“CMBPOL”
B. Winstein
U of Chicago/KICP

• The Science in CMB Polarization
• Report from the Interagency Taskforce 7/05
  – “CMBPOL” means the next satellite mission designed for polarization
• Further developments
  – WMAP 3 Year data release (foregrounds)
Expectations for the power spectra

- **TT spectrum**
- **EE spectrum**
- **E -> B lensing**
  - $(100\%/1\text{ev }\nu \text{ mass})$
- **BB spectrum**
  - **Grav. Waves**
  - $E_{\text{inf}} \sim 6 \times 10^{15} \text{ GeV}$
  - (slow-roll Inflation)

\[ C_T^{Tl}(r=10^{-3}) \]
\[ C_T^{Bl}(r=10^{-8}) \]
E/B Mode Polarization Patterns

E: from Density Perturbations
B: Only from Gravity Waves

5/23/06
Fundamental Physics in Space
An exaggerated example of the lensing effect on a $10^6 \times 10^6$ field. Top: (left-to-right) unlensed temperature field, unlensed $E$-polarization field, spherically symmetric deflection field $d(n)$. Bottom: (left-to-right) lensed temperature field, lensed $E$-polarization field, lensed $B$-polarization field. The scale for the polarization and temperature fields differ by a factor of 10.
Foregrounds Subdominant

\[ \frac{l(l+1)C_l}{2\pi}[\mu K^2] \]

- DASI ('04, 30 GHz)
- CAPMAP ('04, 90 GHz)
- CBI ('04, 30 GHz)
- Boomerang ('05, 145 GHz)

Concordance

5/23/06

Fundamental Physics in Space
Report of the Cosmic Microwave Background Task Force*

• Membership
• The Task Force Recommendations
  – Science & Technology
    • This rapid fly-through no substitute for the report
  – Several meetings
  – Many telecons
  – External readers

*Commissioned by NSF, NASA, and DOE
MEMBERS OF THE CMB TASK FORCE

James Bock  Caltech/JPL
Sarah Church  Stanford University
Mark Devlin  University of Pennsylvania
Gary Hinshaw  NASA/GSFC
Andrew Lange  Caltech
Adrian Lee  University of California at Berkeley/LBNL
Lyman Page  Princeton University
Bruce Partridge  Haverford College
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Peter Timbie  University of Wisconsin
Rainer Weiss (chair)  Massachusetts Institute of Technology
Bruce Winstein  University of Chicago
Matias Zaldarriaga  Harvard University

AGENCY OBSERVERS

Beverly Berger  National Science Foundation
Vladimir Papitashvili  National Science Foundation
Michael Salamon  NASA/HDQTS
Nigel Sharp  National Science Foundation
Kathy Turner  US Department of Energy
Recommendation S1

• **Finding:** A unique CMB polarization signal on large angular scales directly tests inflation and probes its energy scale.

• **Recommendation:** As our highest priority, we recommend a phased program to measure the large-scale CMB polarization signal expected from inflation. The primary emphasis is to test whether GUT-scale inflation occurred by measuring the signal imprinted by gravitational waves to a sensitivity limited only by our ability to remove the astrophysical foregrounds.
The phased program …begins with a strong ground- and balloon-based program that will make polarization measurements on small and medium angular scales and culminates in a space mission for larger angular scales specifically optimized, for the first time, to measure CMB polarization. Limits at or below $r = 0.01$ can be set, requiring a sensitivity at least 10 times that of Planck.
Recommendation S2

• **Finding**: The CMB temperature anisotropy on small angular scales contains a wealth of additional information about inflation and the evolution of cosmic structure.

• **Recommendation**: We also recommend a program to measure the temperature and polarization anisotropy on small angular scales, including the signals induced by gravitational lensing and by the Sunyaev-Zeldovich effect.
Neutrinos
Ground-based
Recommendation S3

• **Finding:** Foreground signals, particularly emission from our Galaxy will limit measurements of polarized fluctuations in the CMB.

• **Recommendation:** We recommend a systematic program to study polarized astrophysical foreground signals, especially from our Galaxy.
Recommendation T1

• We recommend technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors.
  – $7M per year for the next 5 to 6 years
  – restores the pre-2003 level of funding for the field
  – Emphasis on bolometer-based polarization sensitive receivers.
A planar-antenna-coupled bolometer. A dual-polarization antenna is on the left. Each double-slot dipole antenna coherently adds the signal from two slot dipoles to form a relatively symmetric antenna pattern. The slots in this chip are lithographed in a superconducting Nb ground plane. They are \(~1\) mm long and have a resonant response centered at 220 GHz. Microstrip transmission lines and transmission line filters are used. The filter combination at the top of the photograph includes a low pass filter (left) and a band pass filter (right). The design bandpass is centered at 220 GHz with a 30% bandwidth. These filters have been tested in an end-to-end receiver optical measurement which shows 20% receiver efficiency. The transmission lines terminate in the matched loads on the leg-isolated TES bolometers at the lower right.
Recommendation T2

• We recommend a strategy that supports alternative technical approaches to detectors and instruments.

