Three-Year WMAP Observations

Mitchell Symposium 2006
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The University of Texas at Austin
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Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Beam Profiles, Data Processing, Radiometer Characterization and Systematic Error Limits


Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Temperature Analysis


THREE YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) OBSERVATIONS: POLARIZATION ANALYSIS


Wilkinson Microwave Anisotropy Probe (WMAP) Three Year Results: Implications for Cosmology

So, It’s Been Three Years Since The First Data Release. What Is New Now?
POLARIZATION DATA!!
Jargon: E-mode and B-mode

- Polarization is a rank-2 tensor field.
- One can decompose it into a divergence-like “E-mode” and a vorticity-like “B-mode”.

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky, Stebbins (1997)
Physics of Polarized CMB Anisotropy

- Testing the Standard Model of Cosmology
- First Star Formation
- Primordial Gravity Waves
POLARIZATION AND SPECTRUM OF THE PRIMEVAL RADIATION IN AN ANISOTROPIC UNIVERSE*

M. J. Rees†
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington
California Institute of Technology
Received May 10, 1968

Polarization and anisotropy of the primordial radiation in an anisotropic universe

M. M. Basko and A. G. Polnarev
Institute for Space Research, USSR Academy of Sciences, Moscow
(Submitted March 14, 1979)

Small-angle anisotropy of the microwave background radiation in the adiabatic theory

Nick Kaiser Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

Received 1982 June 30; in original form 1982 May 28

COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

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Received 1984 June 4; accepted 1984 July 17
Polarized Light
Un-filtered

Polarized Light
Filtered

without PolaVisor

as seen through PolaVisor
Physics of CMB Polarization

• Thomson scattering generates polarization, if...
  • Temperature **quadrupole** exists around an electron
  • Where does quadrupole come from?
• Quadrupole is generated by shear viscosity of photon-baryon fluid, which is generated by velocity gradient.
Boltzmann Equation

\[
\dot{\Theta} + \gamma^k \frac{\partial \Theta}{\partial x^k} = \mathcal{G}_{SW} + \mathcal{G}_C^{\Theta},
\]

\[
(Q \pm iU) \cdot \gamma^k \frac{\partial}{\partial x^k} (Q \pm iU) = \mathcal{G}_C^{Q \pm iU},
\]

\[
\dot{V} + \gamma^k \frac{\partial V}{\partial x^k} = \mathcal{G}_C^V
\]

• Temperature anisotropy, \( \Theta \), can be generated by gravitational effect (noted as “SW” = Sachs-Wolfe).

• Linear polarization (Q & U) is generated only by scattering (noted as “C” = Compton scattering).

• Circular polarization (V) would not be generated.
(Next slide.)
Sources of Polarization

- Linear polarization (Q and U) will be generated from 1/10 of temperature quadrupole.

- Circular polarization (V) will NOT be generated. No source term, if V was initially zero.

\[
G^\Theta_C = -\hat{\tau}_c \Theta + \hat{\tau}_c \int d\tilde{\Omega} \frac{1}{\sqrt{4\pi}} Y^0_0 \tilde{\Theta} \\
+ \hat{\tau}_c \gamma_k v^k_b \\
+ \hat{\tau}_c \int d\tilde{\Omega} \sum_m \frac{1}{10} \left[ \tilde{Y}^m_2 \tilde{Y}^m_2 \tilde{\Theta} - 3 \tilde{Y}^{m*}_2 \tilde{Y}^m_2 (\tilde{Q} + i\tilde{U}) - \sqrt{3} \tilde{Y}^{m*}_2 \tilde{Y}^m_2 (\tilde{Q} - i\tilde{U}) \right],
\]

\[
G^{Q\pm iU}_C = -\hat{\tau}_c (Q \pm iU) \\
+ \hat{\tau}_c \int d\tilde{\Omega} \sum_m \frac{1}{10} \left[ -\sqrt{6} \tilde{Y}^{m*}_2 \tilde{Y}^m_2 \tilde{\Theta} + 3 \tilde{Y}^{m*}_2 \tilde{Y}^m_2 (\tilde{Q} + i\tilde{U}) + 3 \tilde{Y}^{m*}_2 \tilde{Y}^m_2 (\tilde{Q} - i\tilde{U}) \right],
\]

\[
G^V_C = -\hat{\tau}_c V \\
+ \hat{\tau}_c \int d\tilde{\Omega} \sum_m \frac{1}{2} \tilde{Y}^{m*}_1 \tilde{Y}^m_1 \tilde{V}.
\]
Photon Transport Equation

\[ \dot{\delta}_\gamma = -\frac{4}{3}kV_\gamma - 4\Phi_H, \]
\[ \dot{V}_\gamma = k\left(\frac{1}{4}\delta_\gamma + \Phi_A - \frac{1}{6}\pi_\gamma\right) - \tau_C(V_\gamma - V_b), \]
\[ \dot{\pi}_\gamma = k\left(\frac{8}{5}V_\gamma\right) - \tau_C f_2\pi_\gamma, \]

