Progress in the Precision Measurements of the Cosmic Microwave Background

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NOW2010
Conca Specchiulla
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Cosmological Neutrino Background

At present $112 (\nu + \bar{\nu}) \text{cm}^{-3}$ per flavour

Extremely low energy ($\ll$eV)

- Direct detection not possible at present
- They influence several cosmological observables, and can be constrained indirectly
### Primordial Nucleosynthesis

**BBN**

- $T \sim \text{MeV}$
- $\nu_e$ vs $\nu_{\mu,\tau}$, $N_{\text{eff}}$
- $N_{\text{eff}}$ fixes the expansion rate during BBN
- Direct effect of electron $\nu$ on the $n$-$p$ reactions

### Cosmic Microwave Background

**CMB**

- $T < \text{eV}$
- No flavour sensitivity

### Formation of Large Scale Structures

**LSS**

- $\nu$ remove power at large angular scales
- Indirect effect on CMB polarization properties
- Non-zero $\Omega_\nu$ today implies a modified background evolution
- A modification of the angular power spectrum of the CMB
CMB is *simple* and *effective*

- Because its anisotropy/polarization is formed in the linear regime, when the universe is still very simple (a diluted plasma of photons, baryons, dark matter) and in the small perturbations regime.
- Don’t forget that it is difficult to relate with high precision galaxy power spectra to the underlying matter power spectra …
- Simple to perform accurate calculations / predictions
- Methods to measure it have reached a high degree of maturity
- There is still a large discovery potential.
Power of the fluctuations

$I(l+1)C_I / 2\pi (\mu K)^2$

Angular scale

no v's
$f_v=0$
$f_v=0.1$
TABLE II: Representative cosmological data sets and corresponding $2\sigma$ (95\% C.L.) constraints on the sum of $\nu$ masses $\Sigma$.

<table>
<thead>
<tr>
<th>Case</th>
<th>Cosmological data set</th>
<th>$\Sigma$ (at $2\sigma$)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>CMB</td>
<td>$&lt; 1.19$ eV</td>
</tr>
<tr>
<td>2</td>
<td>CMB + LSS</td>
<td>$&lt; 0.71$ eV</td>
</tr>
<tr>
<td>3</td>
<td>CMB + HST + SN-Ia</td>
<td>$&lt; 0.75$ eV</td>
</tr>
<tr>
<td>4</td>
<td>CMB + HST + SN-Ia + BAO</td>
<td>$&lt; 0.60$ eV</td>
</tr>
<tr>
<td>5</td>
<td>CMB + HST + SN-Ia + BAO + Ly$\alpha$</td>
<td>$&lt; 0.19$ eV</td>
</tr>
</tbody>
</table>

From Fogli et al. 2008, Astro-ph/0805.2517

With Planck: $< 0.2$ eV
What is the CMB

According to modern cosmology:

An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 μs after the Big Bang ($10^9 \gamma$ for each baryon) from a small $b - \bar{b}$ asymmetry

- **Thermalized** in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons

- **Redshifted** to microwave frequencies ($z_{\text{CMB}} = 1100$) and **diluted** in the subsequent 14 Gyrs of expansion of the Universe
FIRAS data with 400σ errorbars

2.725 K Blackbody

CMB Temperature (1992): 3K
Detailed Views of the Recombination Epoch (z=1088, 13.7 Gyrs ago)
Fig. 18.— The WMAP three-year power spectrum (in black) compared to other recent measurements of the CMB angular power spectrum, including Boomerang (Jones et al. 2005), Acbar (Kuo et al. 2004), CBI (Readhead et al. 2004), and VSA (Dickinson et al. 2004). For clarity, the $l < 600$ data from Boomerang and VSA are omitted; as the measurements are consistent with WMAP, but with lower weight. These data impressively confirm the turnover in the 3rd acoustic peak and probe the onset of Silk damping. With improved sensitivity on sub-degree scales, the WMAP data are becoming an increasingly important calibration source for high-resolution experiments.

