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The WMAP[1] Data and Results

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ABSTRACT

The Wilkinson Microwave Anisotropy Probe (*WMAP*) science team has released results from the first year of operation at the Earth-Sun L_2 Lagrange point. The maps are consistent with previous observations but have much better sensitivity and angular resolution than the *COBE* DMR maps, and much better calibration accuracy and sky coverage than ground-based and balloon-borne experiments. The angular power spectra from these ground-based and balloon-borne experiments are consistent within their systematic and statistical uncertainties with the *WMAP* results. *WMAP* detected the large angular-scale correlation between the temperature and polarization anisotropies of the CMB caused by electron scattering since the Universe became reionized after the "Dark Ages", giving a value for the electron scattering optical depth of 0.17 ± 0.04. The simplest ΛCDM model with $n = 1$ and $\Omega_{tot} = 1$ fixed provides an adequate fit to the *WMAP* data and gives parameters which are consistent with determinations of the Hubble constant and observations of the accelerating Universe using supernovae. The time-ordered data, maps, and power spectra from *WMAP* can be found at `http://lambda.gsfc.nasa.gov` along with 13 papers by the *WMAP* science team describing the results in detail.

Subject headings: cosmic microwave background, cosmology: observations, early universe, dark matter, space vehicles, space vehicles: instruments, instrumentation: detectors, telescopes

1. INTRODUCTION

The cosmic microwave background (CMB) radiation was discovered by Penzias & Wilson (1965). After its discovery, a small number of experimentalists worked for years to better characterize the spectrum of the CMB and to search for anisotropy in the CMB temperature. A leader of this effort, and of the *WMAP* effort, was our recently deceased colleague, Professor David T. Wilkinson of Princeton University. He was the supervisor of the doctoral theses that led to the second (Henry 1971) and third (Corey & Wilkinson 1976) measurements of the dipole anisotropy of the CMB caused by the Solar System's motion relative to the Universe. He was also a leading member of the *Cosmic Background Explorer (COBE)* mission team, which accurately characterized the spectrum of the CMB (Mather et al. 1990, 1999) and first discovered the intrinsic (non-dipole) anisotropy (Smoot et al. 1992; Bennett et al. 1992; Kogut et al. 1992; Wright et al. 1992) of the CMB. The *WMAP* science working group, led by Principal Investigator Charles L. Bennett of

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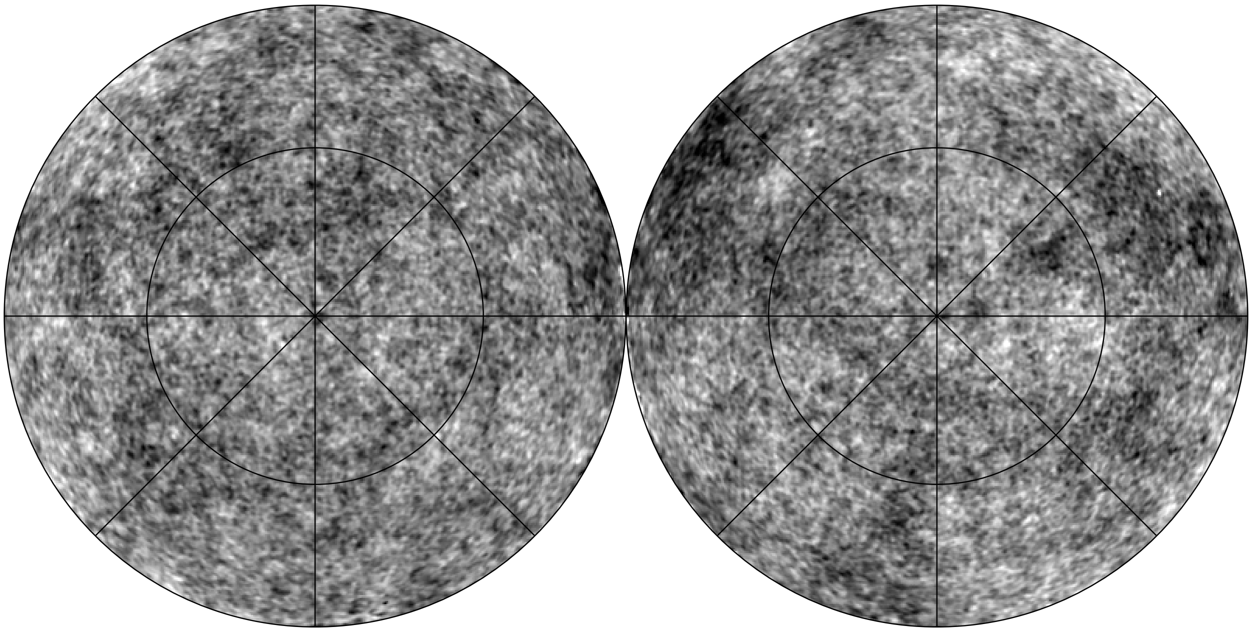

Fig. 1.— Internal linear combination reduced galaxy map from the *WMAP* data. This map is smoothed to about 1° FWHM.

