the first results from the Wilkinson Microwave Anisotropy Probe, WMAP, which completed its first year of observations on August 9, 2002. The satellite was named after Dave Wilkinson in February 2003. Dave was a leader in the development of the CMB as a potent cosmological probe. He was a founder of both COBE and WMAP. He died on Sept 5, 2002 after battling cancer for 17 years, all the while advancing our understanding of the origin and evolution of the universe.

The primary goal of WMAP is to produce high-fidelity polarization-sensitive maps of the microwave sky that may be used for cosmological tests. WMAP was proposed in June 1995, the major push started in June 1997 after the confirmation review, and it was launched on June 30, 2001. The mission is described in Bennett *et al.* (2003a) with more detailed descriptions of the radiometers, optics, and feed horns in Jarosik *et al.* (2003a), Page *et al.* (2003a), and Barnes *et al.* (2002). During the planning, bulding, and integration of the satellite, the emphasis was on

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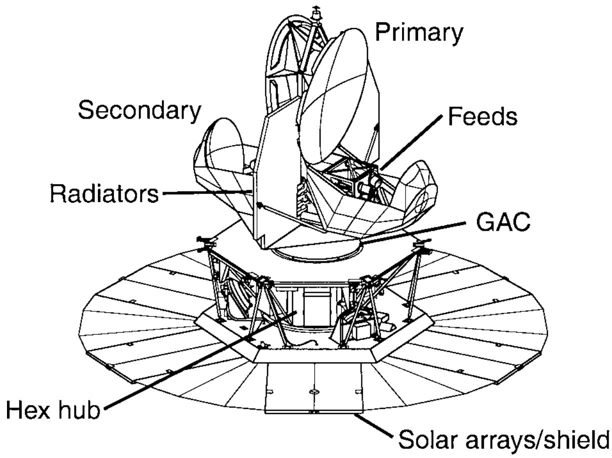

Fig. 1. Outline of the WMAP satellite. The overall height is 3.6 m, the mass is 830 kg, and the diameter of the large disk on the bottom is 5.1 m. The gamma alumina cylinder (GAC) thermally isolates the spacecraft body (hex hub) from the thermal reflector system. The radiators, each of area 2.8 m^2, radiatively cool the microwave components to <90 K.

minimizing systematic errors so that the data could be straightforwardly interpreted. The first year of data has been analyzed. The results are sumarized in Bennett *et al.* (2003b).

2. SUMMARY OF THE MISSION AND INSTRUMENT

Figure 1 shows an outline of the WMAP satellite. The instrument is composed of 10 symmetric, passively cooled, dual polarization, differential microwave receivers. The receivers are fed by two back-to-back 1.4 m by 1.6 m Gregorian telescopes. As shown in Table I, there are four receivers in W band (~94 GHz),

Table I. Characterisitics of the Instrument

Band	$\nu_{\rm center}$ (GHz)	$\Delta\nu_{\rm noise}$ (GHz)	$N_{\rm chan}$	ΔT/pix (μK)	$\theta_{\rm FWHM}$ (deg)
K	23	5	2	20	0.82°
Ka	33	7	2	20	0.62°
Q	41	7	4	21	0.49°
V	61	11	4	24	0.33°
W	94	17	8	23	0.21°

Note. The ΔT/pix is the Rayleigh-Jeans sensitivity per 3.2×10^{-5} sr pixel for the 4-year mission for all channels of one frequency combined.