CMB Temperature Anisotropy (1998 ... ): 100 $\mu$K

**E-modes**: $3 \mu K$ (2002…)

**Velocity field**

**Resulting anisotropy seen by e-**

**Resulting polarization pattern**

**WMAP7 measured data** (stacked)

**Cold Spot Simulation**

**Hot Spot Simulation**

CMB Polarization (2002 ...): E-modes 3 \( \mu K \)
primordial B-modes

Chiang et al. 2010

CMB Polarization (2002 ... ): E-modes 3 $\mu$K
CMB Polarization (2002 … ): E-modes $3 \, \mu K$
CMB Polarization (2002 ... ): E-modes 3 $\mu$K

B-modes from Lensing of E-modes

Chiang et al. 2010
Lensing of E-modes

- E-modes have been measured already with good accuracy, and will be measured with exquisite accuracy by Planck and other experiments.
- They depend on the distribution of mass (mainly dark matter) so their study can shed light on the nature of dark matter (including massive neutrinos).
- While the primordial B-mode is maximum at multipoles around 100 ($\theta=2^\circ$), the lensed B-mode is maximum at multipoles around 1000 ($\theta=0.2^\circ$), requiring high angular resolution polarization experiments.
CMB Polarization (2002 ...): E-modes 3 $\mu$K

Chiang et al. 2010

Inf 

flation 

Neutrinos !!

BB: 95% confidence upper limits

Inflation !!

Neutrinos !!

CMB Polarization (2002 ...): E-modes 3 $\mu$K
How to improve?

1. Knowledge of Foregrounds (Planck)
2. Sensitivity
3. Control of Systematic Effects
4. Resolution & Sky Coverage
1. Knowledge of the foregrounds

- Main message: primordial B-modes are extremely difficult to detect, because Galactic contamination is higher than E-modes at these wavelengths and in the average high-latitude sky.
BOOMERanG deep region (Masi et al. 2006): dust anisotropy $\ll$ CMB anisotropy @ 150 GHz
FIG. 1.— BICEP’s CMB and Galactic fields are outlined on the 150-GHz FDS Model 8 prediction of dust emission (Finkbeiner et al. 1999), plotted here in equatorial coordinates.
Sweet Spots

Chiang et al. 2010
BICEP
2. Knowledge of the foregrounds

- This is the most difficult part of the path towards B-modes.
  - We need wide multiband observations
  - We need a detailed (3-D) model of galactic emission, able to predict the local polarized signal with <1% accuracy
Planck is a very ambitious experiment.

It carries a complex CMB experiment (the state of the art, a few years ago) all the way to L2, improving the sensitivity wrt WMAP by at least a factor 10,

extending the frequency coverage towards high frequencies by a factor about 10
Almost 20 years of hard work of a very large team, coordinated by:

**ESA** : Jan Tauber
**HFI PI** : Jean Loup Puget (Paris)
**HFI IS** : Jean Michel Lamarre (Paris)
**LFI PI** : Reno Mandolesi (Bologna)
**LFI IS** : Marco Bersanelli (Milano)
Observing strategy
The payload will work from L2, to avoid the emission of the Earth, of the Moon, of the Sun.
Why so far?

• Good reasons to go in deep space:
  – Atmosphere
  – Sidelobes
  – Stability
FIG. 6.— The individual 150 GHz timestreams within a PSB pair (red and blue) are differenced (black) in this plot using a single relative gain fit over the plotted 9-hour period. For the actual CMB analysis, relative gains are updated for every one-hour scan set.
• In the case of CMB observations, the detected brightness is the sum of the brightness from the sky (dominant for the solid angles directed towards the sky, in the main lobe) and the Brightness from ground (dominant for the solid angles directed towards ground, in the sidelobes).

\[ W = A \left[ \int_{\text{main lobe}} B_{\text{sky}}(\theta, \varphi) RA(\theta, \varphi) d\Omega + \int_{\text{side lobes}} B_{\text{Ground}}(\theta, \varphi) RA(\theta, \varphi) d\Omega \right] \]

• The angular response (beam pattern) \( RA(\theta, \phi) \) is usually polarization-dependent
Going to L2 reduces the solid angle occupied by the Earth by a factor \( \frac{2\pi}{2\times10^{-4}} = 31000 \), thus relaxing by the same factor the required off-axis rejection.

<table>
<thead>
<tr>
<th>FWHM</th>
<th>( \Omega_{\text{mainlobe}} )</th>
<th>(&lt;RA_{\text{sidelobes}}&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^\circ)</td>
<td>(2\times10^{-2}) srad</td>
<td>(&lt;1)</td>
</tr>
<tr>
<td>(1^\circ)</td>
<td>(2\times10^{-4}) srad</td>
<td>(&lt;0.01)</td>
</tr>
<tr>
<td>(10')</td>
<td>(7\times10^{-6}) srad</td>
<td>(&lt;3\times10^{-4})</td>
</tr>
<tr>
<td>(1')</td>
<td>(7\times10^{-8}) srad</td>
<td>(&lt;3\times10^{-6})</td>
</tr>
</tbody>
</table>