• We recommend the continued development of HEMT-based detectors as they might lead to an alternative space mission and will certainly be used in ground-based measurements. …these relatively inexpensive enhancements would lower risk by keeping a wider set of technology channels open until an accepted best method has emerged.
Left: Photograph of a prototype HEMT polarimeter with cover on and input waveguides shown. Center: The complete 90 GHz Q/U module shown with cover off. Right: The 40 GHz Q/U module shown with lid off. Photographs courtesy of Todd Gaier.
QUIET L/R Correlator: Simultaneous Q/U measurements

\[ |L \pm R|^2 = \left| \left( E_x + iE_y \right) \pm \left( E_x - iE_y \right) \right|^2 = 4E_x^2, 4E_y^2 \]

4kHz phase switching

\[ \text{Im}(RL^*) = \text{Im}\left( E_x + iE_y \right)^2 = 2E_xE_y = E_a - E_b \]

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QUIET Produces Very Deep Polarization Maps

Stokes Q over a 400 square degree patch
Beam FWHM = 0.15 deg

Large scale
W-band sensitivity:

\begin{align*}
\text{Phase I: } & 400 \text{ nK/deg}^2 \\
\text{Phase II: } & 85 \text{ nK/deg}^2
\end{align*}

H.K. Eriksen
Recommendation T3

- We recommend funding for development of technology and for planning for a satellite mission to be launched in 2018.
  - development of technology
    - Background (CMB) noise limited receivers with thousands of elements
    - sub-Kelvin cryogenics
  - and planning for a satellite mission to be launched in 2018.
    - modeling the mission based on improved knowledge of foreground emissions
    - optimal spatial scale and frequency bands
    - Separation of B modes
Recommendation T4

• We recommend strong support for CMB modeling, data analysis and theory.
Fundamental Physics in Space

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</tr>
</thead>
<tbody>
<tr>
<td>Polarization Sensitivity</td>
<td>100 μK·s⁻¹</td>
<td>10 μK·s⁻¹</td>
<td>1 μK·s⁻¹</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Polarization Systematic Limit</td>
<td>10 μK</td>
<td>1 μK</td>
<td>0.1 μK</td>
<td></td>
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<tr>
<td>Polarization Map Sensitivity</td>
<td>10 μK</td>
<td>1 μK</td>
<td>0.1 μK</td>
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Maps of Temperature
Maps of E-Mode
Maps of B-Mode

WMAP
PLANCK

Ground-Based HEMT
- CBI, DASI, CAPMAP

Ground-Based Bolometric Receivers
- BICEP, MBI, QUAD, and proposed

Ground-Based HEMT/MIMICS
- Proposed

Cryogenic Techniques
- Observing Strategies
- 100 Element Arrays
- Data Analysis/Comp.
- 1000 Element Arrays

Ground – Bolo.
- Acbar, Bolocam

Balloon – Bolo.
- Boomerang, Maxipol

Balloon – Bolometer
- PAPFA, EEEX, and proposed

Foregrounds - DUST

Advanced Receivers

GOAL: Produce a Polarization MAP down to the fundamental astrophysical foreground limits. First space mission designed to measure the CMB Polarization.
## Systematic Challenges for the Ultimate Mission

### Table 6.1: Instrument Performance Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect</th>
<th>Goal</th>
<th>Method</th>
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</thead>
<tbody>
<tr>
<td>Cross-Polar Beam response</td>
<td>$E \rightarrow B$</td>
<td>$&lt; 0.003$</td>
<td>Rotate Instrument, Wave Plate</td>
</tr>
<tr>
<td>Main lobe ellipticity (0.5° beam)</td>
<td>$dT \rightarrow B$</td>
<td>$&lt; 10^{-4}$</td>
<td>Rotate Instrument, Wave Plate</td>
</tr>
<tr>
<td>Polarized sidelobes (response at Galaxy)</td>
<td>$dT \rightarrow B$</td>
<td>$&lt; 10^{-6}$</td>
<td>Baffles/shielding/measure</td>
</tr>
<tr>
<td>Instrumental polarization</td>
<td>$dT \rightarrow B$</td>
<td>$&lt; 10^{-4}$</td>
<td>Rotate Instrument, Wave Plate</td>
</tr>
<tr>
<td>Polarization angle</td>
<td>$E \rightarrow B$</td>
<td>$&lt; 0.2 ^\circ$</td>
<td>Measure</td>
</tr>
<tr>
<td>Relative pointing (of differenced samples)</td>
<td>$dT \rightarrow B$</td>
<td>$&lt; 0.1''$</td>
<td>Dual-polarization pixels</td>
</tr>
<tr>
<td>Relative calibration</td>
<td>$dT \rightarrow B$</td>
<td>$&lt; 10^{-5}$</td>
<td>Modulators</td>
</tr>
<tr>
<td>Relative calibration drift (scan synchronous)</td>
<td>$T \rightarrow B$</td>
<td>$&lt; 10^{-9}$</td>
<td>Modulators</td>
</tr>
<tr>
<td>Lyot Stop Temperature (10% spill, scan synch.)</td>
<td>$dT_{opt} \rightarrow B$</td>
<td>$dT_{opt} &lt; 30 \text{nK}$</td>
<td>Measure</td>
</tr>
<tr>
<td>Cold stage T drifts (scan synch.)</td>
<td>$dT_{CS} \rightarrow B$</td>
<td>$dT_{CS} &lt; 1 \text{nK}$</td>
<td>Improve uniformity, measure</td>
</tr>
</tbody>
</table>
WMAP Foregrounds