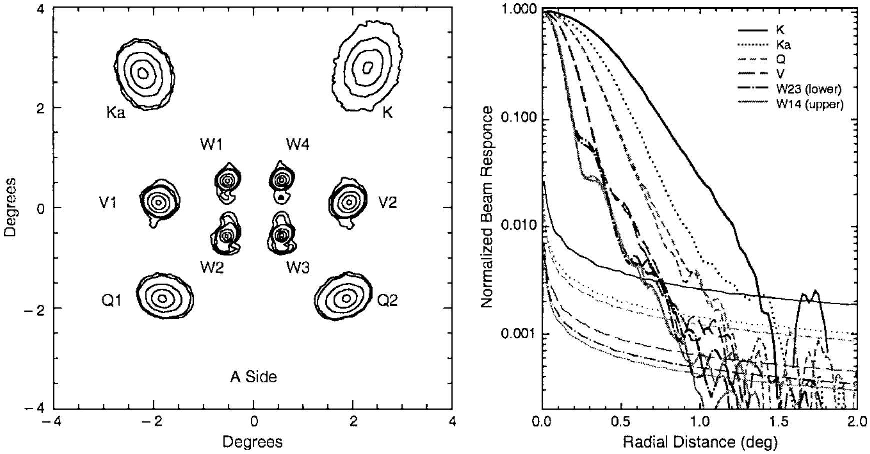

Fig. 2. *Left:* The A-side focal plane obtained from observations of Jupiter. Note that the beam widths are a function of frequency. The scan pattern symmetrizes all the beams. The contour levels correspond to 0.9, 0.6, 0.3, 0.09, etc. of the peak value. *Right:* The normalized, symmetrized beam response. Except in K band, the beams are mapped to better than −30 dB of their peak value. The lower set of lines shows the noise level in the maps.

two in V band (∼61 GHz), two in Q band (∼41 GHz), one in Ka band (∼33 GHz), and one in K band (∼22 GHz). WMAP is designed to measure only temperature differences from two regions of sky separated by roughly 140°. From a set of differential measurements over the full sky, a map of the anisotropy can be reconstructed (Wright *et al.*, 1996).

Precise knowledge of the beams is essential for accurately computing the CMB angular spectrum. The beams are mapped in flight with the spacecraft in the same observing mode as for CMB observations (Page *et al.*, 2003b). Using Jupiter as a source, we measure the beam to less than −30 dB of its peak value. Because of the large focal plane the beams are not symmetric, as shown in Fig. 2, neither are they Gaussian. In addition, as anticipated, cool down distortions of the primary mirrors distort the W-band and V-band beam shapes. Fortunately, also as anticipated, the scan strategy effectively symmetrizes the beam, greatly facilitating the analysis.

WMAP uses a type of correlation receiver to measure the differences in power coming from the outputs of the OMTs at the base of the feeds. At the heart of each of the 20 differential receivers are HEMT-based amplifiers developed by Marian Pospieszalski (1992, 1997) at the National Radio Astronomy Observatory (NRAO). In total, there are 40 signals (two for each radiometer) plus intrument housekeeping data. It is difficult to overemphasize the importance of understanding the radiometer noise and the stability of the satellite. Jarosik *et al.* (2003b) show that the radiometer noise is Gaussian over five decades in frequency.

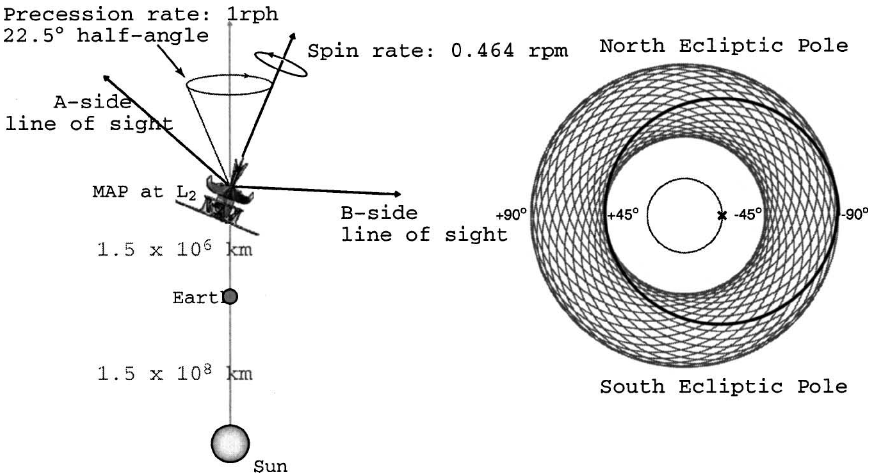

Fig. 3. WMAP's scan pattern from the second Lagrange point, L_2. The dark circle on the left hand drawing depicts the path covered by two beams for one rotation, the innermost circle is the path of the spin axis during one precession. The orbit follows a low maintenance Lissajous pattern with the Sun, Earth, and Moon always behind.