No day-night changes up there … extreme stability
ESA’s mission to map the Cosmic Microwave Background

Image of the whole sky at wavelengths near the intensity peak of the CMB radiation, with

- high instrument sensitivity ($\Delta T/T \sim 10^{-6}$)
- high resolution ($\approx 5$ arcmin)
- wide frequency coverage (25 GHz-950 GHz)
- high control of systematics
- Sensitivity to polarization

Launch: 14/May/2009; payload module: 2 instruments + telescope

- Low Frequency Instrument (LFI, uses HEMTs)
- High Frequency Instrument (HFI, uses bolometers)
- Telescope: primary (1.50x1.89 m ellipsoid)
Spider-web bolometers
Made in JPL
BOOMERanG 1998 (0.3K),
Archeops 2001 (0.1K),
....
Planck – HFI polarization sensitive focal plane

Scan direction

Ponthieu et al. 2010
Measured dark noise equivalent power (NEP) of the focal plane detectors, including 6.5 nV / sqrt(Hz) amplifier noise at nominal bias. The open diamond symbols are the NEP for detectors installed in the focal plane. The open square symbols are the NEP of spare bolometers. The thick solid line segments indicate the photon background limit from a 35 K telescope and astrophysical sources in each band for a 30% bandwidth and 30% in-band optical efficiency. Unpolarized detectors at 100 GHz were made and delivered but were replaced by polarized detectors. (from Holmes et al. (2008))

\[
\text{NEP}_b = 15 \text{ aW/Hz}^{1/2} \quad \rightarrow \quad 70 \text{ } \mu \text{K/Hz}^{1/2}
\]

Total NET (bolo+photon) = 85 \text{ } \mu \text{K/Hz}^{1/2}
LFI
Pseudo-correlation
Differential radiometer
Measures I,Q,U
30, 44, 70 GHz
Off-axis Dragone Telescope, wide field, good polarization properties, 1.89mx1.50m aperture
Off-axis Dragone Telescope, wide field, good polarization properties, 1.89mx1.50m aperture
T=0.1K
Dilution Cooler
For bolometer arrays

Sun
Cooling system

V-groove radiators (to 60 K)

20 K H₂ sorption coolers (JPL)

4 K Stirling cooler (RAL/MMS)

0.1 K³He/⁴He dilution cooler (CRTBT)
<table>
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<tr>
<th>Instrument Characteristic</th>
<th>LFI</th>
<th>HFI</th>
</tr>
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<tr>
<td>Detector Technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Center Frequency [GHz]</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>Bandwidth ($\Delta\nu/\nu$)</td>
<td>0.2</td>
<td>0.33</td>
</tr>
<tr>
<td>Angular Resolution (arcmin)</td>
<td>33</td>
<td>10</td>
</tr>
<tr>
<td>$\Delta T/T$ per pixel (Stokes $I$)$^a$</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>$\Delta T/T$ per pixel (Stokes $Q$ &amp; $U$)$^a$</td>
<td>2.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

$^a$ Goal (in $\mu$K/K) for 14 months integration, 1σ, for square pixels whose sides are given in the row “Angular Resolution”.

From the Blue Book (2005)
Launch
May 14th, 2009

Cruise
May-June 2009

First All-sky survey
Completed May 2010
The sky explored by Planck in the First Light Survey, 2 weeks in August 2009
Planck one-year all-sky survey

(c) ESA, HFI and LFI consortia, J
Blue-White = Galactic Foreground

Red-Yellow = Pure CMB
This is a simulation
Real data (from just 15 days of operation)
Fig 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of WMAP observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of Planck.
Fig 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance 
$\Lambda$CDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been 
generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals 
between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. 
The left and right plots show simulations for WMAP and Planck, respectively.
Figure 3. QML estimates of the $E$ and $B$-mode polarization spectra for the simulations with $r = 0.05$. Figures 3a and 3b show power spectra for the nominal Planck mission. Figures 3c and 3d show power spectra for an extended Planck mission. The error bars are computed from the diagonal components of the inverse of the QML Fisher matrix using the theoretical input spectra for $r = 0.05$ (shown by the red lines).
Large increase ($3-10\times$) in precision of cosmological parameters

$\implies$ high discovery potential

WMAP has confirmed the Standard Model

Planck will challenge it

Projected WMAP likelihood
Projected Planck likelihood on Hubble constant
FIG. 4: A 2D contour plot indicating how a partial parameter degeneracy using only Planck data is lifted when Lyman-α data is added. 68% and 95% confidence intervals are illustrated for the following three datasets (from broadest to tightest): blue, Planck alone; green, Planck with $P_{5\%}^{3\%}$; red, Planck with $P_{1\%}^{3\%}$.
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From Fogli et al. 2008, Astro-ph/0805.2517

