Probing Inflation with CMBPol

Gary Hinshaw, NASA/GSFC
Presentation to NRC Beyond Einstein Program Assessment Committee
November 7, 2006

Gary Hinshaw, NRC-BEPAC, 11/7/06
The Concept Study Team

- Chuck Bennett (GFSC)
- Mark Devlin (U. Penn)
- Dale Fixsen (GSFC)
- Gary Hinshaw (GSFC, PI)
- Wayne Hu (U. Chicago)
- Kent Irwin (NIST/Boulder)
- Norm Jarosik (Princeton)
- Alan Kogut (GSFC)
- Arthur Kosowsky (Rutgers)
- Michele Limon (GSFC)
- Steve Meyer (U. Chicago)
- Amber Miller (Columbia)
- Harvey Moseley (GSFC)
- Barth Netterfield (U. Toronto)

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- Angelica Oliviera-Costa (U. Penn)
- Lyman Page (Princeton)
- John Ruhl (Case Western)
- Uros Seljak (Princeton)
- David Spergel (Princeton)
- Suzanne Staggs (Princeton)
- Max Tegmark (U. Penn)
- Bruce Winstein (U. Chicago)
- Ed Wollack (GSFC)
- Ned Wright (UCLA)
- Matias Zaldarriaga (Harvard)
- Cliff Jackson (GSFC)
1965: Penzias & Wilson Discover the CMB

Microwave Receiver - Bell Labs
New Jersey

1978 Nobel Prize in Physics

1989-1993: COBE Unleashes the CMB

COBE-DLR anisotropy of the CMB

COBE-FIRAS spectrum of the CMB

COBE Spacecraft

2006 Nobel Prize in Physics

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Tremendous progress has been made!

$\Delta T \sim 0.1 \text{ K in 1965}$

$\Delta T \sim 0.1 \mu\text{K in 2005}$

Advances in space - largely based on experience gained in numerous balloon and ground-based campaigns.
The only thing standing between the CMB and inflation is a thin layer of warm plasma.

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Six Tests of Inflation (after Steinhardt)

- The following are “generic” predictions of inflation, phenomena for which we had little evidence when inflation was introduced in 1980:
  - **nearly-scale-invariant fluctuations**
    - spectral index - measured with ~20% precision by COBE
  - **flat universe**
    - position of 1st acoustic (BAO) peak - measured by TOCO, Boomerang, WMAP1
  - **adiabatic fluctuations**
    - coherence of acoustic (BAO) peaks - measured by Boomerang, ..., WMAP1
  - **gaussian fluctuations**
    - limits on $f_{NL}$, measured by WMAP1
  - **super-horizon fluctuations**
    - TE anti-correlation on >2° scales, measured by WMAP1
  - **spectral tilt, $n_s < 1$**
    - favored by WMAP3
  - **gravity waves (a.k.a. tensor fluctuations)**
    - measured by the Inflation Probe...
Inflation and Gravity Waves - I

- Inflation predicts two forms of fluctuations:
  - Scalar modes (density perturbations) with slope $n_s$:
    - generate CMB anisotropy and lead to structure formation
  - Tensor modes (gravity waves) with slope $n_t$:
    - generate CMB anisotropy but do not contribute to structure formation

- Gravity wave amplitude, $r$, proportional to energy scale of inflation:

$$ r^{1/4} \propto \frac{V_{\phi}^{1/4}}{m_{pl}} = \frac{E_{\text{infl}}}{3.3 \times 10^{16} \text{ GeV}} \quad \text{with} \quad r \equiv \frac{(\Delta T)_{\text{tensor}}^2}{(\Delta T)_{\text{scalar}}^2} $$

- Both types of fluctuations contribute to CMB temperature anisotropy:
“We find that, except for (inflation models) with numerous unnecessary degrees of fine-tuning, $n_s < 0.98$, measurably different from exact HZ. Furthermore, if $n_s > \sim 0.95$, in accord with current measurements, the tensor/scalar ratio satisfies $r > \sim 10^{-2}$, a range that should be detectable in proposed CMB polarization experiments.”

