WMAP and Beyond
David Spergel
The application of physics in the domain of astronomy constitutes a line of investigation that seems to possess almost unbounded possibilities. In the stars we examine matter in quantities and under conditions unattainable in the laboratory. The increase in scope is counterbalanced, however, by a serious limitation—the stars are not accessible to experiment, only to observation, and there is no very direct way to establish the validity of laws, deduced in the laboratory, when they are extrapolated to stellar conditions.

The verification of physical laws is not, however, the primary object of the application of physics to the stars. The astrophysicist is generally obliged to assume their validity in applying them to stellar conditions. Ultimately it may be that the consistency of the findings in different branches of astrophysics will form a basis for a more general verification of physical laws than can be attained in the laboratory; but at present, terrestrial physics must be the groundwork of the study of stellar conditions.
Requirements for Observational Physics

- Simple system
- Sensitive to Interesting Physics
- Precision Measurements of Signals

Examples: Binary Pulsar, CMB, Binary Inspiral,...
CMB and LSS Observations as Physics Probes

\[ c_l = \int d^3 k P(k)[T_l^{\text{CMB}}(k)]^2 \]

\[ P(k, t) = b \int d^3 k P(k)[T^{\text{LSS}}(k, t)]^2 \]

Initial Conditions

Composition of the Universe
Science Team

GODDARD
- C. Bennett (JHU)
- G. Hinshaw
- R. Hill
- A. Kogut
- M. Limon
- N. Odegard
- J. Weiland
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Princeton
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- R. Bean (Cornell)
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- S. Meyer (Chicago)
- G. Tucker (Brown)
- E. Wright (UCLA)
Angular Scale

Multipole moment ($l$)

Angular Scale

$\frac{\ell+1}{2}\pi (\mu k^2)$

$\ell+1$ $\pi / 2$ $\mu k^2$ $TT$

$\ell+1$ $\pi / 2$ $\mu k^2$ $TE$

Multipole moment ($l$)

Angular Scale

$\frac{\ell+1}{2}\pi (\mu k^2)$

$\ell+1$ $\pi / 2$ $\mu k^2$ $TT$

$\ell+1$ $\pi / 2$ $\mu k^2$ $TE$

Multipole moment ($l$)
Multipole moment ($l$)

Angular Scale

0

1000

2000

3000

4000

5000

6000

0.90

0.95

1.00

1.05

1.10

90° 20° 0.5° 0.2°

Foregrounds

More Data

ML analysis
A simple cosmological model with only 6 parameters fits the WMAP data

- At high $l$, errors have dropped by more than a factor of 3, improves from $1.07$/d.o.f. to $1.04$/d.o.f.
- Better beams
- Better foreground model
- Finer pixelization in map-making ($0.1 \rightarrow 0.05$ diameter pixels)
What Took So Long?

- Our detected polarization signal is weak: we have errors below 200 nanoKelvin.
- Making a convincing detection of large-scale polarization required understanding the experimental systematics, modeling the interplay between noise and scan strategy and understanding galactic emission.
What is New?

- Improved Gain Model
- Improved Beam Model and more accurate treatment of sidelobes
- Improved Noise Model
- Improved Foreground Model
- Finer pixelization
- Exact treatment of low l likelihood for temperature and polarization
Improvements in Data Analysis

\[ d(t) = G(t)M(t, p)[B(p, t) \otimes x(p)] + n(t) \]

\[ < n(t)n(t + \Delta t) > = N(\Delta t, t) \]

WMAP design is a success: N and B are stationary!
Gain Model

- Gain model now include RXB temperature and FPA temperature

Changes due to new Gain

\[ G = \frac{\bar{V} - V_0 - \beta(T_{\text{RXB}} - 290)}{T_{\text{FPA}} - T_0}, \]
Beams

- Determined from 6 seasons of Jupiter observations
- Full physical optics model (DADRA code) of beams using 122 fourier modes on primary and 30 fourier modes on secondary
- V and W band window functions are 1.5% lower between l=200-600
Map Making

Improved Measurement Model

\[d_1 = (1 + x_{\text{im}})(i(p_A) + q(p_A) \cos 2\gamma_A + u(p_A) \sin 2\gamma_A + s(p_A)) +
(1 - x_{\text{im}})(-i(p_B) - q(p_B) \cos 2\gamma_B - u(p_B) \sin 2\gamma_B - s(p_B))\]

Noise Filtering

\[\tilde{t}_0 = M^T N^{-1} d = M^T N^{-1} M t = \Sigma^{-1} t\]

solved iterative by CG methods with preconditioner
Pixel Noise Matrix

\[ \Sigma^{-1} = M^T N^{-1} M = \Sigma^{-1}(p_1, p_2) = \sum_{t_1, t_2} M(t_1, p_1) N^{-1}(t_1 - t_2) M(t_2, p_2), \]