With Planck : \(< 0.2 \text{ eV}\)
After Planck

- New experiments have many more detectors than Planck (Sensitivity issue 2.)
- However,
  - it is difficult to obtain the same wide sky and frequency coverage if you are not working from space.
  - Sidelobes rejection is a big issue for large-scale surveys
- So I believe that the final word for primordial B-modes will come from a new space-based experiment
- Current and planned experiments are extremely useful to invent and test new configurations, to minimize and/or fully control systematic effects.
2. Sensitivity

- Reduce noise from the environment
  - Radiation noise from instrument, window, telescope, atmosphere
  - Get to astrophysical background limited conditions
  - Thermal noise in the detector

- Increase the number of detectors to boost the mapping speed.

Space + Cryogenics

Large Arrays of mm-wave detectors
**EBEX Focal Plane**

- Total of 1476 detectors
- Maintained at 0.27 K
- 3 frequency bands/focal plane

<table>
<thead>
<tr>
<th>G</th>
<th>NEP</th>
<th>NEQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-30 pWatt/K</td>
<td>$1.4 \times 10^{-17}$ (150 GHz)</td>
<td>$156 \mu K \cdot \tau(\text{sec})$ (150 GHz)</td>
</tr>
</tbody>
</table>

- $\tau = 3$ msec,

*Slide: Hanany*
Science Goals

- Detect or set upper bound on inflation B-mode
- Measure lensing B-mode
- Understand Polarized Dust
- Improve estimation of cosmological parameters
Focal Plane Hardware
William Jones
Princeton University
for the
Spider Collaboration

The Path to CMBpol
June 31, 2009
Spider: A Balloon Borne CMB Polarimeter

Suborbital Polarimeter for Inflation Dust and the Epoch of Reionization

- Long duration (~30 day cryogenic hold time) balloon borne polarimeter
- Surveys 60% of the sky each day of the flight, with ~0.5 degree resolution
- Broad frequency coverage to aid in foreground separation
- Will extract nearly all the information from the CMB E-modes
- Will probe B-modes on scales where lensing does not dominate
- Technical Pathfinder: solutions appropriate for a space mission
Carbon Fiber Gondola

Six single freq. telescopes

30 day, 1850 lb, 4K / 1.4 K cryostat

Attitude Control
- flywheel
- magnetometer
- rate gyros
- sun sensor

Pointing Reconstruction
- 2 pointed cameras
- boresight camera
- rate gyros

Flight Computers/ACS
- 1 TB for turnaround
- 5 TB for LDB
3. Control of systematic effects

- Polarized sidelobes (large baffles, space)
- Polarization modulators (many different methods)
- Orthogonal measurement methods:
  - Coherent imagers (QUIET, ..)
  - Bolometric imagers (BOOMERanG, MAXIPOL, Planck, BICEP, EBEX, SPIDER, PIPER, LSPE, …)
  - Coherent interferometers (DASI, CBI, …)
  - Bolometric interferometers (MBI, QUBIC)
**BICEP instrument characterization**