A highly interlocking scan strategy is essential for producing a high fidelity map with minimal striping. In any measurement, a baseline instrumental offset along with its associated drift, must be subtracted. Without cross hatched scans this subtraction can preferentially correlate pixels in large swaths, resulting in striped maps. WMAP's noise matrix is nearly diagonal. A typical off-diagonal element of the pixel-pixel covariance matrix is $<0.1\%$ the diagonal value, except in W4 where it is $\sim$0.5% at small lag (Hinshaw *et al.*, 2003a).

To achieve the interlocking scan, WMAP spins around its axis with a period of 2 min and precesses around a 22.5° cone every hour so that the beams follow a spirograph pattern as shown in Fig. 3. As a result $\approx$30% of the sky is covered in 1 h, before the instrument temperature can change appreciably. The axis of this combined rotation/precession sweeps out approximately a great circle as the Earth orbits the sun. In 6 months, the whole sky is mapped. The combination of WMAP's four observing time scales (2.5 kHz, 2.1 min, 1 h, 6 months) and the heavily interlocked pattern result is a strong spatiotemporal filter for any signal fixed in the sky.

With this scan, the instrument is continuously calibrated on the CMB dipole. The CMB dipole signal averages to zero over the 1-h precession period enabling a clean separation of gain and baseline variations. The final absolute calibration is actually based on the component of the dipole due to the Earth's velocity around the Sun. As a result, WMAP is calibrated to 0.5% (1σ, which will improve).

3. THE DATA PIPELINE AND MAPS

The primary scientific result from WMAP is the set of maps of the microwave sky of unprecedented precision and accuracy. The maps have a well defined systematic error budget (Hinshaw *et al.*, 2003a) and may be used to address the most basic cosmological questions (Spergel *et al.*, 2003) as well as to understand galactic and extragalactic emission (Bennett *et al.*, 2003c).

All of the instrument data, 110 MBy/day, are downlinked to the ground without any on-board flight data processing, thus allowing full insight into potential systematic effects. A small fraction is lost in the flow from the satellite to the processing center and about 1% is not used due to systematic error concerns (e.g., data taken during or near station-keeping maneuvers). Of the $\sim$99% good data, the processing pipeline flagged observations where bright planets were in the beams so that these data would not used be used in making maps.

There are a number of check that can be made of the maps. For example, the sum of two channels of the same frequency give a robust signal whereas the difference gives almost no signal. With the manifold instrumental redundancy, a myriad of other internal consistency checks are possible. In a comparison to the *COBE*/DMR map one sees that to within the limits of the noise WMAP and DMR are the same. This is a wonderful confirmation of the results from both satellites: they observe from different places, use different techniques, and have different systematic errors.

4. ANALYSIS OF MAPS

The first step in going from the maps to cosmology is to select a region of sky for analysis. Roughly 20% of the sky that is significantly contaminated by diffuse emission from our galaxy and by point source emission is masked. The selection process is described in Bennett *et al.* (2003c).

With the maps in hand, we show that the fluctuations in the CMB are Gaussian to the level that can be probed with WMAP (Komatsu *et al.*, 2003). The simplest expression for the overall primordial gravitational curvature perturbation, $\Phi(\mathbf{x})$, is a sum of a linear $\Phi_{\rm L}(\mathbf{x})$ and weak nonlinear components: $\Phi(\mathbf{x}) = \Phi_{\rm L}(\mathbf{x}) + f_{\rm NL}\,[\Phi_{\rm L}^2(\mathbf{x}) - \langle\Phi_{\rm L}(\mathbf{x})\rangle^2]$ where $\Phi_{\rm L}$ is the linear Gaussian portion of the curvature perturbation and $f_{\rm NL}$ is a nonlinear coupling constant. Then, $f_{\rm NL} = 0$ corresponds to the purely linear Gaussian case. For the bispectrum and Minkowski functionals, Komatsu *et al.* (2003) find $-58 < f_{\rm NL} < 134$ (95% CL) and $f_{\rm NL} < 139$ (95% CL), respectively. The two consistent results demonstrate that the CMB anisotropy follows Gaussian statistics.

