The Inflation Probe Science Analysis Group

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for
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Testing Inflation with CMB Polarization

Key Inflationary Observables
1. Nearly scale-invariant fluctuations
2. Flat universe
3. Adiabatic fluctuations
4. Nearly Gaussian fluctuations
5. Super horizon fluctuations
6. Departure from scale invariance?
7. Non-Gaussianity?
8. Inflationary gravitational waves?

First Definitive CMB Result
COBE
Boomerang + Maxima + TOCO
Boomerang + Maxima + WMAP
WMAP
WMAP
Planck
Planck
Inflation Probe

Comprehensively measure inflationary CMB polarization signal corresponding to inflation at GUT energy scales
Significance of Inflationary Polarization

- B-modes cannot be produced by density variations
- Constrains Big Bang physics at GUT energy scales
- Simplest Inflation models predict a detectable level of \( r > 0.01 \)
- Slow-roll models predict a relationship between \( (1 - n_s) \) and \( r \)

“Detection of B-mode polarization in the CMB polarization … would represent a watershed discovery.” - New Worlds New Horizons
CMB Polarization Science is Deep and Broad

CMB Polarization Spatial Power Spectra

Scalar Perturbations
- E-modes
  - Precision cosmology
  - Departure from scale inv.
  - Reionization history

Gravitational Lensing
- B-Modes
  - Neutrino mass hierarchy
  - Dark energy at z > 2

Galactic Magnetic Fields
- E & B-Modes
  - Star formation
  - Large-scale fields

Inflationary
- Gravitational Waves
  - B-modes
  - GUT energy scale
  - Large field inflation
  - n_s / r consistency test

E-mode patterns

B-mode patterns
Using CMB Lensing to Study Large Scale Structure

Caltech workshop to study space and ground-based surveys of CMB lensing

CMB polarization measures projected gravitational potential
- neutrino masses
- late dark energy
- relation between galaxy formation and dark matter
- a legacy data product for galaxy-based studies of structure formation
A successful detection of B-modes from inflation could trigger a mid-decade shift in focus toward preparing to map them over the entire sky. In this case a notional decadal budget of $60 million is proposed. However, the level of late-decade investment required is uncertain, and the appropriate level should be studied by a decadal survey independent advice committee review. It could range between the notional budget used here up to a significant (perhaps on the order of $200 million) mission-specific technology program starting mid-decade.”
The ESA / NASA Planck Satellite

Instrument Status
- HFI sensitivity exceeds pre-launch goals
- Thermal system performance as expected
- 100 mK operations ended in January 2012
- Extended observations continuing

Planck Strengths
- Comprehensive temperature measurements
- 9 bands for foregrounds separation
- Good polarization sensitivity
  - High-fidelity E-mode polarization measurements
  - Sensitivity for B-mode detection?

Mission Events
- 14 May 2009: Launch
- March 2010: First sky map complete
- March 2011: Third sky map complete
- January 2012: End of HFI life (LFI continues)

Planned Data Releases
- January 2011: Point Source Catalog & Astrophysics
- March 2013: CMB Temperature
- Early 2014: CMB Polarization #1
# Sub-Orbital and Ground-Based Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technology</th>
<th>Resolution (arcmin)</th>
<th>Frequency (GHz)</th>
<th>Detector Pairs</th>
<th>Modulator</th>
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<td>US-led Balloon</td>
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<td>VPM</td>
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<td>40/90/150</td>
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<td>10-30</td>
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- Push to higher sensitivity than Planck: new detector array technologies
- Focused on B-mode science: target small, deep fields
- Explore the diversity of technology approaches
- Test new methodologies for systematic error control
- Rapid progress in sensitivity and systematic error control
High Significance E-Mode Polarization Detections

QUIET Collaboration et al. (2012)

$C_l^{EE} (l+1)/2\pi (\mu K^2)$

Multipole Moment, $l$
B-Modes? Improving Upper Limits

QUIET Collaboration et al. (2012)

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

\[ \text{Multipole Moment, } l \]

BICEP data from 2006-7

Lensing

\[ r = 0.1 \]
A Taste of What is to Come

16 times more data in the can from BICEP2/Keck!
The Race for Inflationary B-Modes

- PIPER
- EBEX
- POLARBEAR
- BICEP3
- QUIET
- SPT-POL
- RED

RED indicates experiment has been fielded.
Task Force for CMB Research Weiss Report: Projected Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Temperature</th>
<th>Sensitivity</th>
<th>Systematic Limit</th>
<th>Map Sensitivity</th>
<th>Mode</th>
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<td>100μK-s^2/Hz</td>
<td>1μK-s^2/Hz</td>
<td>Maps of Temperature</td>
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<td>2018</td>
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Where we are today:

- WMAP
- PLANCK
## Inflation Probe Technology Development

### Priorities from the Inflation Probe Technology Roadmap

<table>
<thead>
<tr>
<th>Technology</th>
<th>Priority</th>
<th>Timescale</th>
<th>Candidates</th>
<th>TRL</th>
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</thead>
<tbody>
<tr>
<td>Detector Arrays</td>
<td>High</td>
<td>Sub-orbital experiments</td>
<td>TES+SQUID+Antenna HEMT / MMIC</td>
<td>4-5</td>
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<tr>
<td>Optics</td>
<td>Medium</td>
<td>Sub-orbital experiments</td>
<td>Polarization modulators AR coatings</td>
<td>2-5</td>
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<tr>
<td>Coolers</td>
<td>Low</td>
<td>Develop for space</td>
<td>Passive+mechanical+sub-K</td>
<td>3-9</td>
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<tr>
<td>Advanced Arrays</td>
<td></td>
<td>Develop for simplified space implementation. Connects to X-ray, far-IR and optical astronomy</td>
<td>MKID+RF resonator TES+RF resonator</td>
<td>3</td>
</tr>
</tbody>
</table>

### Community Technology Plan

- Very directed: 4 technologies
- Effective: implement in sub-orbital and ground-based experiments
- Cross-cutting: overlap with X-ray and far-infrared needs
- Prioritization: clearly described

The IPSAG supports the streamlined PCOS/COR technology prioritization criteria
Historical Interplay: Suborbital Experiments serve to

- Shape scientific objective of a space mission
- Develop experimental methodologies
- Train leaders of future orbital missions
- Develop technologies at systems level
Inflation Probe Technology Challenges

- Most urgent Inflation Probe technology needs are at mid-TRLs
- CMB technology funding has been extremely limited to date
- Technology readiness is governing rate of scientific progress needed for the mid-decade assessment

The IPSAG recommends increased mid-TRL funding for Inflation Probe technology development in preparation for the mid-decade assessment.
The European CORE Consortium will propose an Inflation Probe mission for the next ESA opportunity, expected in 2014.

The CORE Consortium held a “Workshop on Spectral Polarimetry” 11-12 December to explore a lost-cost polarized spectroscopic instrument concept.

JAXA is studying the Explorer-class LITEBIRD discovery mission, selectable as early as 2013.

**CORE**
ESA 2010 proposal
1.2 m aperture

**LITEBIRD**
JAXA Explorer-class concept
60 cm aperture
Inflation Probe Mission Studies: US

- There is no US mission study activity at present. Study effort in was very effective with wide participation from the CMB community in 4 workshops.

- The Astrophysics Implementation Plan states an Inflation Probe mission study is “under consideration for 2015”

- Advantages of starting Inflation Probe mission studies:
  - Needed for the mid-decade assessment
  - A probe option for the 2015 decision
  - Injects US participation in the European proposal during its development

- Disadvantages?
  - Planck polarization data will be released in 2014, but with significant analysis and concurrent interpretation by the Planck team in place.
  - Readiness of sub-orbital and ground-based measurements is difficult to predict. But this does not gate studies which can proceed in parallel.

The IPSAG recommends starting mission study activities at the earliest opportunity, which provide advantages for NASA for little cost. We encourage NASA to engage the CMB community about starting a mission study effort in 2014.
1) Planck data are excellent and will be released on schedule to inform the design of the Inflation Probe

2) The CMB community is making rapid progress in sub-orbital and ground-based experiments searching first detection of B-mode polarization. The lensing B-mode signal is in the detectable range and is a future cosmological tool

3) Technology funding has lagged behind expectations. We recommend augmenting mid-TRL technology funding, as this will gate progress towards the mid-decade assessment and beyond

4) We recommend starting mission study activities at the earliest opportunity
Backups
CMB Polarization Satellite Mission Concepts

Experimental Probe of Inflationary Cosmology
*CMB community mission developed for Decadal*

**1.4 m Crossed Dragone Telescope**
- Resolution to measure lensing signal cosmic limits

**Large Focal Plane**
- *equates to 1000 Planck missions!*
- Wide band coverage for foregrounds

**Cooling system**
- 100 mK
- *Improved Planck system*

**L2 Halo Orbit**
- Scan strategy for large-scale polarization
- Simple operations, conventional spacecraft

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**CORE**
Cosmic ORigins Explorer
- ESA 2010 proposal
- 1.2 m aperture

**LITEBIRD**
Japanese concept
- 30 cm aperture

**EPIC-Low Cost**
JPL concept
- 30 cm apertures

**PIXIE**
SMEX proposal
- Multi-mode FTS

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*The EPIC Intermediate Mission*
Bock et al. arXiv 0906.1188
Technology Needed for Space: An Evolution from Planck

1.5 m Telescope

100 mK Cooler

3-stage V-groove

4 K Cooler

Polarized bolometer

100 mK Focal Plane

Planck Heading to L2!

CMB Community Workshop:
Technology Development for a CMB Probe of Inflation, Boulder CO, 25-28 August 2008
How does large-scale Galactic field related to field in embedded star-forming regions?
EBEX Launch