First cosmological results from Planck

Cyrille Rosset - APC
EPS 2013
Planck 2013 publications

> 1000 pages

First cosmological results from Planck - Cyrille Rosset
History of Universe
The Planck challenge

- To perform the “ultimate” measurement of the Cosmic Microwave Background (CMB) temperature anisotropies, needed:
  - full sky coverage and angular resolution, to survey all scales at which the CMB primary anisotropies contain information (~5’)
  - sensitivity, essentially limited by ability to remove the astrophysical foregrounds
    - enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1 year in CMB primary window)
- Get the best performances possible on the polarization with the technology available
- ESA selection in 1996 (after ~ 3 year study)
- NB: with the Ariane 5 01 failure delaying us by several years (2003 ➔ 2007) and WMAP then flying well before us, polarization measurements became more and more a major goal
The target at selection time

![Angular scale graph](image-url)
Foregrounds

ΔH0 = 2%
### Performance goals

<table>
<thead>
<tr>
<th>Telescope</th>
<th>LFI</th>
<th>HFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>View angle (deg)</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>System noise temperature (K)</td>
<td>44</td>
<td>143</td>
</tr>
<tr>
<td>Detector technology</td>
<td>HEMT LNA arrays</td>
<td>Bolometer arrays</td>
</tr>
<tr>
<td>Detector temperature (K)</td>
<td>~20</td>
<td>0.1</td>
</tr>
<tr>
<td>Cooling requirements</td>
<td>H₂ sorption cooler</td>
<td>H₂ sorption + 4 K J-T stage + Dilution cooler</td>
</tr>
<tr>
<td>Number of unpol. detectors</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Number of linearly polarised detectors</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Angular Resolution (FWHM, arcmin)</td>
<td>33</td>
<td>9.5</td>
</tr>
<tr>
<td>Bandwidth (GHz)</td>
<td>6</td>
<td>33</td>
</tr>
<tr>
<td>Average $\Delta T/T_1$ per pixel#</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Average $\Delta T/T_{U,0}$ per pixel#</td>
<td>2.8</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($x10^6$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

# A pixel is a square whose side is the FWHM extent of the beam.

$^*$ Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($x10^6$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).
Planck breakthroughs

- Technological performance never achieved in space before:
  - sensitive and fast bolometers for HFI
    - \( \text{NEP} < 2 \times 10^{-17} \text{W/Hz}^{1/2} \), time constant \( \sim 5 \text{ ms} \) (requires cooling at 100 mK)
  - low noise electronics: 6 nV/Hz\(^{1/2}\), from 10 mHz to 100 Hz
  - excellent temperature stability from 10 mHz to 100 Hz
    - \(< 10 \mu\text{K/Hz}^{1/2}\) for 4 K box
    - \(< 30 \mu\text{K/Hz}^{1/2}\) for 1.6 K filter plate
    - \(< 20 \text{nK/Hz}^{1/2}\) for 100 mK detector plate
  - low noise HEMT amplifier for LFI
Planck breakthroughs

- Low emissivity, very low side lobes telescope
- Minimum warm surface in front of detectors
- Complex cryogenic cooling chain: 50 K (passive) + 20K, 4K, 0.1K active coolers
  - 20K for LFI
  - 4K, 1.6K and 100mK for HFI
- Thermal architecture optimised to damp thermal fluctuations
- Integration of 3 complex chains - electronic, optics, cryogenics
High Frequency Instrument

HFI cut-away

filters @ 1.6K

Bolometers @ 100mK

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Low Frequency Instrument
Launch on 14th May 2009

Herschel

Planck
Cooling

Planck/HFI thermometers
100 mK stage (dilution)
1.6 K stage
4 K stage (JT Stirling cooler)
18K stage (H₂ sorption cooler)
50 K stage (passive cooling)

end of anti-contamination
active cooldown start

93 mK
July 3rd 2009
Temperature stability

- Bolometer plate
  - Temperature stability: 0.1 mK

- 1.4K optical plate
  - Bandpass filters
  - Temperature stability: 0.1 mK

- 4K optical plate
  - Temperature stability: 1 mK

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Short Log book

• Start of survey on August 13th 2009, instruments very stable
• No major problem till the end of life of HFI (January 2012)
• Expected sensitivities achieved in flight: HFI reaches or exceeds its goals
• June 2010: first full sky maps obtained with 10 months of data. Planck early results in January 2011
• November 2010: nominal mission completed (15.5 months), the sky has been seen twice by all detectors
  - public data delivery in 21st March 2012 with 28 “Planck early results” papers
• January 12th 2012 : all HFI data acquired. 5 surveys (twice the nominal duration). Next data delivery in mid-2014.
Scanning strategy
Data processing
HFI raw detector signal