The determination of Gaussanity is a key step in the interpretation of the data. It means that all of the information in the CMB is contained in the angular power spectrum. In the parlance of CMB analyses, it means that if the temperature distribution is expanded in spherical harmonics as

$$T(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi), \tag{1}$$

then the real and the imaginary parts of the a_{lm} are normally distributed. In other words, the phases between all the harmonics are random. There are no features in the CMB like strings or textures that require some definite relation between the phases. The gaussanity of the CMB is a triumph for models like inflation.

From the masked and cleaned maps, the angular power spectrum is produced as detailed in Hinshaw *et al.* (2003b). In producing the power spectrum only the cross correlations between the eight individual Q, V, and W intensity maps that have had the two polarizations combined are used. In addition, the process of the production of the power spectrum from the raw data is simulated in a large Monte Carlo program. The results are shown in the top panel of Fig. 4.

Maps of the Stokes Q and U polarization components are also produced (Hinshaw *et al.*, 2003a; Kogut *et al.*, 2003). These maps are derived from the difference of the two differential measurements common to one pair of feeds. We find a correlation between the temperature maps and the E-mode of the polarizations maps. This is due to the E-mode of the polarization (Kamionkowski *et al.*, 1997; Zaldarriaga and Seljak, 1997). The TE cross power spectrum is shown in the bottom panel of Fig. 4.

While the correlation at $l > 10$ is expected from the temperature distribution, the observed TE correlation for $l < 10$ changes our understanding of cosmic history. The E-mode in polarization of the CMB at these large angular scales is the result of reionization of the universe by the first stars. In our fiducial model, one assumes that the first generation of stars completely reionized the universe at a fixed redshift, z_r. The optical depth, τ, is then just the line integral out to z_r. We find that $\tau = 0.17 \pm 0.04$. Because quasar spectra show there is neutral hydrogen at $z = 6$ (Becker *et al.*, 2001; Djorgovski *et al.*, 2001; Fan *et al.*, 2002), the ionization history may not be as simple as in our model. After accounting for uncertainties, we find $z_r = 20^{+10}_{-9}$ (Kogut *et al.*, 2003).

The large optical depth changes the way one interprets the TT power spectrum. It means that the intrinsic CMB fluctuations are 30% larger than the TT plot shown. This in turn affects the σ_8 (or overall normalization) one gets for the CMB data.

5. COSMOLOGICAL INTERPRETATION

The CMB is a powerful probe of the early universe. Its potency lies in the fact that, given a model, the properties of the anisotropy can be computed to high accuracy. Nature has been kind to us in that the anisotropy can be measured to high accuracy without contamination by foreground emission.

