RESULTS FROM WMAP

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ABSTRACT

The Wilkinson Microwave Anisotropy Probe (*WMAP*) was launched on 30 June 2001. The results from the first year of operation at the Earth-Sun L_2 Lagrange point were released on 11 Feb 2003. *WMAP* 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 *WMAP* angular power spectrum is consistent with the power spectra from these ground-based and balloon-borne experiments within their systematic and statistical uncertainties. The large angular-scale correlation between the temperature and polarization anisotropies of the CMB due to electron scattering since the Universe became reionized after the "Dark Ages" was detected by *WMAP*, giving $\tau = 0.17 \pm 0.04$ for the electron scattering optical depth. A simple ΛCDM model with the primordial spectral index and the total density fixed at the values predicted by inflation, $n = 1$ and $\Omega_{tot} = 1$, 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 power spectra, maps, and time-ordered data 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.

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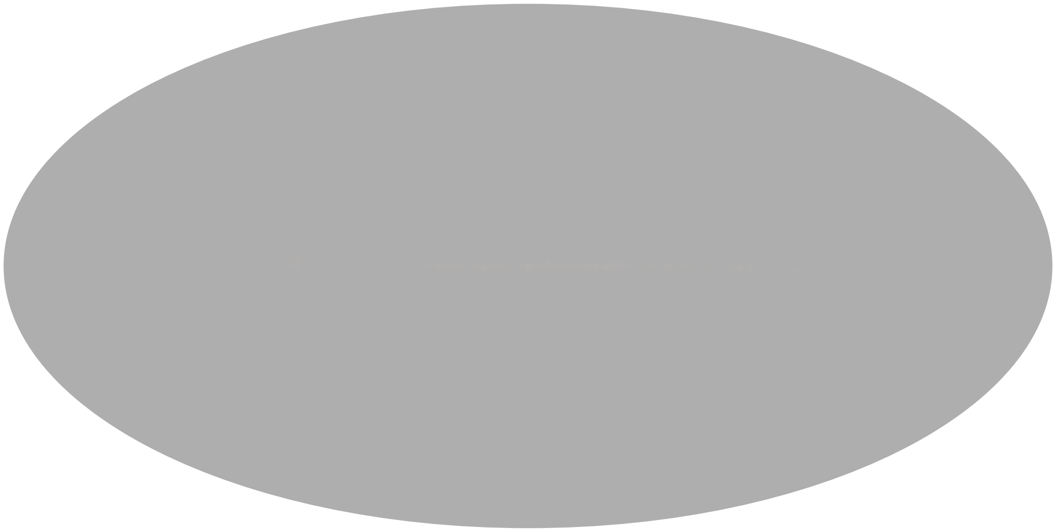

Figure 1: The CMB sky without contrast enhancement as preferred by the Los Angeles Times. The red channel is the 23 GHz brightness, the green channel is the 41 GHz brightness, and the blue channel is the 94 GHz brightness, all on a 0..4 K Planck brightness temperature scale. This figure is not quite a pure constant gray, but it is close.

1 Introduction

Penzias & Wilson.[1] discovered the cosmic microwave background (CMB) radiation. Later, a few 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 supervised the doctoral theses that led to the second[2] and third[3] measurements of the dipole anisotropy of the CMB caused by the Solar System's motion relative to the Universe. He was vital to the success of the *Cosmic Background Explorer (COBE)* mission, which accurately characterized the spectrum of the CMB[4,5] and first discovered the intrinsic (non-dipole) anisotropy[6–9] of the CMB. The science working group of *WMAP*, and its Principal Investigator Charles L. Bennett of Goddard Space Flight Center, were happy to have the opportunity to honor David T. Wilkinson by renaming the Microwave Anisotropy Probe as the Wilkinson Microwave Anisotropy Probe.

Figure 2: The CMB sky with the monopole subtracted and the contrast enhanced by a factor of 400. The red channel is the 23 GHz brightness, the green channel is the 41 GHz brightness, and the blue channel is the 94 GHz brightness, all on a -4..6 mK Planck brightness temperature scale. The dipole anisotropy due to the motion of the Solar System by 368 km/sec relative to the observable Universe is clearly seen.