Boyle, Steinhardt, Turok (2005)
Inflation and Gravity Waves - II

• Both types of fluctuations contribute to CMB polarization anisotropy:
  – Scalar modes produce only “E-mode” polarization patterns, by symmetry
  – Tensor modes produce both “E-mode” and “B-mode” polarization patterns (see below)

• The observation of B-mode polarization uniquely separates scalar and tensor modes from inflation and measures the energy scale of inflation.

• Only known probe of physics at $E \sim 10^{16}$ GeV… 12 orders of magnitude higher than planned accelerators!

E – scalar+tensor

B – tensor only
Task Force on CMB Research (TFCR)

- The value of CMB polarization measurements was emphasized in the last National Academy of Science *Decadal Survey*.

- The 2003 National Research Council report, *Connecting Quarks with the Cosmos*, recommended that NASA, NSF, and DoE:
  - “Measure the polarization of the cosmic microwave background with the goal of detecting the signature of inflation” and “undertake research and development to bring the needed experiments to fruition.”

- OSTP response to the CPU report:
  - "The three agencies (NASA, NSF, DoE) will work together to develop by 2005 a roadmap for decisive measurements of both types of CMB polarization. The road map will address needed technology development and ground-based, balloon-based, and space-based CMB polarization measurements."

- TFCR Report (“The Weiss Report”) was issued Fall 2005
  - “We recommend that NASA, NSF and DoE carry out a phased program of ground-, balloon- and space-based measurements of the CMB polarization anisotropy, with a primary emphasis on mapping the $B$-mode (gravity wave) signal to a sensitivity limited only by our ability to model and subtract the astrophysical foregrounds.”
Task Force Membership

- **Task Force:**
  - Rainer Weiss (chair), MIT
  - James Bock, Caltech / JPL
  - Sarah Church, Stanford University
  - Mark Devlin, University of Pennsylvania
  - Gary Hinshaw, NASA / GSFC
  - Andrew Lange, Caltech
  - Adrian Lee, U.C. Berkeley / LBNL
  - Lyman Page, Princeton University
  - Bruce Partridge, Haverford College
  - John Ruhl, Case Western Reserve
  - Max Tegmark, Penn. / MIT
  - Peter Timbie, University of Wisconsin
  - Bruce Winstein, University of Chicago
  - Matias Zaldarriaga, Harvard University

- **Agency Observers:**
  - Beverley Berger, NSF
  - Vladimir Papitashvili, NSF
  - Michael Salamon, NASA/HQ
  - Nigel Sharp, NSF
  - Kathy Turner, DoE
Predicted Polarization Signal, $r=1.00$

Temperature spectrum (as before)

E-mode polarization spectrum, scalar (blue) & tensor (red) terms

B-mode polarization spectrum, tensor (red) & gravitational lensing (green) terms
Predicted Polarization Signal, $r=0.10$

Temperature spectrum (as before)

E-mode polarization spectrum, scalar (blue) & tensor (red) terms

B-mode polarization spectrum, tensor (red) & gravitational lensing (green) terms
Predicted Polarization Signal, $r=0.01$

Temperature spectrum (as before)

E-mode polarization spectrum, scalar (blue) & tensor (red) terms

B-mode polarization spectrum, tensor (red) & gravitational lensing (green) terms
Current Polarization Data - WMAP3

- TT – temperature anisotropy
- TE – temperature - polarization correlation, (measured in 1st year data)
- E-mode polarization, (measured in 3-year data)
- B-mode polarization (data upper limit from 3-year data, model upper limit from TT data)

Page et al., 2006

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Green - lensing foreground (EE→BB from scalars), frequency independent

Red - gravity wave signal:
r=0.3: current upper limit
r=0.01: target sensitivity for CMBPol
Grey shaded band - 1-sigma sensitivity for 1000-channel system with 1-yr observing and 1° FWHM resolution.
Sensitivity & Foreground Estimates

- **Blue band** - Galactic foreground estimate from WMAP3, frequency dependent
- **Green line** - Lensing (EE→BB), frequency independent
- **Red lines** - Gravity wave signal(s)
- **Grey shaded band** - 1-sigma sensitivity for 1000-channel system with 1-yr integration, 1° FWHM resolution

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The Road to nanoKelvin Measurements

Measuring CMB polarization at the nanoKelvin level requires:

• Sensitivity:
  – Employ ~1000 background-limited detectors.
  – Mostly a fabrication problem, not a fundamental one.

