CMB Cosmology and The Planck Mission

Prof. George F. Smoot: Essential Cosmology for the Next Generation
COBE, launched 1989

Polar orbit, 900 km altitude

Structure in the Cosmic Microwave Background

WMAP, launched 2001

In orbit around L2 point of Sun-Earth system
1.5 million km from Earth in the anti-Sun direction
Angular power spectrum 1996

\[
\theta \approx \frac{180^\circ}{l}
\]

Standard cosmology 2009: Big bang + cold dark matter + dark energy + inflation (primordial density perturbations probably generated by quantum fluctuations during inflation)
Using potential theory, the power spectrum of these temperature variations can be predicted. The peaks in the spectrum are controlled by the density of matter, composition, and expansion rate.

\[ \Delta T = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi). \]

\[ Y_{l,m} = \frac{\sqrt{2l + 1(l - m)!}}{4\pi(l + m)!} P_l^m(\cos \theta) e^{i m \phi} \]

\[ C^T_\ell = \langle |a_{\ell m}|^2 \rangle. \]
• Planck will constrain the power spectrum of the CMB at small scales
Planck satellite (ESA)

- Launch in 2009
- Orbit around L2
- Surpasses WMAP in
  - resolution: 5 vs 14 arcmin
  - sensitivity: CMB polarization
  - frequency coverage: foreground separation
Planck will map the polarization of the CMB and derive the polarization power spectrum of the CMB at high resolution ...
Planck

• European Space Agency (ESA) satellite, to be launched from Kourou, French Guyana, with Ariane 5 rocket
• NASA participating partner
• Collaboration of about 10 European countries,
  – France, Italy, UK, Spain, Germany, Finland, Switzerland, Norway, ...
• USA and Canada
• High Frequency Instrument (HFI)
• Low Frequency Instrument (LFI)
• California:
  – UC Berkeley, LBNL,
  – UC Davis & Santa Barbara
  – JPL
  – CalTech
Planck will measure foreground sources accurately so as to separate the foreground signals from the CMB signal...
Planck measures the microwave sky at 9 frequencies

- **Low Frequency Instrument (LFI):** 30, 44, 70 GHz, 100 GHz
- **High Frequency Instrument (HFI):** 100, 143, 217, 353, 545, 857 GHz

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**Fig 5.1.**—False colour images of the simulated sky in the nine frequency channels of Planck, after subtraction of the monopole and dipole CMB components. From top left to bottom right: 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz channels.
Fig 1.3.— Spectrum of the CMB, and the frequency coverage of the Planck channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the WMAP Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for $\sim 1^\circ$. On small angular scales, extragalactic sources dominate. The minimum in diffuse foregrounds and the clearest window on CMB fluctuations occurs near 70 GHz. The highest HFI frequencies are primarily sensitive to dust.
Polarization

- 7 channels (all except 545, 857GHz) measure polarization
- Probes different physics than temperature anisotropies
  - picks up signal only from photon scattering
  - no integrated Sachs-Wolfe effect
  - sensitive to reionization (low multipoles)
- Breaks degeneracies
- Signal weaker (the high sensitivity of Planck needed)
- E and B modes
- B mode comes from tensor perturbations (Planck may detect if r ~ 0.1) and lensing of E mode (high multipoles)
TE spectrum

projected Boomerang and 4-year WMAP data

projected Planck data

actual WMAP 3-year data

actual Boomerang data
EE spectrum

projected Boomerang and 4-year WMAP data

projected Planck data

actual WMAP 3-year data

actual Boomerang data
BB spectrum

Projected Planck data (assumes $r = 0.1$)

Existing WMAP 3-year data
February 2008
Planck at Alcatel in Cannes, France
- almost complete
- telescope mirrors not yet attached
The Planck spacecraft is 4.2 m high and has a maximum diameter of 4.2 m, with a launch mass of around 1.8 tons. The spacecraft comprises a service module, which houses systems for power generation and conditioning, attitude control, data handling and communications, together with the warm parts of the scientific instruments, and a payload module. The payload module consists of the telescope, the optical bench, with the parts of the instruments that need to be cooled - the sensitive detector units - and the cooling systems.
The Planck telescope is an off-axis tilted Gregorian design with a primary mirror 1.75 x 1.5 meters in size.
HFI (High frequency Instrument): an array of microwave detectors using spider bolometers, cooled to 0.1 K

LFI (Low frequency Instrument): an array of radio receivers using high electron mobility transistor mixers, cooled to 20 K
Fig 1.8.—Cutaway view of the HFI focal plane unit. Corrugated back-to-back feedhorns collect the radiation from the telescope and deliver it to the bolometer cavity through filters which determine the bandpass. The bolometers are of two kinds: (a) “spider-web” bolometers, which absorb radiation via a spider-web-like antenna; and (b) “polarisation-sensitive” bolometers, which absorb radiation in a pair of linear grids at right angles to each other. Each grid absorbs one linear polarization only. The absorbed radiant energy raises the temperature of a thermometer located either in the center of the spider-web, or at the edge of each linear grid.
Low Frequency Instrument

- Freq.: 30 - 100 GHz
- Techn.: HEMT correlation receivers (56)
- Temp.: 20 K (Front-end), 300 K (Back-end)
- Ang. res.: 10’ (100 GHz) to 33’ (30 GHz)
- Best Temp. sens.: 12 μK (100 GHz)
- PI: N. Mandolesi (CNR - Bologna)
Array of differential microwave radiometers (DMRs) designed to measure the CMB at 30, 44, and 70 GHz using High Electron Mobility Transfer (HEMT) technology, cooled to 20K using hydrogen sorption coolers.
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)
## Summary of Planck Instrument Characteristics