Bennett *et al.*[10] gives a description of the *WMAP* mission. Jarosik *et al.*[11] describes the on-orbit performance of the *WMAP* radiometers. Page *et al.*[12] discusses the beam sizes and window functions for the *WMAP* experiment. Barnes *et al.*[13] describes the large angle sidelobes of the *WMAP* telescopes. Hinshaw *et al.*[14] describes the *WMAP* data processing and systematic error limits. Bennett *et al.*[15] describes the observations of galactic and extragalactic foreground sources. Hinshaw *et al.*[16] gives the angular power spectrum derived from the the *WMAP* maps. Page *et al.*[17] 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.*[18] describes the cosmological parameters derived by fitting the *WMAP* data and other datasets. Verde *et al.*[19] describes the fitting methods used. Peiris *et al.*[20] describes the consequences of the *WMAP* results for inflationary models. Kogut *et al.*[21] describes the *WMAP* observations of polarization in the CMB. Komatsu *et al.*[22] addresses the limits on non-Gaussianity that can be derived from the *WMAP* data. Bennett *et al.*[23] summarizes the results from first year of *WMAP*

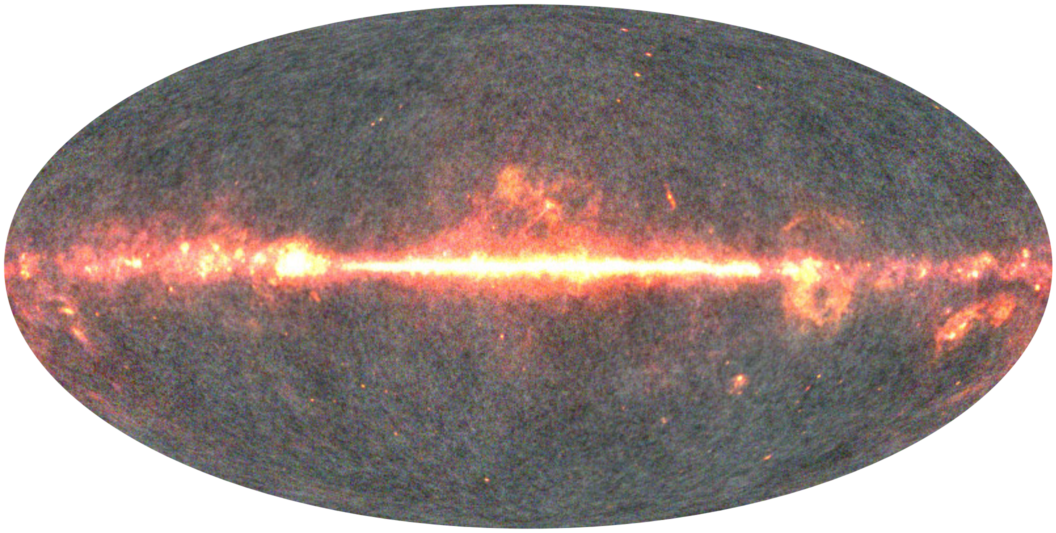

Figure 3: The CMB sky with the monopole and dipole subtracted and the contrast enhanced by a factor of 2000. The red channel is the 23 GHz brightness, the green channel is the 41 GHz brightness, and the blue channel is the 94 GHz brightness, all on a -0.75..1.25 mK Planck brightness temperature scale. The "red" signal from the Milky Way is clearly seen running across the middle of the oval in this plot. Away from the Milky, "gray" blobs due to true CMB fluctuations are seen along with "red" extragalactic radio sources.

observations.

2 OBSERVATIONS

WMAP Observatory was launched from the Cape Canaveral Air Force Station on 30 June 2001 at 19:46:46.183 UTC by a Delta expendable launch vehicle. MAP executed three phasing loops in the Earth-Moon system before a lunar-gravity-assist swingby one month after launch which propelled *WMAP* to an orbit about the second Lagrange point of the Sun-Earth system, L_2. About 4 station-keeping maneuvers per year are needed to stay at L_2 because it is only metastable. *WMAP* is actually in a "halo" orbit around L_2 to avoid the deep partial eclipse of the Sun that exists at L_2.