**TABLE 3**

**SYSTEMATIC ERRORS POTENTIALLY PRODUCING FALSE $B$-MODE POLARIZATION**

<table>
<thead>
<tr>
<th></th>
<th>Benchmark$^a$</th>
<th>Measured</th>
<th>Measurement notes</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative gain uncertainty: $\Delta (g_1/g_2)/(g_1/g_2)$</td>
<td>0.9%</td>
<td>&lt; 1.1%</td>
<td>Upper limit, rms error over the array.$^b$</td>
<td>$^3.1$</td>
</tr>
<tr>
<td>Differential pointing: $\left( r_1 - r_2 \right)/\sigma$</td>
<td>1.9%</td>
<td>1.3%</td>
<td>Average, each repeatedly characterized to 0.4% precision.$^d$</td>
<td>$^3.2$</td>
</tr>
<tr>
<td>Differential beam size: $(\sigma_1 - \sigma_2)/\sigma$</td>
<td>3.6%</td>
<td>&lt; 0.3%</td>
<td>Upper limit, rms over the array.</td>
<td>$^3.2$</td>
</tr>
<tr>
<td>Differential ellipticity: $(e_1 - e_2)/2$</td>
<td>1.5%</td>
<td>&lt; 0.2%</td>
<td>Upper limit, rms over the array.</td>
<td>$^3.2$</td>
</tr>
<tr>
<td>Polarization orientation uncertainty: $\Delta \psi$</td>
<td>2.3°</td>
<td>&lt; 0.7°</td>
<td>Upper limit, rms absolute orientation error over the array.</td>
<td>$^3.3$</td>
</tr>
<tr>
<td>Telescope pointing uncertainty: $\Delta b$</td>
<td>5'</td>
<td>0.2'</td>
<td>Fit residual rms in optical star pointing calibration.</td>
<td>$^3.4$</td>
</tr>
<tr>
<td>Polarized sidelobes (100, 150 GHz)</td>
<td>-9, -4 dBi</td>
<td>-26, -17 dBi</td>
<td>Response at 30° from the beam center.</td>
<td>$^3.5$</td>
</tr>
<tr>
<td>Focal plane temperature stability: $\Delta T_{FP}$</td>
<td>3 nK</td>
<td>1 nK</td>
<td>Scan-synchronous rms fluctuation on $\ell\sim100$ time scale.</td>
<td>$^3.6$</td>
</tr>
<tr>
<td>Optics temperature stability: $\Delta T_{RI}$</td>
<td>4 $\mu$K</td>
<td>0.7 $\mu$K</td>
<td>Scan-synchronous rms fluctuation on $\ell\sim100$ time scale.</td>
<td>$^3.6$</td>
</tr>
</tbody>
</table>

$^a$ Benchmarks correspond to values that result in a false $B$-mode signal of at most $r = 0.1$. For $r = 0.01$, all benchmarks would be lower by $\sqrt{10}$.

$^b$ If relative gain errors are detected, we anticipate removing their effects in future analyses using a CMB temperature template map.

$^c \sigma = FWHM/\sqrt{8\ln(2)} = \{0.39°, 0.26°\}$ at $\{100, 150\}$ GHz.

$^d$ This measurement of differential pointing could be used in future analyses to remove the small predicted leakage of CMB temperature into polarization maps.
The result from BICEP 2 years is a 95% upper limit \( r < 0.73 \)

Entirely dominated by receiver noise and relative gain uncertainty.

<table>
<thead>
<tr>
<th>Description</th>
<th>Measured</th>
<th>max false ( B ), equiv. ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Relative gain uncertainty: ( \Delta(g_1/g_2)/(g_1/g_2) )</td>
<td>&lt; 1.1%</td>
<td>&lt; 0.15</td>
</tr>
<tr>
<td>2. Differential pointing: ( (r_1-r_2)/\sigma )</td>
<td>1.3%</td>
<td>0.05</td>
</tr>
<tr>
<td>3. Focal plane temperature stability: ( \Delta T_{FP} )</td>
<td>1 nK</td>
<td>0.011</td>
</tr>
<tr>
<td>4. Polarization orientation uncertainty: ( \Delta \psi )</td>
<td>&lt; 0.7°</td>
<td>&lt; 0.009</td>
</tr>
<tr>
<td>5. Optics temperature stability: ( \Delta T_{RJ} )</td>
<td>0.7 ( \mu )K</td>
<td>0.003</td>
</tr>
<tr>
<td>6. Differential ellipticity: ( (e_1-e_2)/2 )</td>
<td>&lt; 0.2%</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>7. Differential beam size: ( (\sigma_1-\sigma_2)/\sigma )</td>
<td>&lt; 0.3%</td>
<td>&lt; 0.0007</td>
</tr>
<tr>
<td>8. Polarized sidelobes (100, 150 GHz)</td>
<td>-26, -17 dBi</td>
<td>0.0002</td>
</tr>
<tr>
<td>9. Telescope pointing uncertainty: ( \Delta b )</td>
<td>0.2′</td>
<td>0.0002</td>
</tr>
</tbody>
</table>
A 10x improvement is possible:

- The best way to remove relative gain uncertainty is to use the same bolometer for both polarizations i.e. insert a polarization modulator.
- Then, to improve the sensitivity, boost the number of bolometers and reduce the background. EBEX, SPIDER, PIPER, LSPE are balloon borne instruments doing exactly this.
3. Control of systematic effects

• Polarized sidelobes (large baffles, space)
• Polarization modulators (many different methods)
• Orthogonal measurement methods:
  – Coherent imagers (QUIET, ..)
  – Bolometric imagers (BOOMERanG, MAXIPOL, Planck, BICEP, EBEX, SPIDER, PIPER, LSPE, …)
  – Coherent interferometers (DASI, CBI, …)
  – Bolometric interferometers (MBI, QUBIC)
low sidelobes & reduced solid angle: Planck
Full Pattern of the LFI9 at 100 GHz, $\varphi = 45$ deg