\( f_2 = \frac{3}{4} \)
\( \Phi_A = -h_{00}/2, \quad \Phi_H = h_{ii}/2 \)
\( \tau_C = \text{Thomson scattering optical depth} \)
Polarization and anisotropy induced in the microwave background by cosmological gravitational waves

A. G. Polnarev

Institute for Space Research, USSR Academy of Sciences, Moscow
(Submitted April 12, 1984)


POLARIZATION OF THE MICROWAVE BACKGROUND DUE TO PRIMORDIAL GRAVITATIONAL WAVES

Robert Crittenden, Richard L. Davis, and Paul J. Steinhardt

Department of Physics, University of Pennsylvania, Philadelphia, PA 19104

Signature of Gravity Waves in the Polarization of the Microwave Background

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Matias Zaldarriaga†

Department of Physics, MIT, Cambridge, Massachusetts 02139
(Received 13 September 1996)

A Probe of Primordial Gravity Waves and Vorticity

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Department of Physics, Columbia University, 538 West 120th Street, New York, New York 10027

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and Department of Physics, Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138

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NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500
(Received 19 September 1996)
Primordial Gravity Waves

- Gravity waves create quadrupolar temperature anisotropy -> Polarization
- Directly generate polarization without $kV$.
- *Most importantly, GW creates B mode.*
Polarization From Reionization

- CMB was emitted at $z \sim 1088$.
- Some fraction of CMB was re-scattered in a reionized universe.
- The reionization redshift of $\sim 11$ would correspond to 365 million years after the Big-Bang.

$z=1088, \tau \sim 1$

$z\sim 11, \tau \sim 0.1$

$z=0$

First-star formation
Polarization from Reionization

"Reionization Bump"
Measuring Optical Depth

Since polarization is generated by scattering, the amplitude is given by the number of scattering, or optical depth of Thomson scattering:

\[
\tau(z) = \sigma_T n_e 0 \int_0^z dz' \frac{c dt}{dz'} x_e(z')(1 + z')^3
\]

which is related to the electron column number density as

\[
\frac{\tau}{\sigma_T} = 1.5 \times 10^{23} \left( \frac{\tau}{0.1} \right) \text{cm}^{-2}
\]
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 $v^{-3.2}$ 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 eyes) may contaminate in W band more than in V band.
Polarization Mask (P06)

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

\( f_{\text{sky}} = 0.743 \)
Masking Is Not Enough: Foreground Must Be Cleaned

- Outside P06
  - EE (solid)
  - BB (dashed)
- Black lines
  - Theory EE
    - $\tau=0.09$
  - Theory BB
    - $r=0.3$
- Frequency = Geometric mean of two frequencies used to compute $C_\ell$

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Rough fit to BB FG in 60GHz
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Template-based FG Removal

- The first year analysis (TE)
  - We cleaned synchrotron foreground using the K-band correlation function (also power spectrum) information.
  - It worked reasonably well for TE (polarized foreground is not correlated with CMB temperature); however, this approach is bound to fail for EE or BB.

- The three year analysis (TE, EE, BB)
  - We used the K band polarization map to model the polarization foreground from synchrotron in pixel space.
    - The K band map was fitted to each of the Ka, Q, V, and W maps, to find the best-fit coefficient. The best-fit map was then subtracted from each map.
  - We also used the polarized dust template map based on the stellar polarization data to subtract the dust contamination.
    - We found evidence that W band data is contaminated by polarized dust, but dust polarization is unimportant in the other bands.
    - We don’t use W band for the three year analysis (for other reasons).
It Works Well!!

- Only two-parameter fit!
- Dramatic improvement in chi-squared.
- The cleaned Q and V maps have the reduced chi-squared of ~1.02 per DOF=4534 (outside P06)

**Table 4**

Comparison of $\chi^2$ between pre-cleaned and cleaned maps

<table>
<thead>
<tr>
<th>Band</th>
<th>$\chi^2/\nu$ Pre-cleaned</th>
<th>$\chi^2/\nu$ Cleaned</th>
<th>$\nu$</th>
<th>$\Delta\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ka</td>
<td>10.65</td>
<td>1.20</td>
<td>6144</td>
<td>58061</td>
</tr>
<tr>
<td>Q</td>
<td>3.91</td>
<td>1.09</td>
<td>6144</td>
<td>17326</td>
</tr>
<tr>
<td>V</td>
<td>1.36</td>
<td>1.19</td>
<td>6144</td>
<td>1045</td>
</tr>
<tr>
<td>W</td>
<td>1.38</td>
<td>1.58</td>
<td>6144</td>
<td>1229</td>
</tr>
<tr>
<td>Ka</td>
<td>2.142</td>
<td>1.096</td>
<td>4534</td>
<td>4743</td>
</tr>
<tr>
<td>Q</td>
<td>1.289</td>
<td>1.018</td>
<td>4534</td>
<td>1229</td>
</tr>
<tr>
<td>V</td>
<td>1.048</td>
<td>1.016</td>
<td>4534</td>
<td>145</td>
</tr>
<tr>
<td>W</td>
<td>1.061</td>
<td>1.050</td>
<td>4534</td>
<td>50</td>
</tr>
</tbody>
</table>

The top half of the table compares $\chi^2/\nu$ for the full-sky pre-cleaned map to $\chi^2/\nu$ for full-sky cleaned map. The bottom half makes a similar comparison for the region outside the P06 mask.
BB consistent with zero after FG removal.