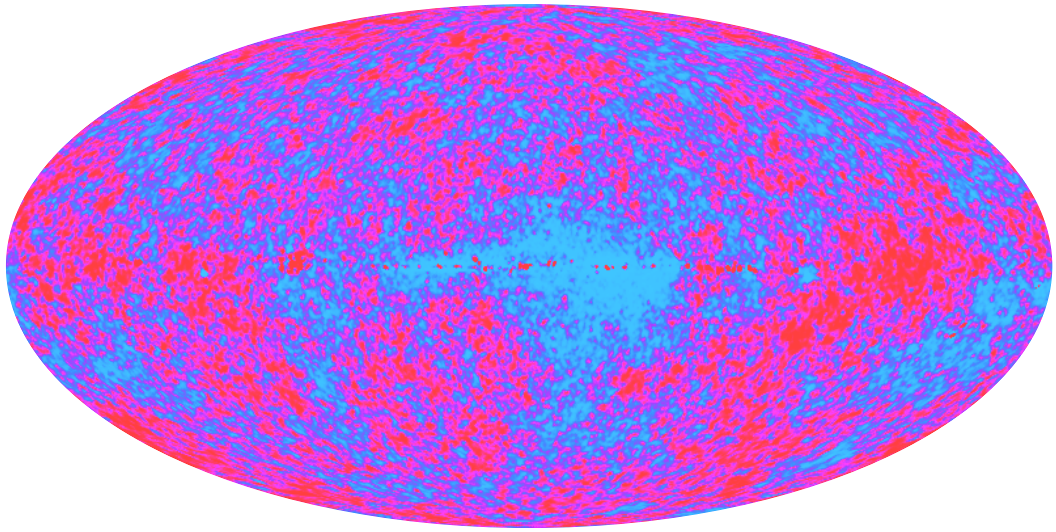

Figure 4: The CMB sky with the monopole, dipole and galaxy subtracted by making a linear combination of all 5 *WMAP* frequencies to suppress the Milky Way signal. The contrast is enhanced by a factor of 20,000. The red areas are hot and the blue areas are cold. Except for the line of dots exactly on the galactic plane, everything on this map is probably true CMB fluctuations.

3 Analysis

WMAP observes at 5 different frequencies and these can be combined to make false color images. Figure 1 shows the CMB sky without any contrast enhancement – the view we would see if our eyes were sensitive to waves 10,000 times longer than visible light. Figure 2 shows the sky after the monopole $T_\circ = 2.725$ K is subtracted and expanding the contrast by $400\times$. The dipole anisotropy is clearly seen as a gray shading that is darkest in the lower left and brightest in the upper right. This pattern is due to the motion of the Solar system at 368 km/sec relative to the observable Universe. Figure 3 shows the sky after the dipole pattern is subtracted and expanding the contrast by $2000\times$. Now the bright "red" signal of the Milky Way dominates the sky but "gray" blobs due to true CMB temperature fluctuations and "red" extragalactic radio point sources are seen off the galactic plane. Figures 2 and 3 are similar to Figure 10 of Bennett *et al.*[23] but cover a wider frequency range and the contrast between CMB and galactic signals is higher.