Response

Main Beam

$10^7$

Far Sidelobes

Near Sidelobes

Angle from boresight

F. Villa, LFI
3. Control of systematic effects

• Polarized sidelobes
• Polarization modulators
• Orthogonal measurement methods:
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  – Coherent interferometers (DASI, CBI, …)
  – Bolometric interferometers (MBI, QUBIC)
Polarization modulators (quasi-optical mode)

- Throughput advantage wrt coherent systems
- HWP + Polarizer (Stokes polarimetry)
  - Dielectric waveplates with ARC (EBEX, SPIDER, KECK…) Savini, Pisano, Hanany, Bryan
  - Metal mesh waveplates (LSPE …) Pisano
- Reflecting HWP (PolKA) Siringo
- VPM (Variable delay polarization modulator, PIPER) Kogut
Polarimetry with an achromatic Half Wave Plate

Rotates on a superconducting magnetic bearing

6 Hz rotation (2 Hz North American Flight)

0.25 degree angular encoding limited by sampling

< 10% attenuation from 3 msec time constant

5 stack achromatic HWP (sapphire)

0.98 efficiency for 120< ν < 420 Gz
Polarization Modulator

\[ P_x = \frac{1}{2} \left( I + Q \cos \delta - V \sin \delta \right) \]

\[ P_y = \frac{1}{2} \left( I - Q \cos \delta + V \sin \delta \right) \]

Measure linear and circular polarization!
3. Control of systematic effects

- Polarized sidelobes
- Polarization modulators
- **Orthogonal measurement methods:**
  - Coherent imagers (QUIET, ..)
  - Bolometric imagers (BOOMERanG, MAXIPOL, Planck, BICEP, EBEX, SPIDER, PIPER, LSPE, …)
  - Coherent interferometers (DASI, CBI, …)
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QUBIC
Large Scale Polarization Explorer

WHY?

• Get important science (complementary to SPIDER, EBEX, etc.)
• Validate needed technology, for next round of ESA cosmic vision

HOW?

• **ASI** polar-night flight -> large sky coverage
• Two instruments to cover from 40 to 220 GHz
• Low angular resolution – large scales
• High-Throughput Channels – High sensitivity
• Single-mode channels – Foregrounds
• Large ground shields
• No optics – no spurious polarization
B-Bpol, lat = 63, elevation = 40, NSIDE = 32
Spinning HWP

Wire Grid

Polyethilene Lens

Beam 2° FWHM

25 cm diam

Polyethilene Lens

B-B-Pol: High Frequency Instrument (one of the two bands shown)

40 overmoded Detectors, diam 1.7 cm
(10 modes @ 150 GHz, 20 modes @ 220 GHz)

2K

0.3K
37 detectors, Photon-noise limited, 15 days, r=0.01

- 350 GHz
- 220 GHz
- 150 GHz
And now let’s dream …
B-Pol
(www.b-pol.org)

- European proposal recently submitted to ESA (Cosmic Vision).
- ESA encourages the development of technology and resubmission for next round.
- Detector Arrays development activities (KIDs in Rome, TES in Oxford, Genova etc.)
- A balloon-borne payload being developed with ASI (LSPE).
Sensitivity and frequency coverage: the focal plane

- Baseline technology: TES bolometers arrays

Corrugated feedhorns for polarization purity and beam symmetry

- 45 GHz 45mm
- 70 GHz 26.5mm
- 100 GHz 18.5mm
- 150 GHz 12.3mm
- 220 GHz 8.4mm
- 350 GHz 5.3mm

Sub-K, 600 mm
B-Pol: Detecting Primordial Gravitational Waves Generated During Inflation

Paolo de Bernardis, Martin Bucher, Carlo Burigana and Lucio Piccirillo
(for the B-Pol Collaboration)*

Received: date / Accepted: date

Abstract B-Pol is a medium-class space mission aimed at detecting the primordial gravitational waves generated during inflation through high accuracy measurements of the Cosmic Microwave Background (CMB) polarization. We discuss the scientific background, feasibility of the experiment, and implementation developed in response to the ESA Cosmic Vision 2015-2025 Call for Proposals.

Keywords Cosmology · Cosmic Microwave Background · Satellite
Space-Borne Measurements of CMB Polarization

The Experimental Probe of Inflationary Cosmology – Intermediate Mission

Jamie Bock (JPL/Caltech)

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Brett Williams  JPL
Jonas Zmuidzinas  Caltech/JPL

The Path to CMBPOL: Upcoming Measurements of CMB Polarization

University of Chicago, 1-3 July 2009
Unprecedented CMB Community Organization!