3 min of demodulated raw data
Cleaning data

More glitches than expected: use of redundancy to remove them

From $\mu$V to fW (calibration)
Sky as seen by Planck

30 GHz

44 GHz

70 GHz

100 GHz

143 GHz

217 GHz

353 GHz

545 GHz

857 GHz
Foreground components

from J. Delabrouille
Low frequency emission
Dust emission
Sunyaev-Zeldovich effect

- Inverse Compton interaction between CMB photons and hot gas in clusters (~millions of K)
- Can be detected at high redshift
- Allow estimation of mass of clusters
- Gas fraction \((M_{\text{gaz}}/M_{\text{tot}})\) : linked to the universal ratio \(\Omega_b/\Omega_m\)
SZ sources

Galaxy clusters
Cleaning the background
Cleaning the background

Contribution of each frequency channel on the final CMB map, depending on angular scale.
Final CMB map from Planck
The Cosmic Microwave Background as seen by Planck and WMAP
Angular power spectrum of CMB

Angular scale

\( D_\ell [\mu K^2] \)

Multipole moment, \( \ell \)

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Likelihood methodology

• Goal: provide $P(\text{Cl} \mid \text{Planck data})$

• Hybrid multi-frequency likelihood approach:
  • Large scales (LL): Gaussian likelihood on maps
  • Small scales (HL): Gaussian likelihood approximation on spectra

• Foregrounds residuals:
  • LL: parametrised at map level
  • HL: parametrised at the spectra level

• Validation:
  • Data selection
  • Null tests
  • Simulations
Data selection for HL

- Minimise foreground impacts
  - spatially
  - in multipole space
  - keeping low cosmic variance
- Galaxy: 353 GHz thresholding
- Sources: 100-353 GHz catalog
- Maps: keep easiest to model and most informative ones

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Multipole range</th>
<th>Mask</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 × 100</td>
<td>50 – 1200</td>
<td>CL49</td>
</tr>
<tr>
<td>143 × 143</td>
<td>50 – 2000</td>
<td>CL31</td>
</tr>
<tr>
<td>143 × 217</td>
<td>500 – 2500</td>
<td>CL31</td>
</tr>
<tr>
<td>217 × 217</td>
<td>500 – 2500</td>
<td>CL31</td>
</tr>
<tr>
<td>Combined</td>
<td>50 – 2500</td>
<td>CL31/49</td>
</tr>
</tbody>
</table>
Planck power spectra
Including foreground modelling

Over 89% of the sky, explain the map spectrum with: best fit Planck + Point Source + Half-Ring noise
Data vs theory

![Graph showing temperature fluctuations vs angular scale for multipole moments.](image-url)
Cosmological parameters

- Using only Planck
- Sound horizon is measured by position of the peaks with a precision of 0.07 %
- Exact scale invariance is excluded at \(~4\sigma~\)
Comparison with other experiments

\[ D_\ell [\mu K^2] \]

\[ \ell \]

- Planck
- WMAP9
- ACT
- SPT
Cosmological parameters with combined data

WMAP polarized data helps constraining reionization. Using other experiments high-l data makes little difference.
Cosmological parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck (CMB+lensing)</th>
<th>Planck+WP+highL+BAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.022242</td>
<td>0.022161</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.11805</td>
<td>0.11889</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04150</td>
<td>1.04148</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.0949</td>
<td>0.0952</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9675</td>
<td>0.9611</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>3.098</td>
<td>3.0973</td>
</tr>
</tbody>
</table>

Using other data, the sound horizon is measured with 0.05% precision and the exact scale invariance is excluded at more than $7\sigma$ (as predicted by inflation models)
Constraint on primordial spectrum

\[ n_s = 0.96 \]
\[ n_s = 1.00 \]
Content of the Universe

Before Planck
- Dark Matter: 22.7%
- Ordinary Matter: 4.5%
- Dark Energy: 72.8%

After Planck
- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%
Expansion rate (Hubble constant)