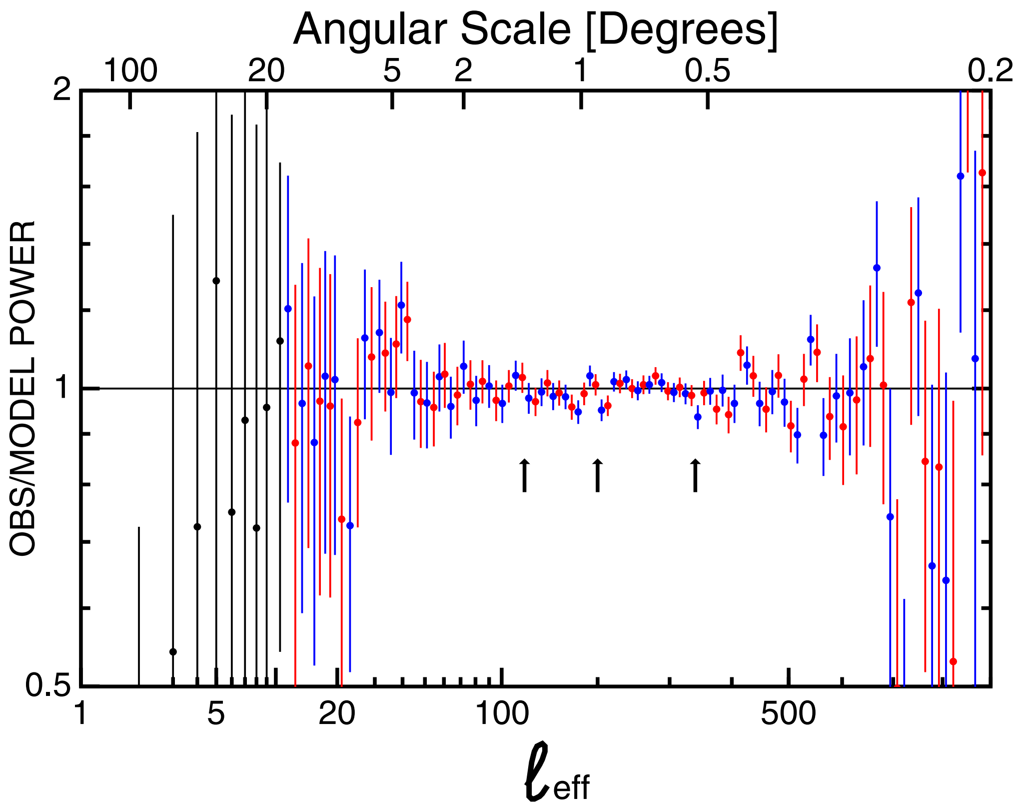

Figure 5: The *WMAP* binned angular power spectrum divided by the best fitting running index flat ΛCDM model. The binned data are double plotted so either the red or the blue points are independent. The black points are unbinned. The arrow point out the "dents" in the power spectrum.

Since the Milky Way has a very different spectrum from the CMB, a linear combination of *WMAP* maps can be made which suppresses the galactic foreground but preserves the amplitude of true CMB temperature fluctuations. Figure 4 shows such a map with the contrast expanded by $20,000\times$ with respect to Figure 1.

Since an extensive analysis of the *WMAP* data has already been posted on the astro-ph preprint server, or at the Legacy Archive for Microwave Background Data Analysis (LAMBDA at http://lambda.gsfc.nasa.gov), there is little point in my repeating this lengthy discussion here. Instead Figure 5 shows the *WMAP* angular power spectrum divided by the best fitting running index flat ΛCDM model. The data points are binned at high ℓ to preserve a high signal-to-noise ratio. The bins are spaced at half their widths, giving adjacent points that are correlated. Thus either red or the blue points in this figure are independent, but both are plotted to give a smoother plot. At low ℓ there is no binning, so the points are plotted in black. The arrows in this plot point are the locations of high χ^2/dof.[18]

4 Conclusions

The *WMAP* first year data provide a cosmic variance limited angular power spectrum of the CMB anisotropy up to $\ell \approx 300$, and have good signal-to-noise ratio up to $\ell = 500$. The TE correlation between temperature and polarization anisotropies has been detected with modest signal-to-noise ratio. *WMAP* is still observing and currently funded for a total of 4 years of operation. This additional integration time will provide substantial improvements in the TE measurement and for $\ell > 500$. Based on the first year results we find

- The densities of matter, both baryonic and dark, are well determined. The baryon density ($\Omega_b h^2 = 0.0224 \pm 0.0009$) agrees with that derived from the D/H ratio seen in high redshift absorption line systems[24] ($\Omega_b = 0.0214 \pm 0.0020$). The dark matter density is 5.03 ± 0.4 times the baryon density.
- The optical depth to electron scattering since reionization is $\tau = 0.17 \pm 0.04$ implying the existence of an early source of ultraviolet radiation.
- The power spectrum of primordial density perturbations is very close to a power law, and the index is very close to the $n = 1$ prediction of naive inflation.
- The positions of the acoustic peaks imply that the Universe lies on a locus in the $\Omega_M - Omega_V$ plane that intersects the flat Universe line at the consensus model with $\Omega_M = 0.27$ and $\Omega_V = 0.73$, and intersects the $\Omega_V = 0$ line at $\Omega_M = 1.3$.
- The age of the Universe at last scattering ($z = 1089 \pm 1$) was 379 ± 8 kyr, while the age of the Universe now is 13.7 ± 0.2 Gyr with $H_\circ = 71 \pm 3.5$ km/sec/Mpc if the Universe is flat.

Acknowledgements:

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