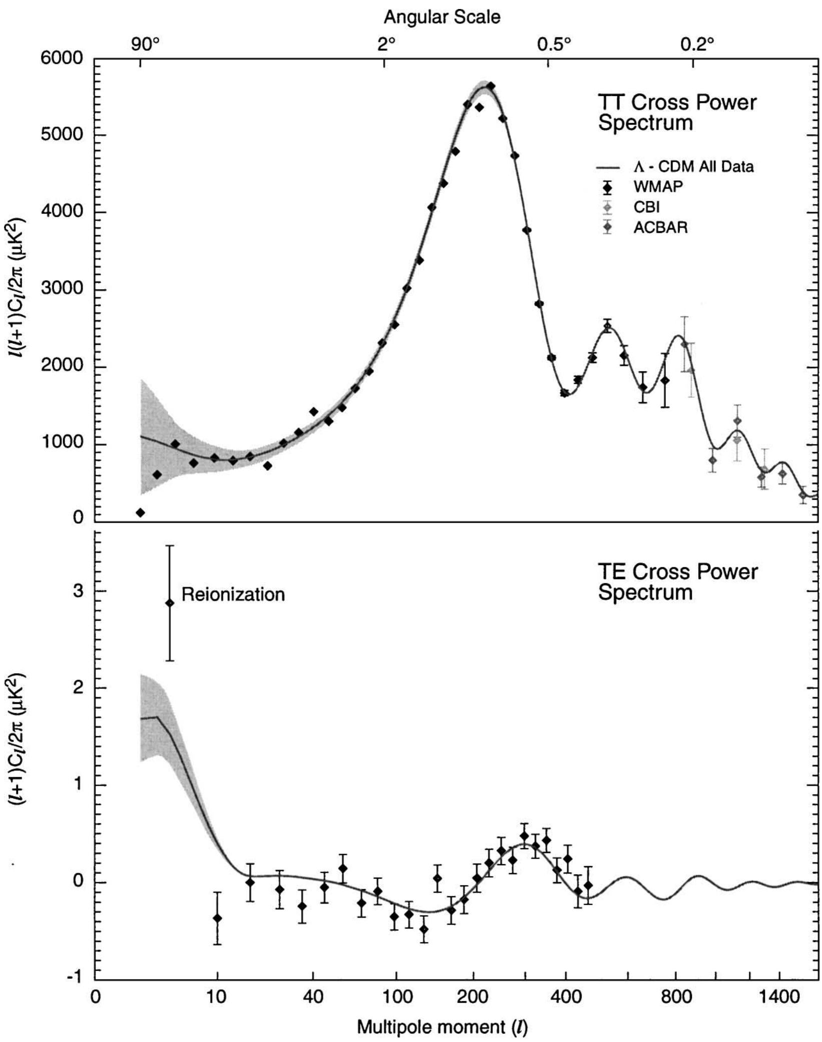

Fig. 4. The top panel shows the combined temperature (TT) cross power spectrum with error bars. The grey band shows the cosmic variance limit. WMAP is cosmic variance dominated up to roughly $l = 350$. Below $l = 100$, the noise is completely cosmic variance dominated and so only V and W bands are used. For $l > 700$ the WMAP data are augmented with data from CBI (Mason *et al.*, 2002) and ACBAR (Kuo *et al.*, 2004). The bottom panel shows the temperature-polarization (TE) cross power spectrum. The point labeled "Reionization" is the weighted average of the lowest eight multipoles. The red line is the best fit model. Note that the y axis of the TE data is scaled to emphasize the low-ℓ region of the spectrum.

For the simplest models of the CMB, there is an intrinsic parameter degeneracy called the "geometric degeneracy" (Bond *et al.*, 1994; Zaldarriaga and Seljak, 1997). Using the TT CMB data alone, one cannot separately determine Ω_m, h, and Ω_Λ even with cosmic variance limited data out to $\mathcal{L} \approx 2000$. One can play these parameters off one another to produce nearly identical spectra. The degeneracy is broken by picking a value of the Hubble parameter, assuming a flat geometry, or something similar. With the WMAP data, supernovae data (Tonry *et al.*, 2003; Perlmutter *et al.*, 1999; Riess *et al.*, 1998), and HST value (Freedman *et al.*, 2001) of $h = 0.72 \pm 3 \pm 7$, one finds $\Omega_T = 1.02 \pm 0.02$. With the WMAP data and a prior of $h > 0.5$, $0.98 < \Omega_T < 1.08$ (95% conf). While this does not *prove* the universe is geometrically flat, Occam's razor and the Dicke arguments that in part inspired inflation lead one to take the universe as flat as the basic model (Kamionkowski *et al.*, 1994).[2]

One way to see what the CMB alone can tell us is to plot the data in the $\Omega_m - \Omega_\Lambda$ plane for a pure cosmological constant, or equation of state $w = -1$. This is shown in Fig. 5 for the WMAP data. All simple, open, flat, and closed cosmological models satisfying the Friedmann equation can be plotted here. One picks a point in the space, a single source of the fluctuations (e.g., adiabatic fluctuations in the metric from an inflationary epoch) and marginalizes over the other parameters (n_s, ω_b, τ, A) with uniform priors. The possibilities are labeled by the Hubble parameter that goes with them.