Goddard Space Flight Center, was happy to have the opportunity to honor David T. Wilkinson by renaming the Microwave Anisotropy Probe as the Wilkinson Microwave Anisotropy Probe.

Bennett et al. (2003a) gives a description of the *WMAP* mission. Bennett et al. (2003b) summarizes the results from first year of *WMAP* observations. Bennett et al. (2003c) describes the observations of galactic and extragalactic foreground sources. Hinshaw et al. (2003b) gives the angular power spectrum derived from the the *WMAP* maps. Hinshaw et al. (2003a) describes the *WMAP* data processing and systematic error limits. Page et al. (2003a) discusses the beam sizes and window functions for the *WMAP* experiment. Page et al. (2003b) discusses results that can be derived simply from the positions and heights of the peaks and valleys in the angular power spectrum. Spergel et al. (2003) describes the cosmological parameters derived by fitting the *WMAP* data and other datasets. Verde et al. (2003) describes the fitting methods used. Peiris et al. (2003) describes the consequences of the *WMAP* results for inflationary models. Jarosik et al. (2003) describes the on-orbit performance of the *WMAP* radiometers. Kogut et al. (2003) describes the *WMAP* observations of polarization in the CMB. Barnes et al. (2003) describes the large angle sidelobes of the *WMAP* telescopes. Komatsu et al. (2003) addresses the limits on non-Gaussianity that can be derived from the *WMAP* data.

2. OBSERVATIONS

WMAP Observatory was launched on 30 June 2001 at 19:46:46.183 UTC from Cape Canaveral by a Delta expendable launch vehicle. After three phasing loops in the Earth-Moon system *WMAP* executed a lunar-gravity-assist swingby one month after launch which catapulted *WMAP* to an orbit about the second Lagrange point of the Sun-Earth system, L_2. L_2 is only metastable so about 4 station-keeping maneuvers

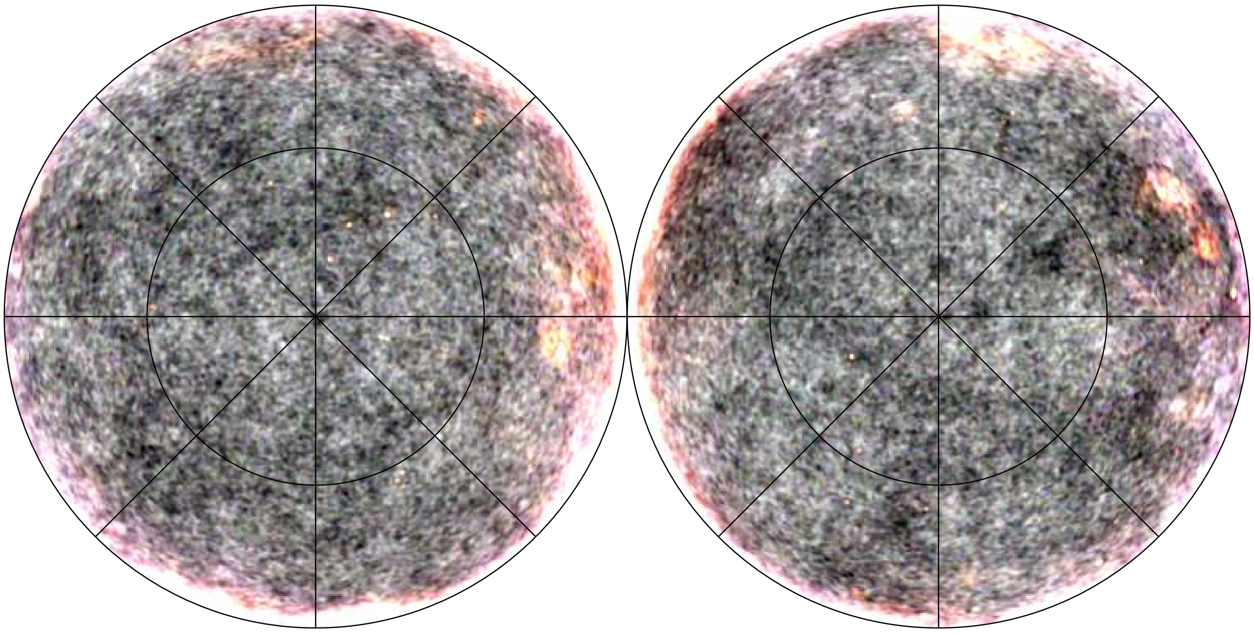

Fig. 2.— A red-green-blue color map made from the *WMAP* Q, V & W band data. This map is smoothed to about 1° FWHM.

per year are required to keep *WMAP* on station. The spacecraft is actually in a "halo" orbit around L_2 and thus avoids the deep partial eclipse of the Sun that exists at L_2.

