WMAP returns

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Recap of previous episodes
What’s new?

In a nutshell:

More data
Lower noise

Improved foreground modeling

Improved analysis

About 200 article pages...

Hinshaw et al. ‘06
Page et al. ‘06
Spergel et al. ‘06
Jarosik et al. ‘06
Still there
...along with the axis of evil
Generation of CMB polarization

- Temperature quadrupole at the surface of last scatter generates polarization.

From Wayne Hu

At the end of the dark ages (reionization)
Polarization for density perturbation

- Radial (tangential) pattern around hot (cold) spots.

Velocities!
Gravity waves stretch space…

Image from J. Rhul.
... and create variations

Image from J. Rhul.
E and B modes polarization

E polarization from scalar, vector and tensor modes

B polarization only from (vector) tensor modes

Kamionkowski, Kosowsky, Stebbings 1997, Zaldarriga & Seljak 1997
What’s new:
Polarization analysis/maps.

- **First Year (TE)**
  - Foreground Removal
    - Done in harmonic space
  - Null Tests
    - Only TB
  - Data Combination
    - Ka, Q, V, W are used
  - Data Weighting
    - Diagonal weighting
  - Likelihood Form
    - Gaussian for $C_l$
    - $C_l$ estimated by MASTER

- **Three Years (TE, EE, BB)**
  - Foreground Removal
    - Done in pixel space
  - Null Tests
    - Year Difference & TB, EB, BB
  - Data Combination
    - Only Q and V are used
  - Data Weighting
    - Optimal weighting ($C^{-1}$)
  - Likelihood Form
    - Gaussian for the pixel data
    - $C_l$ not used at $l<23$

*These are improvements only in the analysis techniques: there are also various improvements in the polarization map-making algorithm. See Jarosik et al. (2006)*
K Band (23 GHz)
Dominated by synchrotron; Note that polarization direction is perpendicular to the magnetic field lines.
Ka Band (33 GHz)

Synchrotron decreases as $\nu^{-3.2}$ from K to Ka band.
Q Band (41 GHz)

We still see significant polarized synchrotron in Q.
V Band (61 GHz)

The polarized foreground emission is also smallest in V band. We can also see that noise is larger on the ecliptic plane.
W Band (94 GHz)

While synchrotron is the smallest in W, polarized dust (hard to see by eye) may contaminate in W band more than in V band.
Polarization Mask (P06)

- Mask was created using
  - K band polarization data
  - MEM dust intensity map

\[ f_{\text{sky}} = 0.743 \]
**Foreground Cleaning is needed**

- **Outside P06**
  - EE (solid)
  - BB (dashed)
- **Black lines**
  - EE
    - \( \tau = 0.09 \)
  - BB
    - \( r = 0.3 \)
- Frequency shown is the geometric mean of two frequencies used to compute the power spectrum.
Cleaning works
Clean BB after FG removal.

3-sigma detection of EE.

The “Gold” multipoles: \( l=3,4,5,6 \).
Low-l TE Data:
Comparison between 1-yr and 3-yr

TE (1yr) and TE (3yr) have about the same error-bars.
- 1yr used KaQVW and white noise
  - Errors significantly underestimated.
  - Incomplete FG errors propagation.
- 3yr used QV and correlated noise
Stand-alone $\tau$

- Tau is almost entirely determined by the EE data. (TE adds very little.)
  - Black Solid: TE+EE
  - Cyan: EE only
  - Dashed: Used $C_l$
  - Dotted: TE+EE from KaQVW
  - Shaded: Kogut et al.’s stand-alone tau analysis from TE
  - Grey: 1-yr full analysis (Spergel et al. 2003)

The 3-yr polarization data essentially fixes $\tau$ independent of the other parameters.
How about cosmology?
Improvements:

Use TT TE EE BB

Use exact likelihood at low $l$ (for $\text{Cl}$ and parameters)

Include $SZ$ signal and marginalize over it

Likelihood routine can be downloaded from the LAMBDA site (CosmoMC has included it already)

For simple cosmological models this is now the bottleneck
Effect of more data

LCDM model

Reducing the noise by 3 → degeneracies broken
Comparison with WMAP I

![Graph showing comparison between different scenarios: best fit LCDM WMAP I, WMAP I, and WMAP II. The graph illustrates the multipole moment $l$ vs. $\ell (\ell + 1) C_\ell / (2\pi)$ (μK²). The plot includes error bars for each scenario.](image)
LCDM model survives!