There are a number of things the plot pulls together. The cluster of points along the line is the geomatric degeneracy. The degeneracy line clearly misses a model in which the universe is flat with $\Omega_m = 1(\Omega_\Lambda = 0)$, the Einstein-deSitter case. If one stretches the data slightly, it is possible to have a model with $\Omega_m \approx 1.3\,(\Omega_\Lambda = 0)$ but the price one pays is a Hubble parameter near 0.3. This value is in conflict with a host of other non-CMB observations. In addition, it is inconsistent at the 3σ level with the Integrated Sachs-Wolfe (ISW) induced cross-correlation between cosmic structure, as measured by radio sources, and the CMB anisotropy (Nolta *et al.*, 2003). Thus, in this minimal picture, there are no models with $\Omega_\Lambda = 0$ that fit the data.

Once one moves off the x axis, the intersection of the flat universe line, $\Omega_\Lambda + \Omega_m = 1$, and the geometric degeneracy is the next least baroque point, at least by today's standards of baroqueness. It is very satisfying that h for the intersection is very close to the value obtained from the Hubble Key project ($h = 0.72 \pm 0.03(\mathit{stat}) \pm 0.07(\mathit{sys})$, Freedman *et al.*, 2001). Additionally, the values agree with probes of the large scale structure and the supernovae data. From the plot, it is easy to see why such a weak prior on h (or Ω_m) picks out a flat universe.

When one takes the flat universe prior the cosmological parameters in Table II are obtained. We give the values for just power law models for the index, n_s. Values

[2] If $\Omega_\Lambda = 0$, then just the position of the first peak shows the universe is flat.

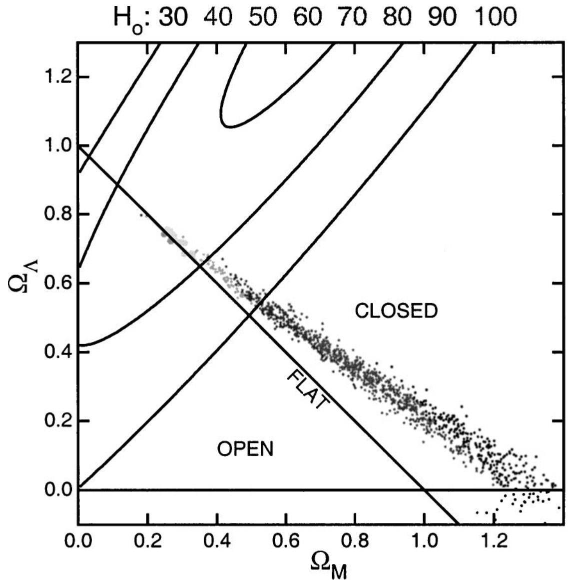

Fig. 5. Models consistent with the WMAP CMB data in the $\Omega_\Lambda - \Omega_m$ plane. The flat models correspond to the line with $\Omega_\Lambda + \Omega_m = 1$. This plot assumes that the dark energy has $w = -1$. The code at the top gives the values of the Hubble constant as one moves along the geometric degeneracy. It is striking that the value picked out by the CMB for a flat universe, $h = 0.71$, is in such agreement with the value from the HST key project. The observations behind these two probes are completely different and correspond to times separated by a good fraction the age of the universe. The 1σ, 2σ, and 3σ contours for the supernovae are plotted as well (Tonry *et al.*, 2003). Constraints from large scale structure would correspond to roughly a vertical swath centered on $\Omega_m = 0.3$. (From Ned Wright)

for a variety of models and parameter combinations are given in Spergel *et al.* (2003).