WMAP observes at 5 different frequencies and can thus yield internal linear combination "no galaxy maps". Figure 1 shows such a map in the "polar eyeball" projection. This equal-area projection maps the North and South galactic hemispheres into circles with the Galactic center in the middle, the North Galactic Pole (NGP) in the center of the left circle, and the SGP in the center of the right circle. Figure 2 shows the 41, 61 & 94 GHz maps as red, green & blue on the same temperature scale in the same projection as Figure 1.

3. Analysis

Given the extensive analysis of the *WMAP* data already posted on the astro-ph preprint server, or at the Legacy Archive for Microwave Background Data Analysis (LAMBDA at http://lambda.gsfc.nasa.gov), I see little point in repeating this lengthy discussion here. I have instead included Figure 3 which shows a ΛCDM model with a power law primordial power spectrum and zero spatial curvature. This particular model was the best fit found in a fairly small Monte Carlo Markov Chain computation that I did as an independent check of the main *WMAP* analysis papers. One easily sees that the *WMAP* data are quite consistent with the previous experiments [ARCHEOPS (Benoit et al. 2003), BOOMERanG (de Bernardis et al. 2000), DASI (Halverson et al. 2002), MAXIMA (Hanany et al. 2000), VSA (Grainge et al. 2003) & CBI (Padin et al. 2001)], some of which overlap with *WMAP* in ℓ-space, and that the ΛCDM model is consistent with both the *WMAP* data and the higher angular resolution interferometric data from CBI.

The largest discrepancies among various CMB anisotropy experiments are due to systematic calibration