WMAP II + rest of the world
LCDM model survives!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First Year</th>
<th>WMAPext</th>
<th>Three Year</th>
<th>First Year</th>
<th>WMAPext</th>
<th>Three Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>ML</td>
<td>ML</td>
<td>ML</td>
</tr>
<tr>
<td>$100\Omega_b h^2$</td>
<td>$2.38_{-0.12}^{+0.13}$</td>
<td>$2.32_{-0.11}^{+0.12}$</td>
<td>$2.23 \pm 0.08$</td>
<td>$2.30$</td>
<td>$2.21$</td>
<td>$2.23$</td>
</tr>
<tr>
<td>$\Omega_m h^2$</td>
<td>$0.144_{-0.016}^{+0.016}$</td>
<td>$0.134_{-0.006}^{+0.006}$</td>
<td>$0.126 \pm 0.009$</td>
<td>$0.145$</td>
<td>$0.138$</td>
<td>$0.128$</td>
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<tr>
<td>$H_0$</td>
<td>$72_{-5}^{+5}$</td>
<td>$73_{-3}^{+3}$</td>
<td>$74_{-3}^{+3}$</td>
<td>$68$</td>
<td>$71$</td>
<td>$73$</td>
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<tr>
<td>$\tau$</td>
<td>$0.17_{-0.07}^{+0.08}$</td>
<td>$0.15_{-0.07}^{+0.07}$</td>
<td>$0.093 \pm 0.029$</td>
<td>$0.10$</td>
<td>$0.10$</td>
<td>$0.092$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.99_{-0.04}^{+0.04}$</td>
<td>$0.98_{-0.03}^{+0.03}$</td>
<td>$0.961 \pm 0.017$</td>
<td>$0.97$</td>
<td>$0.96$</td>
<td>$0.958$</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.29_{-0.07}^{+0.07}$</td>
<td>$0.25_{-0.03}^{+0.03}$</td>
<td>$0.234 \pm 0.035$</td>
<td>$0.32$</td>
<td>$0.27$</td>
<td>$0.24$</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>$0.92_{-0.1}^{+0.1}$</td>
<td>$0.84_{-0.06}^{+0.06}$</td>
<td>$0.76 \pm 0.05$</td>
<td>$0.88$</td>
<td>$0.82$</td>
<td>$0.77$</td>
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</tbody>
</table>
Status of $n_s=1$

<table>
<thead>
<tr>
<th>Model</th>
<th>$-\Delta(2\ln L)$</th>
<th>$N_{\text{par}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Invariant Fluctuations ($n_s = 1$)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>No Reionization ($\tau = 0$)</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>
Deviation from scale invariance

- WMAPII data prefers a scalar spectral index that is significantly less than the Harrison-Zel’dovich scale invariant spectrum ($n_s = 1, r = 0$).
- As CMB data continues to improve, this would be a major clue to how inflation proceeded, and its underlying physics.
- The error on the spectral index and its centroid is somewhat sensitive to:
  - The treatment of the beam error propagation in the likelihood function
  - The prior placed on the SZ amplitude in marginalization
  - Using the larger set KaQVW of WMAP bands for the polarization data rather than QV - stronger upper limit on $\tau$ cuts off residual degeneracy with $n_s$
  - Relaxing the assumption of instantaneous reionization
How many parameters?

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<td>5</td>
</tr>
<tr>
<td>No Reionization ($\tau = 0$)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>No Dark Matter ($\Omega_c = 0, \Omega_\Lambda \neq 0$)</td>
<td>248</td>
<td>6</td>
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<tr>
<td>No Cosmological Constant ($\Omega_c \neq 0, \Omega_\Lambda = 0$)</td>
<td>0</td>
<td>6</td>
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<tr>
<td><strong>Power Law $\Lambda$CDM</strong></td>
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<td></td>
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<tr>
<td>Quintessence ($w \neq -1$)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Massive Neutrino ($m_\nu &gt; 0$)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Tensor Modes ($r &gt; 0$)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Running Spectral Index ($dn_s/d\ln k \neq 0$)</td>
<td>$-3$</td>
<td>7</td>
</tr>
<tr>
<td>Non-flat Universe ($\Omega_k \neq 0$)</td>
<td>$-6$</td>
<td>7</td>
</tr>
<tr>
<td>Running Spectral Index &amp; Tensor Modes</td>
<td>$-3$</td>
<td>8</td>
</tr>
<tr>
<td>Sharp cutoff</td>
<td>$-1$</td>
<td>7</td>
</tr>
<tr>
<td>Binned $\Delta^2_R(k)$</td>
<td>$-22$</td>
<td>20</td>
</tr>
</tbody>
</table>
External data sets:
Large scale structure

And supernovae type 1A
Extensions to the simple LCDM model

Flatness
Dark energy

With DE clustering

2dFGS
H prior
WMAPII
SN
Dark energy

No clustering

The difference is in the ISW
Geometry and dark energy

Only with all data sets combined
Shape of the primordial power spectrum

WMAPII: running = -0.055

Beware of the pivot point
Implications for inflation

- Flat universe: $\Omega_k = -0.064 \pm 0.072$
- Gaussianity: $-54 < f_{NL} < 114$
- Power Spectrum spectral index nearly scale-invariant: $n_s = 0.95 \pm 0.016$
- Adiabatic initial conditions
- Superhorizon fluctuations (TE anticorrelations)

WMAP Consistent with Simplest Inflationary Models
Specific models critically tested
Generic models:

- Large >0 curvature
  - Blue tilt, small r
  - Red tilt small r and run

- Negative curvature
  - Red tilt small r and run

- Intermediate curvature
  - WMAPII

- Small >0 curvature
  - Red tilt, large r
  - Small run

From Peiris & Easther ‘06
Conclusions:

LCDM model has survived another rigorous set of tests

Measuring polarization is difficult but very important

CMB peaks imply dark matter non-baryonic

Flat universe, dominated by dark energy
DE consistent with cosmological constant

\[ n<1 \]

Inflationary models critically tested
Welcome to NASA's data center for Cosmic Microwave Background (CMB) research. This site provides CMB researchers with archive data from NASA missions, software tools, and links to other sites of interest. As a resource for the CMB community, your suggestions for improvement are encouraged.

http://lambda.gsfc.nasa.gov