• Removal of foreground signals:
  – Employ multiple frequencies, roughly 30-300 GHz.
  – Details of frequency coverage depend on complexity of foreground signals.

• Control of systematic errors:
  – Modulate polarization signal on multiple time scales to reject unpolarized light.
  – Control polarized stray light.
    → hardware design and scan strategy.
  – Monitor gain fluctuations to a level commensurate with modulation strategy.
    → calibration strategy
CMB polarization measurements require:
- large arrays of sensitive detectors
- control of systematic errors to -80 dB

GSFC research and capabilities:
- large superconducting detector arrays
- superconducting planar microwave circuits
- advanced light coupling schemes
- laboratory and balloon flight system tests

Platelet feed horn array & planar OMT for coupling light to planar circuits with highly symmetric beams

Fabrication and testing of arrays of superconducting transition edge sensors

Superconducting niobium planar micro-strip microwave circuits with planar antenna coupling

Superconducting SQUID-multiplexed TES detector readout, and large cryogenic test facilities for detector systems

Millimeter-wave modeling and test capabilities

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 Galactic Foreground Emission

- Current estimates of polarized foregrounds have large uncertainties. Frequency of minimum foreground emission is between ~60 – 90 GHz.
- Likely range of required frequency coverage is within 30 – 300 GHz, based on simple linear analyses.
- Key questions:
  - Assess the variation of the foreground emission across the sky in both intensity and frequency spectrum.
  - Assess how non-Gaussian the polarized Galactic emission is, and to what extent we can take advantage of this to detect and remove these contaminants.
Simple Foreground Removal

A simple approach to foreground removal is to form linear combinations of multi-frequency data that cancel signals with known (or specified) foreground spectra.

Examples:

1) logarithmic frequencies from 30-300 GHz

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>30.0</th>
<th>50.0</th>
<th>80.0</th>
<th>125.0</th>
<th>200.0</th>
<th>300.0</th>
</tr>
</thead>
<tbody>
<tr>
<td># channels:</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td>Coefficient</td>
<td>-0.088</td>
<td>0.241</td>
<td>0.312</td>
<td>0.321</td>
<td>0.275</td>
<td>-0.061</td>
</tr>
</tbody>
</table>

Foreground degradation factor*: 1.44
Percentage error in synchrotron & dust removal, assuming Δβ=0.1: 6% 59%

2) logarithmic frequencies from 40-125 GHz

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>40.0</th>
<th>50.0</th>
<th>65.0</th>
<th>80.0</th>
<th>100.0</th>
<th>125.0</th>
</tr>
</thead>
<tbody>
<tr>
<td># channels:</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td>Coefficient</td>
<td>-0.463</td>
<td>0.344</td>
<td>0.691</td>
<td>0.654</td>
<td>0.305</td>
<td>-0.531</td>
</tr>
</tbody>
</table>

Foreground degradation factor*: 3.11
Percentage error in synchrotron & dust removal, assuming Δβ=0.1: 8% 13%

*Foreground Degradation Factor – noise penalty incurred for combining data with sub-optimal weight.
WMAP 61 GHz (V-band) sky map, ±200 μK scale
Plane signal ~5 mK
WMAP Foreground Removal, Stokes I

WMAP Internal Linear Combination (ILC) sky map, ±200 μK scale
Residual plane emission < 100 μK ~2% of 61 GHz signal
WMAP Foreground Removal, Stokes Q

Synchrotron template from WMAP 22 GHz polarization channel

Dust template from model intensity and starlight obs.

Procedure: fit and subtract best-fit synchrotron and dust templates from each of the 4 frequency bands

before
33 GHz
41 GHz
61 GHz
94 GHz

after

-15 μK  0 μK  +15 μK

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Both EE and BB spectra were cleaned by a factor of ~10 in power using a 2 parameter model -- fine for current WMAP sensitivity.

Future data will require the BB signal to be cleaned by a factor of ~10 to ~30 (in amplitude) to reach $r \sim 10^{-2}$.
Candidate Detector Concept

Left – Array of feeds couple radiation to planar superconducting circuitry. Feeds offer excellent control of optical performance.