CMB Inflation Probe ASMCS

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Samuel H. Moseley  GSFC
Lyman Page  Princeton U.
Charles Lawrence  JPL
Tony Readhead  Caltech
Peter Timbie  U. Wisconsin

+ 175 participants

Decadal White Papers

The Origin of the Universe as Revealed Through the Polarization of the CMB, Dodelson et al. and 211 Co-signers

Observing the Evolution of the Universe, Page et al. and 168 Co-signers

A Program of Technology Development and Sub-Orbital Observations of CMB Polarization Leading to and Including a Satellite Mission, Meyer et al. and 141 Co-signers

CMB Community Reports

Theory and Foregrounds: 5 Papers with 135 Authors and Co-Authors

Probing Inflation with CMB Polarization, Baumann et al. 2008, ArXiv 0811.3919

Gravitational Lensing, Smith et al. 2008, ArXiv 0811.3916

Reionization Science with the CMB, Zaldarriaga et al. 2008, ArXiv 0811.3918

Prospects for Polarized Foreground Removal, Dunkley et al. 2008, ArXiv 0811.3915

Foreground Science Knowledge and Prospects, Fraisse et al. 2008, ArXiv 0811.3920

Systematic Error Control: 10 Papers with 68 Authors and Co-Authors

CMB Technology Development: 22 Papers with 37 Authors and Co-Authors

Path to CMBPol: Conference on CMBPol mission in July with 85 participants

Mission Study Reports

Study of the EPIC-Intermediate Mission, ArXiv 0906.1188
The Experimental Probe of Inflationary Cosmology, ArXiv 0805.4207

See http://cmbpol.uchicago.edu for a full compilation
### The Role of the EPIC-IM Design

**EPIC-IM**

<table>
<thead>
<tr>
<th>Low Cost</th>
<th>Intermediate Mission 4 K Option</th>
<th>Comprehensive Science</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Science</strong></td>
<td>Inflationary B-mode polarization only</td>
<td>Inflationary B-modes, E-modes to cosmic variance, gravitational lensing to cosmic limits, neutrino mass, dark energy, Galactic astronomy</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>500 Plancks</td>
<td>3600 Plancks</td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td>2400</td>
<td>11,000 (TES bolometer or MKID)</td>
</tr>
<tr>
<td><strong>Aperture</strong></td>
<td>Six 30 cm refractors</td>
<td>1.4 m Crossed Dragone telescope</td>
</tr>
<tr>
<td><strong>Bands</strong></td>
<td>30 – 300 GHz</td>
<td>30 – 300 GHz + 500 &amp; 850 GHz</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>LHe cryostat + ADR</td>
<td>4 K Cryo-cooler + ADR</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>1320 kg CBE</td>
<td>1670 kg CBE</td>
</tr>
<tr>
<td><strong>Publication</strong></td>
<td>ArXiv 0805.4207 (192 pages)</td>
<td>ArXiv 0906.1188 (157 pages)</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$660M (FY07)</td>
<td>$920M (FY09)</td>
</tr>
</tbody>
</table>

Note: Configurations not shown on same scale
B-Pol 2010 (ESA)

- 1.2 m aperture
- Cold modulator is first optical element

- Launch warm; Telescope assembly cools at 30K radiatively

- Mechanical cooler cools the system on the way.

- Fits the 3.9m diameter fare of the Soyuz (V-grooves critical if not deployable)
Reflective HWP

- See Siringo et al. 2004 for a description
- Works as a HWP at all frequencies

\[ \nu_n = \frac{2n + 1}{4 \cos \phi} \frac{c}{d} \]

- For a given incidence, one can adjust \( d \) so that

<table>
<thead>
<tr>
<th>( n )</th>
<th>( \nu_n )(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>140</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
</tr>
<tr>
<td>5</td>
<td>220</td>
</tr>
<tr>
<td>6</td>
<td>260</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
</tr>
<tr>
<td>8</td>
<td>340</td>
</tr>
</tbody>
</table>

- Usable bandwidth 10-15\% TBC
Back to the earth (almost)