Projecting Loss Imbalance:

\[ \tilde{\Sigma}^{-1} = \Sigma^{-1} - \frac{\Sigma^{-1} v \otimes \Sigma^{-1} v}{v^T \Sigma^{-1} v}, \]

Note \( l=2 \) EE and \( l=3 \) BB errors are large!
Temperature Maps

V-band

W-band

T(μK)

-200

+200

-30

+30
Since our ‘press release” map was being used extensively for science, we have attempted to characterize the uncertainties. There remains large uncertainties in the plane where there is significant foreground removal.
Polarization Maps
Magnetic Field Structure in external galaxies exhibit spiral structure

M83 6cm Polarized Int. + B-Vectors (VLA+Effelsberg)

M51 6cm Total Int. + B-Vectors (VLA+Effelsberg)

Copyright: MPIfR Bonn (R.Beck, N.Neininger, S.Sukumar & R.Auren)

Copyright: MPIfR Bonn (R.Beck, C.Horellou & N.Neininger)
Same bisymmetric spiral pattern is a good global fit to the field structure.

$B(r, \phi, z) = B_0 [\cos \psi(r) \cos \chi(z) \hat{r} + \sin \psi(r) \cos \chi(z) \hat{\phi} + \sin \chi(z) \hat{z}]$

Deviations show regions with shallower spectra.
Optical Depth Measurement is Robust

### Table 9
**Optical Depth vs. Data Selection**

<table>
<thead>
<tr>
<th>Combination</th>
<th>Exact EE Only</th>
<th>Exact EE &amp; TE</th>
<th>Simple tau EE</th>
<th>Simple tau, no $\ell = 5, 7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KaQV</td>
<td>0.111 ± 0.022</td>
<td>0.111 ± 0.022</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Q</td>
<td>0.100 ± 0.044</td>
<td>0.082 ± 0.043</td>
<td>0.08 ± 0.03</td>
<td>0.085 ± 0.03</td>
</tr>
<tr>
<td>V</td>
<td>0.092 ± 0.029</td>
<td>0.092 ± 0.029</td>
<td>0.110 ± 0.027</td>
<td>0.085 ± 0.03</td>
</tr>
<tr>
<td>QV</td>
<td>0.100 ± 0.029</td>
<td>0.092 ± 0.029</td>
<td>0.110 ± 0.027</td>
<td>0.085 ± 0.03</td>
</tr>
<tr>
<td>QV+VV</td>
<td>0.089 ± 0.048</td>
<td>0.094 ± 0.043</td>
<td>0.09 ± 0.03</td>
<td>0.09 ± 0.03</td>
</tr>
<tr>
<td>V</td>
<td>0.145 ± 0.03</td>
<td>0.145 ± 0.03</td>
<td>0.10 ± 0.07</td>
<td>0.10 ± 0.07</td>
</tr>
<tr>
<td>QVW</td>
<td>0.090 ± 0.012</td>
<td>0.090 ± 0.012</td>
<td>0.090 ± 0.015</td>
<td>0.090 ± 0.015</td>
</tr>
<tr>
<td>QVW</td>
<td>0.107 ± 0.018</td>
<td>0.106 ± 0.019</td>
<td>0.095 ± 0.015</td>
<td>0.095 ± 0.015</td>
</tr>
</tbody>
</table>

We find the same optical depth value regardless of frequency choice. We use QV for the parameter estimation.
 Improvement in Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>First Year Mean</th>
<th>WMAPext Mean</th>
<th>Three Year Mean</th>
<th>First Year ML</th>
<th>WMAPext ML</th>
<th>Three Year ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>$100\Omega_b h^2$</td>
<td>2.38$^{+0.14}_{-0.12}$</td>
<td>2.32$^{+0.12}_{-0.11}$</td>
<td>2.23 $\pm$ 0.08</td>
<td>2.30</td>
<td>2.21</td>
<td>2.22</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$^{+3}_{-5}$</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$^{+0.08}_{-0.07}$</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>
Same Model
fits small scale CMB measurements
Fig. 4.— The ΛCDM model fits to the WMAP data predict the Hubble parameter redshift relation. The blue band shows values from the Hubble parameter relation (H(z)), based on fits of synthetic stellar population models to the data. The diamonds show values from Simon et al. (2005) analysis of a high redshift sample of red galaxies.