Above - A schematic diagram of the superconducting circuit for extracting the H and V polarizations from a single beam.
Candidate Modulation Concept

“The closer a modulator is to the sky in the signal path, the more potential systematic effects it can modulate and thus stabilize.” – TFCR Report

Right - the general layout for a single optical path. The primary optical element is a variable-delay polarization modulator (VPM). A single mirror focuses the radiation into a cryostat where it couples to the focal plane.

Left - a Hertz/HHT VPM module.

Philosophy –

• Null response to unpolarized radiation
• Strict control of polarized stray light.
Candidate Observatory Concept

Multiple copies of basic polarimeter module, scaled in frequency, packaged in focal plane, co-aligned along s/c symmetry axis.
Mission Operations Concept

Lifetime
• 15 months: 1 year nominal + IOC + contingency

Orbit
• COBE orbit: 103 min period, 900 km Sun-synchronous, 99° inclination
• Study topic – need for Moon avoidance 1st & 3rd quarters

Scan
• One observing mode: full sky survey
• Moderate spin (1-2 min period) about instrument line-of-sight, 94° off Sun line
• Modulate polarization independently in each pixel
• Study topic – fix spin axis then advance vs. continuous slew (e.g. COBE-FIRAS)

Data rates/comm.
• 1 Gb / orbit – 6 bits/channel (compressed) read out @ 20 Hz + housekeeping
• Stations: Svalbard, Poker Flats, McMurdo, Wallops, ...

Mission control center
• Data capture (once/orbit); command management (weekly)
• Trending, level-0 processing, data archiving

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New Techniques for CMBPol

**Detectors**
- Large format TES detectors *now* in development at GSFC for ACT, GBT.
- Need to develop polarization sensitive optical coupling techniques.
- Many synergies with X-ray detector technologies.

**Polarization modulation**
- Sub-mm variable-delay polarization modulator (VPM) fielded at HHT.
- Need to develop for GHz CMB application. No fundamental issues.

**Focal plane**
- Packaging and thermal control of 1000-channel focal plane.
- Engineering challenge, not a fundamental one.

**Mission concept development**
- Need more sophisticated development for reliable cost estimates.
TFCR Program Summary

• CMB polarization provides the only currently-known probe of physics at the Grand Unified Theory (GUT) scale.
• Concepts for a capable CMB polarization mission -- within the scope of an Einstein Probe -- already exist.
• The program leading to an actual mission requires:
  – **Systems development**
    • Produce and field-test viable instrument components.
  – **Field experience**
    • Hands-on experience with new receivers and observing strategies.
    • Parallels successful lead-up to COBE, WMAP, & Planck.
  – **Foreground and E-mode data**
    • To aid in defining the performance requirements of a space mission.
  – **Mission concept development**
    • Paper studies that integrate mission design with field experience and computer simulations.
Backup
Inflation Parameters: Measurements c. 2006

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WMAP Foreground Spectra

- Solid colors - EE foreground
- Dashed colors - BB foreground
- Dot-dashed red - foreground estimate @ 65 GHz
- Solid black - model CMB

Page et al., 2006

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### Systematics in WMAP 94 GHz Polarization

**Page et al., 2006**

<table>
<thead>
<tr>
<th>L</th>
<th>Polarization Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$K_a, K_aQ, K_aV, QV, QW, V_QW, VW, W</td>
</tr>
<tr>
<td>5</td>
<td>$I=5$ polarization data vs. frequency to look for residual effects.</td>
</tr>
<tr>
<td>6</td>
<td>94 GHz channel exhibits significant residuals that cannot be explained by cleaning errors.</td>
</tr>
<tr>
<td>7</td>
<td>We continue to investigate this with more data.</td>
</tr>
</tbody>
</table>

Underscores risk of not sufficiently modulating the polarization signal.