- $H_0$ is modified:
  - $H_0 = 67.3 \pm 1.2$

- Tension at $2.5\sigma$ between Planck and Cepheids or SNIa measurements
Gravitational lensing

Gravitation bends the path of light through matter between last scattering surface and us. This lensing effect distorts the CMB map.

\[ T(\hat{n}) = T^{\text{unl}}(\hat{n} + \nabla \phi(\hat{n})), \]
\[ = T^{\text{unl}}(\hat{n}) + \sum_i \nabla^i \phi(\hat{n}) \nabla_i T(\hat{n}) + O(\phi^2) \]
Lensing simulation

Map before gravitational lensing
Lensing simulation

Map after gravitational lensing
Reconstructed mass map

- Distribution of matter (dark + baryon) reconstructed from gravitational lensing effect

North galactic hemisphere

South galactic hemisphere
Power spectrum of lensing potential

The black line is the prediction using cosmological parameters from CMB alone.
Correlation with distant galaxies

Arrows show the lensing distortion. From left to right: stacking on maximum of CIB, on minimum and random stacking.
Extension of the model

- Test extension by adding one parameter at a time
  - Spatial curvature
  - Neutrinos properties (total mass, number of effective neutrinos)
  - Curvature of the primordial spectral index
  - Primordial tensor fluctuations (gravitational waves)
- No detection of any of these
Grid of models

Planck + WP

Planck + WP + BAO
Constraints on neutrinos

- Planck constrains neutrinos mass through their effect via lensing
- Removing this constraint weakens the limit:
  - $\sum m_\nu < 0.23$ eV
  - becomes $\sum m_\nu < 1.08$ eV
Number of neutrinos

- No evidence for additional neutrino-like relativistic particle beyond the three families of neutrinos of the standard model

- $N_{\text{eff}} = 3.3 \pm 0.27$

- Note:
  - $H_0$ pushes $N_{\text{eff}}$ high
Number of neutrinos

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WMAP 9</th>
<th>+eCMB</th>
<th>+eCMB+BAO</th>
<th>+eCMB+BAO+H₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of relativistic species ( N_{\text{eff}} )</td>
<td>&gt; 1.7 (95% CL)</td>
<td>3.89 ± 0.67</td>
<td>3.55 ± 0.60</td>
<td>3.84 ± 0.40</td>
</tr>
</tbody>
</table>

- WMAP-9 data were in favor of a fourth family of neutrinos... (Bennett et al, 2013)
Constraints on inflation

- Exponential potential, monomial potential of degree $n>2$, simplest hybrid model (SB SUSY) do not fit well the data.
Large scale anomaly

- The first 30 modes measured are lower than expected from the model.
- Probability of 1% to happen...
Large scale anomaly
Large scale anomaly
Aberration

- Optical effect due to our movement with respect to the CMB
- Induces distortion of the measured CMB map (exaggerated on the plot beside):
  - spots are smaller in direction of earth motion
  - dipolar amplitude modulation
- Can measure our speed wrt CMB independently of the dipole ($\ell=1$ term in power spectrum)
  - $v = 384 \pm 78$ (stat) $\pm 115$ (syst) km.s$^{-1}$
  - $v_{\text{dipole}} = 368 \pm 2$ km.s$^{-1}$
Conclusion

- Planck instruments and scanning strategy allows wide range of consistency tests
- Gives confidence in the robustness of the measurements
- Excellent agreement of T power spectrum with ΛCDM and simplest inflationary models
- Improved precision on cosmological parameters:
  - H0 value slightly shifted, increase of Ωm and decrease of ΩΛ
  - No evidence of additional family of neutrinos: Neff = 3.3 ± 0.27
  - Limits on total mass of neutrinos: Σmν < 0.23 eV
  - No evidence for running spectral index
  - No detection of non-gaussianity, but stricter constraints
- Exponential potential, monomial potential of degree n>2, simplest hybrid model (SB SUSY) do not fit well the data
- Next data release (mid-2014) will include improvements in the analysis (better understanding of the instruments) and polarization
Polarization spectra

ΛCDM model fitted on temperature data only

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Polarization stacking