(Ned Wright)
Opening Up Studies That Are Arguably:

THE Most Fundamental Research in Space- from the Quantum to the Cosmos
$V(\phi) \propto \phi^\alpha$

Consistency relations

\[
\begin{align*}
\Delta_R^2(k) &= \left(\frac{k}{k_0}\right)^{n_s - 1} \\
1 - n_s &= \frac{4\alpha}{N} \\
N &\approx \frac{\alpha + 2}{2N}
\end{align*}
\]

These models predict almost no running

Similar constraints for B03+ACBAR
Summary

• Ground and Balloon Program Important
  – Early foreground characterization
  – Exploring scanning strategies, other systematics
  – Exploring detection technologies
  – Could achieve sensitivity to $r < 0.1$ using LSS

• Satellite (“CMBPOL”)
  – Uniquely probes $r < 0.01$ using re-ionized plasma
  – Most stable environment for instrumentation challenge
    • Extremely low noise requirements
    • The regime of $S/N = 10^{-8}$

• Polarization is HARD
  – 9 pages in Page et al. devoted to Foregrounds
  – Analysis took a very long time
From the Executive Summary ..

• The search for CMB polarization offers an ideal arena for DoE, NASA, NIST and NSF interagency co-operation. Indeed, given the need for receiver development, ground-based observations, foreground characterization, and a space mission, the road map requires such cooperation.
Figure 10.3: Past (2004–2005) and projected (2006–2011) funding levels for CMB research. The plot is made in 2005 dollars.
Astrophysical Foregrounds

Estimates by WMAP of the temperature RMS as a function of frequency (extrapolation from maps at different frequencies)

Level of polarization not well determined with measurements, dependent on scan region.

Best estimates for average fraction of intensity:

- Synchrotron: 10-75%
- Free-free: <10%
- Dust: <10%
Science Targets:

- Fine scale E-pol
- Lensing: E→B
Science Targets:

- **Lensing**
  - $E \gg B$
  - $E_{\text{inf}} \sim 6 \times 10^{15} \text{GeV}$ (slow-roll Inflation)

- **Grav. Waves**
  - Cosmic Strings
    - (Brane Inflation)
    - Pogosian, Tye, Wasserman, Wyman:
      - Astro-ph:03041488

- **Fine scale E-pol**
  - $C_T(r=10^{-3})$

- **Lensing: E→B**

- **Grav. Waves**

- **Cosmic Strings**
  - (Brane Inflation)
  - Pogosian, Tye, Wasserman, Wyman:
    - Astro-ph:03041488

- **Grav. Waves**
  - $E_{\text{inf}} \sim 6 \times 10^{15} \text{GeV}$ (slow-roll Inflation)
Role for DOE/HEP?

• Science
  – Inflation: extraordinary idea outside Standard Model!
  – Very rich phenomenology

• Agency Problems
  – Crunch at NSF
  – NASA on the ground?

• Contributions to Experiments
  – The challenge of the instrumentation
    • Extremely low noise requirements
    • The regime of S/N=10^{-8}
  – (warm) Electronics
  – Data analysis, large scale computing
  – Engineering; Management
Testing Inflationary Models

![Graph showing the testing of inflationary models with axes for tensor-to-scalar ratio and scalar spectral index. The graph includes regions marked as 'Ruled out by CMB', ' Allowed', '+Galaxy clustering', ' +Quasar spectra', and 'Hybrid inflation', 'Large-field inflation', 'Small-field inflation'.]
Schematic timeline of research programs observing CMB small-scale temperature fluctuations, CMB polarization, and the Sunyaev-Zel'dovich effect. The projects included in technology development are needed for ground-based, balloon and space observations.
Foreground Estimates

$2<l<20$

Multi-frequencies
Current and Near-Term Polarization Measurements

Angular Scale

EE progress
BB goal
reionization
“large scale”
(unique to satellite)
2 bumps
R=0.01

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