Supernovae

WMAP fits predict $H(z)$

Galaxy Ages + HST Key Project
uncertainties and the estimate is based on several different methods (Type Ia supernovae, Type II supernovae, ... and have a scatter much larger than the quoted observational errors. Recently, Crighton et al. (2004) report a deuterium

\[
s \sim \pm 2.5 \times 10^{-4}
\]

Baryon density \( \Omega_b h^2 \)

\( \Omega_b h^2 = 0.0223 \pm 0.0008 \)

\( \eta_{10} = 6.1 \pm 0.3 \)

\begin{table}
\begin{tabular}{|c|c|c|}
\hline
10^5 y_D^{TT} & CMB-based BBN prediction & Observed Value \\
10^5 y_3 & 2.58^{+0.14}_{-0.13} & 1.6 - 4.0 \\
10^5 y_3 & 1.05 \pm 0.03 \pm 0.03 (syst.) & < 1.1 \pm 0.2 \\
Y_P & 0.24815 \pm 0.00033 \pm 0.00006 (syst.) & 0.232 - 0.258 \\
[Li] & 2.64 \pm 0.03 & 2.2 - 2.4 \\
\hline
\end{tabular}
\end{table}

**WMAP fits predict abundances**
WMAP fits predict galaxy and mass distribution
Simple Model Fits!

- Age
- CMB Observations
- Hubble Constant
- Element Abundances
- Cluster abundances
- Lensing (Weak and Strong)
- Galaxy Clustering & Galaxy Properties
New Questions

- What is the dark energy?
- What is the dark matter?
- How did the universe begin?
Inflationary Paradigm

Developed in 1980s by Guth, Linde, Steinhardt, ...

Motivated by recognition that the universe has gone through a series of phase transition

During its first moments, universe gets trapped in a false vacuum state, drives exponential expansion
Inflationary Predictions

- Nearly Scale Invariant Fluctuations (COBE)
- Flat (TOCO, Boomerang, CBI,...,WMAP)
- Adiabatic (Boomerang, CBI, ...,WMAP I)
- Superhorizon Fluctuations (WMAP I)
- Gaussian (WMAP I, WMAP II)
- $n < 1$ (WMAP II)
- Gravitational Waves (TBD)
Looking Flat...

The figure shows a comparison of data from various experiments. The graphs display the constraints on the density parameters \( \Omega_m \) and \( \Omega_L \) obtained from different combinations of data: WMAP, WMAP + HST, WMAP + LRGs, WMAP + SNLS, and WMAP + SN gold. The figure highlights the agreement of different datasets with the assumption of a flat prior on \( H_0 \).
Looking Pretty Gaussian....

```
0.100
0.100
0.010
0.010
0.001
0.001
0.001

-3 -2 -1  0  1  2  3
T/σ_{max}

V band

-4 -2  0  2  4
T/σ_{max}

V band

-4 -2  0  2  4
T/σ_{max}

V band

Nside = 16, 64, 256

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

-4 -2  0  2  4
T/σ_{max}

V band

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

-4 -2  0  2  4
T/σ_{max}

V band

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

-4 -2  0  2  4
T/σ_{max}

W band
```

As we lower the resolution, the value of σnoise slowly drops with pixel size. The red line shows the best fit Gaussian, which is an excellent fit to the one point distribution function.
Superhorizon Fluctuations
Deviations from Scale Invariance

The black curve is the likelihood surface after marginalizing over the amplitude of the SZ contribution.
WMAP + LSS
Inflation consists of taking a few numbers that we don’t understand and replacing it with a function that we don’t understand.”

David Schramm 1945 -1997

Why is the potential so flat?

Why did the field start here?

Where did this function come from?

How do we convert the field energy completely into particles?
New Approach: CMB as a back light
Atacama Cosmology Telescope
Conclusions

- CMB observations provide a “clean observational laboratory” for studying both the early universe and the basic properties of the universe today.

- Current data consistent with a simple cosmological model

- CMB a powerful tool for addressing fundamental questions in cosmology and physics
ABRAHAM LINCOLN WAS ELECTED TO CONGRESS IN 1846.
JOHN F. KENNEDY WAS ELECTED TO CONGRESS IN 1946.

ABRAHAM LINCOLN WAS ELECTED PRESIDENT IN 1860.
JOHN F. KENNEDY WAS ELECTED PRESIDENT IN 1960.

ANDREW JOHNSON, WHO SUCCEEDED LINCOLN, WAS BORN IN 1808.
LYNDON JOHNSON, WHO SUCCEEDED KENNEDY, WAS BORN IN 1908.

JOHN WILKES BOOTH, REPORTEDLY ASSASSINATED LINCOLN.
LEE HARVEY OSWALD, REPORTEDLY ASSASSINATED KENNEDY.
BOTH ASSASSINS WERE KNOWN BY THREE NAMES.
BOTH NAMES CONTAINED FIFTEEN LETTERS.

BOOTH AND OSWALD WERE ASSASSINATED BEFORE THEIR TRIALS.