So…

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## CMBPol Statistics

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>30-300 GHz in 6 bands</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1024 allocated to 6 bands</td>
</tr>
<tr>
<td>Resolution (FWHM)</td>
<td>1°</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Background limited</td>
</tr>
<tr>
<td>Detection</td>
<td>Feed/OMT-fed TES</td>
</tr>
<tr>
<td>Modulation</td>
<td>VPM, 50 cm clear aperture</td>
</tr>
<tr>
<td>Optics</td>
<td>Parabaloid primary</td>
</tr>
<tr>
<td>Orbit</td>
<td>900 km sun-sync polar</td>
</tr>
<tr>
<td>Observing</td>
<td>Spin about line-of-sight</td>
</tr>
<tr>
<td>Power (instrument)</td>
<td>600 W</td>
</tr>
<tr>
<td>Data rate</td>
<td>1 Gb / orbit (103 min)</td>
</tr>
</tbody>
</table>
System Concept

- System has these functions:
  - Coupling of radiation from telescope to microstrip circuit
  - Appropriate phase combination of signals
  - Filtering
  - Detection
Advantages: • can insert other components between antenna and detector
• microstrip transmission lines and planar components are more compact than 3D versions
CMBPol Detector Design Process

System Components

- horn antenna
- probe antennas
- superconducting microstrip
- cross-overs
- 180 degree hybrid
- bandpass filter
- thermal break
- terminator
- TES detector

Probe antennas: waveguide to planar transition; separate polarizations

Filter: set measurement band

Hybrid: add & subtract signals

Terminator: absorb power

TES: measure temperature rise to detect power

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CMBPol Detector Design Process
Modeling and Test of Individual Components

- modular set of design tasks (many completed with this funding!)
- simulation & optimization of one component takes \( \approx 1-2 \) weeks
- most designs involve significant innovations
- simulation input: materials properties and geometry
- competing designs can be evaluated

\[ b_i = \sum S_{ij} a_j \]

Scattering Matrix = reflection and transmission coefficients

Filter Response Function

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CMBPol Detector Design Process

Mathematical Combination of Elements into System

- combine S-matrices (measured or simulated)
- predict system performance
- trade competing designs for components

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CMBPol Detector Design Process

Tests on Model Skies

- Bandpass filter response convolved with sky signals
- Beam patterns and cross-polarization
- Scan and modulation strategies
## Fabrication & Development of Test Parts

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Critical Fabrication Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterization of Fundamental Dielectric Properties</td>
<td>Design &amp; Construction of Probes Chips &amp; Resonators</td>
</tr>
<tr>
<td>Components: Filters, Couplers, &amp; Crossovers</td>
<td>Control of $\mu$-strip linewidth &amp; Isolation of 2 Nb $\mu$-strip layers with good step coverage</td>
</tr>
<tr>
<td>Noise requirement in polarization measurement</td>
<td>Low noise Transition Edge Sensor detectors</td>
</tr>
</tbody>
</table>
Characterization of Dielectric Properties of $\text{Al}_2\text{O}_3$

- Devices design basic structure
  - superconducting Nb $\mu$-strip, lossless up to 700 GHz

- Waveguide Probe Chips:
  Funded by PAPPA

100 $\mu$m thick Si cantilever
Characterization of Al₂O₃ & Si Dielectric Properties

- Ring Resonators on Si (funded under previous DDF) and Al₂O₃ Dielectric layers -- resonator $Q$, coupling strength, and dielectric loss measurement

Different coupling geometries between $\mu$-strip & resonators

Predicted Ring Resonator Performance

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30GHz Bandpass Filters -- Competing Design

Antenna
Waves
Bandpass Filter
OR?
Power Detector
Transmission Line
Transmission Line

Good linewidth control!!
Currently, under evaluation

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**Major Challenge:** Cleanly isolate 2 Nb microstrip layers with good step coverage

Trim patterned Nb by Ion-Milling

Deposit $\text{Al}_2\text{O}_3$ with Ion-Milling on $\text{Al}_2\text{O}_3$ Planarization
Fabrication/Process Development Challenge

**Our Approach to Nb isolation:**

1. Modify Nb Deposition Method: RF bias & DC deposition separately
2. Increase ratio between dielectric layer thickness and step height
Low Noise Mo/Au Transition Edge Sensor Detectors

- TES detector process used for Atacama Cosmology Telescope & Constellation - X development
- Integrate TES with Nb μ-strips
Complete Devices -- Arrays for Polarization measurement

**Al₂O₃** as the dielectric layer  **Si** as the dielectric layer

TES + Au Terminator on membrane

- Membrane: thermal isolation for TES

Probe antennas on membrane

- Membrane: mechanical support for antennas on waveguides
Galactic Foreground Estimate

Blue band - galactic foreground estimate from WMAP3 @ 65 GHz, frequency dependent

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