• Imagine to have a large telescope on a balloon,
  – using large throughput bolometric detectors,
  – on a polar night long duration flight
• Something like our OLIMPO, with slightly larger primary (4m ?) and with many more large throughput detectors :
  – Spectral bandwidth : 20% centered @ 145 GHz
  – Detector temperature: 0.25 K
  – Number of large throughput polarisation-sensitive bolometers: 100
  – Angular resolution [FWHM arcminutes] 7.0’
  – Detector Noise-Equivalent Temperature [µKs^{0.5}] : 25
  – ΔT/T Intensity [10^6 µK/K] : 0.16
  – ΔT/T Polarization [10^6 µK/K]: 0.23
  – Observed sky fraction 30%
OLIMPO

- Long Duration Balloon experiment for mm and sub-mm astronomy PI Silvia Masi
- Operate from the stratosphere
- Launch from Svalbard
- Cassegrain, 2.6 m primary with scanning capability
- Multi-frequency array of bolometers

<table>
<thead>
<tr>
<th>ch</th>
<th>$v_{\text{eff}}$ [GHz]</th>
<th>$\Delta v_{\text{FWHM}}$ [GHz]</th>
<th>Res. [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>148.4</td>
<td>21.5</td>
<td>4.2</td>
</tr>
<tr>
<td>II</td>
<td>215.4</td>
<td>20.6</td>
<td>2.9</td>
</tr>
<tr>
<td>III</td>
<td>347.7</td>
<td>33.1</td>
<td>1.8</td>
</tr>
<tr>
<td>IV</td>
<td>482.9</td>
<td>54.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>
RIC Rivelatori Induttanza Cinetica
INFN Gruppo V project

Our first LEKID mask:

Design →

Fabrication ↓
Higher $T \rightarrow$ Lower $n_{cp} \rightarrow$ Lower $f_0$

Results in:
http://www.springerlink.com/content/102887/?Content+Status=Accepted
Fabrication at FBK “Fondazione Bruno Kessler”, Trento

Results:

<table>
<thead>
<tr>
<th>Dimension (mm)</th>
<th>1.58</th>
<th>2.38</th>
<th>2.78</th>
<th>3.56</th>
</tr>
</thead>
<tbody>
<tr>
<td># membranes</td>
<td>306</td>
<td>60</td>
<td>68</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SiO$_2$/Si$_3$N$_4$/TEOS/ Si$_3$N$_4$: 98% success</th>
</tr>
</thead>
<tbody>
<tr>
<td># damaged</td>
</tr>
<tr>
<td># good</td>
</tr>
<tr>
<td>percentage</td>
</tr>
</tbody>
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</tr>
<tr>
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</tr>
<tr>
<td>percentage</td>
</tr>
</tbody>
</table>

Hopefully, membranes will:

- decrease the number of CR observed
- decrease the noise contribution due to the substrate
Large Throughput Bolometers
(from ASI mm technology study)

\[ \text{\(\lambda = 2\text{mm}, \Delta\lambda /\lambda = 20\%\)} \]
\[ \text{\(\varepsilon_{\text{mir}} = 0.4\%\)} \]
\[ \text{\(T_{\text{bol}} = 0.3\text{K}\)} \]
\[ \text{\(\text{E}_{\text{bolo}} = 20\%\)} \]

\(T_m = 300\text{K}\)
\(35\mu\text{K/Hz}^{1/2}\)

\(T_m = 4\text{K}\)
\(22\mu\text{K/Hz}^{1/2}\)
\(15\mu\text{K/Hz}^{1/2}\)

\(\text{G}_e\)

P. de Bernardis & S. Masi
Sensitivity to $m_v$ good enough to probe hierarchy & precision $N_{\text{eff}}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck</th>
<th>Planck+NEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta(\Omega_b h^2)$</td>
<td>0.00022</td>
<td>0.000099</td>
</tr>
<tr>
<td>$\Delta(\Omega_c h^2)$</td>
<td>0.0026</td>
<td>0.0011</td>
</tr>
<tr>
<td>$\Delta(\theta_S)$</td>
<td>0.00045</td>
<td>0.00016</td>
</tr>
<tr>
<td>$\Delta(\tau)$</td>
<td>0.0049</td>
<td>0.0028</td>
</tr>
<tr>
<td>$\Delta(n_S)$</td>
<td>0.0078</td>
<td>0.0038</td>
</tr>
<tr>
<td>$\Delta(\log[10^{10} A_S])$</td>
<td>0.020</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Delta(N_{\text{eff}})$</td>
<td>0.19</td>
<td>0.083</td>
</tr>
</tbody>
</table>

*TABLE III: 1 $\sigma$ errors.*

From A. Melchiorri, L. Pagano, M. Martinelli, hear later
See also Galli et al. Astro-ph/1005.3808
Stay tuned!