3-sigma detection of EE.

The “Gold” multipoles: \(l=3,4,5,6\).
• It’s very powerful to have three years of data.
  • Year-year differences must be consistent with zero signal.
    • yr1-yr2, yr2-yr3, and yr3-yr1
    • We could not do this null test for the first year data.
  • We are confident that we understand polarization noise to a couple of percent level.
• Statistical isotropy
  • TB and EB must be consistent with zero.
• Inflation prior…
  • We don’t expect 3-yr data to detect any BB.
Tau is almost entirely determined by the EE data.

- TE adds very little.
- Black Solid: TE+EE
- Cyan: EE only
- Dashed: Gaussian $C_i$
- Dotted: TE+EE from KaQVW
- Shaded: Kogut et al.'s stand-alone tau analysis from $C_i$ TE
- Grey lines: 1-yr full analysis (Spergel et al. 2003)
Tau is Constrained by EE

- The EE data alone give
  - $\tau = 0.100 \pm 0.029$
- The TE+EE data give
  - $\tau = 0.092 \pm 0.029$
- The TT+TE+EE give
  - $\tau = 0.093 \pm 0.029$
- This indicates that the EE data have exhausted most of the information on tau contained in the WMAP data.
  - *This is a very powerful statement:* this immediately implies that the 3-yr polarization data essentially fixes tau independent of the other parameters, and thus can break massive degeneracies between tau and the other parameters.
Our ability to constrain the amplitude of gravity waves is still coming mostly from TT.
- \( r < 0.55 \) (95%)
- BB information adds very little.
- EE data (which fix the value of \( \tau \)) are also important, as \( r \) is degenerate with the tilt, which is also degenerate with \( \tau \).
Temperature Data: First Year
Three Year

Significant improvement at the second and third peak.
"WMAPext"
Parameter Determination: First Year vs Three Years

- The simplest LCDM model
  - A power-law primordial power spectrum
  - Three relativistic neutrino species
  - Flat universe with cosmological constant
- The maximum likelihood values very consistent
  - Matter density and sigma8 went down

<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>
</tr>
<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>
</tr>
<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>
</tr>
</tbody>
</table>
Red: First-year WMAP only Best-fit
Orange: First-year WMAPext Best-fit
Black: Three-year WMAP only Best-fit

The third peak is better constrained by the three-year data, and is lower than the first year best-fit.
Degeneracy Finally Broken: Negative Tilt & Low Fluctuation Amplitude

Temperature Data Constrain “$\sigma_8 \exp(-\tau)$”

Polarization Nailed Tau

Lower 3rd peak

Degeneracy Line from Temperature Data Alone

Polarization Nailed Tau

Lower $\tau$
What Should WMAP Say About Inflation Models?

**Hint for ns<1**

- **r=0**
  - The 1-d marginalized constraint from WMAP alone is $ns=0.95 \pm 0.02$.

- **r>0**
  - The 2-d joint constraint still allows for $ns=1$ (HZ).
What Should WMAP Say About Flatness?

Flatness, or “Super Sandage”?

If $H=30\text{km/s/Mpc}$, a closed universe with $\Omega=1.3$ w/o cosmological constant still fits the WMAP data.
What Should WMAP Say About Dark Energy?

Not much!

The CMB data alone cannot constrain \( w \) very well. Combining the large-scale structure data or supernova data breaks degeneracy between \( w \) and matter density.
What Should WMAP Say About Neutrino Mass?

WMAP alone (95%):
- Total mass < 2eV

WMAP+SDSS (95%)
- Total mass < 0.9eV

WMAP+all (95%)
- Total mass < 0.7eV
• Understanding of
  • Noise,
  • Systematics, 
  • Foreground, and

• Analysis techniques
  • have significantly improved from the first-year release.

• To-do list for the next data release(!)
  • Understand FG and noise better.
  • We are still using only 1/2 of the polarization data.
  • These improvements, combined with more years of data, would further reduce the error on $\tau$.
    • Full 3-yr would give $\delta(\tau) \sim 0.02$
    • Full 6-yr would give $\delta(\tau) \sim 0.014$ (hopefully)
  • This will give us a better estimate of the tilt, and better constraints on inflation.
Low-l TE Data: Comparison between 1-yr and 3-yr

- 1-yr TE and 3-yr TE have about the same error-bars.
- 1yr used KaQVW and white noise model
  - Errors significantly underestimated.
  - Potentially incomplete FG subtraction.
- 3yr used QV and correlated noise model
  - Only 2-sigma detection of low-l TE.
The amplitude and phases of high-l TE data agree very well with the prediction from TT data and linear perturbation theory and adiabatic initial conditions. (Left Panel: Blue=1yr, Black=3yr)
When QVW are coadded, the high-I EE amplitude relative to the prediction from the best-fit cosmology is $0.95 \pm 0.35$.

Expect ~4-5sigma detection from 6-yr data.