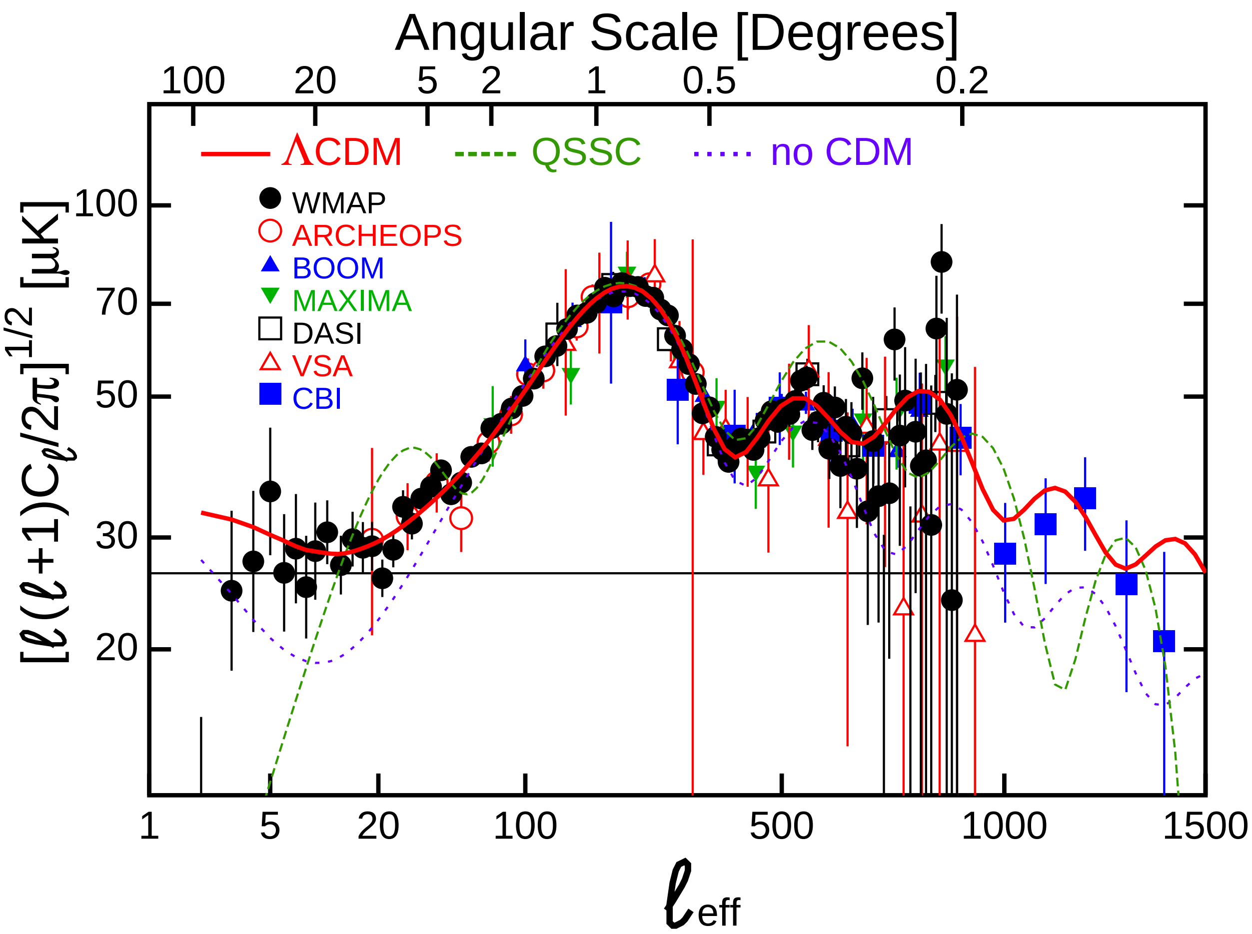

Fig. 3.— The angular power spectrum of the CMB from *WMAP* and earlier balloon-borne and ground-based data. The ΛCDM model is a good fit to all of these datasets. The Quasi-Steady-State cosmology and the no-CDM model inspired by MOND (Modification Of Newtonian Dynamics) both give unacceptable best fits to the CMB angular power spectrum, with large deviations in the low ℓ region observed by *COBE* and confirmed by *WMAP*.

uncertainties. Therefore, in doing these fits, a calibration correction for each experiment other than WMAP has been introduced as a new parameter in the fits, and the sum of the squares of calibration corrections divided by their stated uncertainties has been added to the χ^2 of the model fit. None of the calibration corrections is inconsistent with its stated uncertainty. The data are plotted with the calibration corrections applied, which emphasizes the concordance between recent measurments of C_ℓ.

This plot is a good way to verify that *WMAP* is consistent with earlier experiments, but when setting limits on cosmological parameters one should not combine *WMAP* with experiments like ARCHEOPS that cover the same ℓ range since the cosmic variance is correlated between the two datasets. Combining *WMAP* only with high angular resolution datasets like ACBAR (Kuo et al. 2002) and CBI is the correct procedure.

I then used the MCMC code to optimize the parameters for two alternative cosmological models that have published claimed fits to the CMB angular power spectrum. The "no CDM" model is an update of the

McGaugh (2000) fit to the BOOMERanG data using CMBfast (Seljak & Zaldarriaga 1996) with a zero CDM density. It is clear that this model is a terrible fit, and it was a terrible fit to the combined CMB dataset including COBE which existed in 2000. If CMBfast with no CDM were a good predictor of the anisotropy expected from the Modification Of Newtonian Dynamics then MOND would be killed by this bad fit. But CMBfast assumes that general relativity is a good description of gravity and thus McGaugh (2000) is not a definitive prediction of the C_ℓ expected under MOND. Thus the failure of the McGaugh (2000) model to fit the data only rules out this specific attempt to extend MOND to the early Universe.

More recently Narlikar et al. (2003) claim to have calculated the CMB anisotropy expected in the Quasi-Steady-State Cosmology (QSSC), and also claim that the QSSC gives a better fit to the *binned* data than ΛCDM. This model is an *ad hoc* superposition of two populations of Gaussian blobs with two different sizes and a population of hard-edged circular spots all of a single size. These hard-edged circular disks have an oscillatory Fourier transform which gives a series of peaks in the angular power spectrum. But the low-ℓ behavior of this model is $C_\ell = \text{const}$, which corresponds to a primordial power spectrum $P(k) \propto k^n$ with a power law index of $n = 3$ which is 6σ away from the COBE value of $n = 1.2 \pm 0.3$ (Bennett et al. 1996). Narlikar et al. (2003) hide this failing of their model by using a binning which puts all the COBE data into one bin. I have re-optimized the six arbitrary parameters in the Narlikar et al. (2003) model to give the best possible fit to the data in Figure 3, but even the best fit is totally unacceptable. As with MOND, if Narlikar et al. (2003) had presented a valid theory for the anisotropy predicted by the QSSC, then this bad fit would have killed the QSSC. But unfortunately neither the theory nor the fit is acceptable.

4. Summary and Conclusions

WMAP has presented the results from its first year of observation at L_2, and these data agree with the concordance ΛCDM model and yield dramatic improvements in the accuracy of the cosmological parameters. *WMAP* is funded for 3 more years of operation, and the results from a 4 year dataset will have a much improved signal-to-noise ratio for $\ell > 400$ in the temperature anisotropy angular power spectrum, and a much improved SNR for all ℓ's in the polarization measurements.

The *WMAP* mission is made possible by the support of the Office of Space Sciences at NASA Headquarters and by the hard and capable work of scores of scientists, engineers, technicians, machinists, data analysts, budget analysts, managers, administrative staff, and reviewers.

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