It is of interest that the reduced χ^2 for the best fit model has a probability to exceed of $\approx 5\%$. The reduced χ^2 is slightly large but on its own does not signal that the model is wrong. In fact, no matter what model is tried, the χ^2/ν more or less stays the same. If isocurvature modes are added to fit the low-ℓ region of the spectrum, $\chi^2/\nu = 1468/1378 = 1.065$ (Peiris *et al.*, 2003); if one adds tensor modes, allows the spectral index n_s to run, and the 2dFRGS (Colless *et al.*, 2001) are added, $\chi^2/\nu = 1465/1379 = 1.062$; if a step is added to the power spectrum that attempts to fit bumps and wiggles in the WMAP angular power spectrum, $\chi^2/\nu = 1422/1339 = 1.062$ (Peiris *et al.*, 2003). In other words, the admixture

Table II. Sample of Best Fit Cosmological Parameters

Parameter	WMAP only, flat	WMAP + others
A	0.9 ± 0.1	$0.75^{+0.08}_{-0.07}$
τ	$0.166^{+0.076}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
$\Omega_b h^2$	0.024 ± 0.001	0.0226 ± 0.0008
$\Omega_m h^2$	0.14 ± 0.02	0.133 ± 0.006
h	0.72 ± 0.05	0.72 ± 0.03
n_s	0.99 ± 0.04	0.96 ± 0.02
$\chi^2_{\rm eff}/\nu$	$1431/1342 = 1.066$	...

Note. The best fit parameters for the WMAP data for two of the models tested. The second column is for WMAP alon; the third is for a combination of WMAP+CBI+ACBAR+2DFGRS+Lyα. The Lyα data come from Croft *et al.* (2002). The χ^2 is not given because the Lyman-α data are correlated. (Spergel *et al.*, 2003).

of additional model elements does not substantially improve the fit over the basic model.

Though the simple model is a wonderful fit to the WMAP data, the small quadrupole and the related lack of correlation at large angular separations is striking. Though largely obscured by cosmic variance, there appears not even a hint of an upturn at low ℓ, as expected in ΛCDM models. (However, COBE also found no evidence for such an upturn.) This departure from the model constitutes a small (though possibly important) fraction of the total fluctuation power and does not cast doubt on the interpretation of the $\ell > 40$ spectrum.

Before it was widely appreciated that so many of the cosmological parameters could be deduced directly from the CMB (*e.g.*, Jungman *et al.*, 1995), the motivation for studying the anisotropy was that it would tell us the initial conditions for the formation of cosmic structure. In this vein, we summarize here some of the grander conclusions learned from WMAP.

1. A flat Λ-dominated CDM model with just six parameters, A, τ, $\Omega_m h^2$, $\Omega_b h^2$, h, and n_s, is an excellent description of the statistical properties of $> 10^6$ measurements of the anisotropy over 85% of the sky. This does not mean that simple flat ΛCDM is complete but any other model must look very much like it.
2. An Einstein-deSitter model, that is flat with $\Omega_\Lambda = 0$, is ruled out at $> 5\sigma$. This statement is based on just the CMB with no prior information (e.g., no prior on h).
3. A closed model with $\Omega_m = 1.28$ and $\Omega_\Lambda = 0$ fits the data but requires $h = 0.33$, in conflict with HST observations. It also disagrees with cluster abundances, velocity flows, and other cosmic probes.

4. The fluctuations in the the metric are superhorizon (Peris *et al.*, 2003). Turok (1996) showed that in principle one can construct models based on subhorizon processes that can mimic the TT ΛCDM spectra. However, these models cannot mimic the observed TE anti-correlation at $50 < \ell < 150$ (Spergel and Zaldarriaga, 1997).

WMAP data are available through the Legacy Archive for Microwave Background Data Analysis (LAMBDA) at http://lambda.gsfc.nasa.gov. This is a new NASA data center dedicated to the rapidly growing field of microwave background data archiving and analysis. WMAP continues to collect data and is currently approved for 4 years of operations at L_2. The additional data, and more elaborate analyses, will help to further constrain models. The addition of other continuously improving CMB and large scale structure observations is essential for progress toward the ultimate goal of a complete understanding of the global properties of the universe.

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