### Goal Planck instrument characteristics

<table>
<thead>
<tr>
<th>Telescope</th>
<th>1.5 m. (projected aperture) Gregorian; shared focal plane; system emissivity 1% Viewing direction offset 80-85° from spin axis.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center Frequency (GHz)</td>
<td>30</td>
</tr>
<tr>
<td>Detector Technology</td>
<td>HEMT radio receiver arrays</td>
</tr>
<tr>
<td>Detector Temperature</td>
<td>~20 K</td>
</tr>
<tr>
<td>Cooling Requirements</td>
<td>H₂ sorption cooler</td>
</tr>
<tr>
<td>Number of Detectors</td>
<td>4</td>
</tr>
<tr>
<td>Angular Resolution (arcmin)</td>
<td>33</td>
</tr>
<tr>
<td>Bandwidth (Δν/ν)</td>
<td>0.2</td>
</tr>
<tr>
<td>ΔT/T Sensitivity per res. element (12 months, 1σ, 10⁻⁶ units)</td>
<td>1.6 (P)</td>
</tr>
</tbody>
</table>

### Instrument Characteristic

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<th>HFI</th>
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<tr>
<td>Angular Resolution (arcmin)</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td>ΔT/T per pixel (Stokes I)¹</td>
<td>2.0</td>
<td>2.7</td>
</tr>
<tr>
<td>ΔT/T per pixel (Stokes Q and U)¹</td>
<td>2.8</td>
<td>3.9</td>
</tr>
</tbody>
</table>

¹Goal (in μK/K) for 14 months integration, 1s, for square pixels whose sides are given in the row "Angular Resolution"
ESA’s Arianne 5 Rocket will launch both Planck and Herschel from ESA’s launch base in French Guiana, near the equator. The launch is currently set for the end of April, 2009.
Planck will be inserted into an L2 orbit, about 4 times farther from the Earth than the Moon, and on the opposite side from the Sun, so that it will not have to deal with the constant effects of going into and out of the Sun’s heat. Herschel will be inserted into a separate L2 orbit.
The telescope will spin at ~ 1rpm, constantly pointed away from the Sun, moving with the Earth at 1°/day.
Current Timetable

• April 10, 2009: Launch

• June 2009 – March 2011: Scientific data taking
• Extension possible
• March 2011 – March 2013: proprietary period
  – data analyzed, Planck publications prepared
• March 2013: Planck data in the public domain
**Data Analysis Pipeline**

Raw data

- Cleaning, calibration

Time-ordered data

- Map-making

9 frequency maps (3 LFI, 6 HFI)

- Component separation

Component maps: CMB, foregrounds

- Power spectrum estimation

Angular power spectra

- Parameter estimation

Cosmological parameters: $\Omega, \omega_b, \omega_{\text{cdm}}, \Omega_\Lambda, H_0, A, n_s, r, \tau$
Science from Planck

- Cosmological parameters determined to high accuracy
- Current (WMAP + other) data consistent with a “concordance” model of cosmology with 6 parameters
- Assuming this concordance model:
  - $\omega_b$, $\omega_{cdm}$, $\Omega_\Lambda$, $A$ known already to good accuracy
  - $n_s$, $\tau$ not known well before Planck
- Deviations from the concordance model
  - additional parameters (pre-Planck data mostly not enough)
- Inflation parameters: $n_s$, $r$, $dn_s/d\ln k$
  - select among inflation models
- Nature of primordial perturbations (adiabaticity)
  - how they were generated
- Non-gaussianity, check WMAP large-scale anomalies
In 1992, data from the Cosmic Background Explorer (COBE) satellite, launched by NASA in 1989, showed evidence for minute temperature variations (anisotropy) in the CMB at a level of just one part in \(10^5\), at angular scales around 10° or so.

The COBE sky at 53 GHz
The sky at 150 GigaHz (~2 mm)

An interesting comparison:

The sky at 545 TeraHz (~550 nm)
Current constraints on inflation models

Hints of Isocurvature Perturbations in the Cosmic Microwave Background

Reijo Keski-Kota,1,2, * Hannu Kurki-Suonio,2 Vesa Muohen,1,2 and Jussi Valiviita3

Δχ² = -3.9 with 1 extra parameter

Fitting CMB data with cosmic strings and inflation

Neil Bevis,1 Mark Hindmarsh,1 Martin Kunz,2 and Jon Urrestilla1,3

Δχ² = -9.6 with 4 extra parameters

Figure 2: The CMB temperature angular power spectrum for our best-fit model (black) compared to the best-fit adiabatic model (red/gray). The dashed blue curve shows the nonadiabatic contribution. The inset shows the 2nd and 3rd peaks.

FIG. 1: The temperature power spectrum contribution from cosmic strings, normalized to match the WMAP data at ℓ = 10, as well as the best-fit cases from inflation only (model PL) and inflation plus strings (PL+S). These are compared to the WMAP and BOOMERANG data. The lower plot is a repeat but with the best-fit PL case subtracted, highlighting the deviations between the predictions and the data.

Δχ² = -3.9 with 1 extra parameter
The Universe is close to spatially flat, is dominated by dark energy and dark matter, is currently accelerating in its expansion rate, and present-day structure grew from nearly scale invariant primordial fluctuations.
Variations in the temperature of space today have precisely the size we would expect if the shape of the Universe is FLAT!
From Type Ia Supernovae, we have determined that the expansion rate of the Universe began accelerating about 5 billion years ago.
\[ \rho = \rho_{\text{baryon}} + \rho_{\text{dark matter}} + \rho_{\text{radiation}} + \rho_\Lambda \]
Polarization of the CMB can hopefully resolve some of these questions.
The most commonly considered and familiar types of perturbations are scalar modes. These modes represent perturbations in the (energy) density of the cosmological fluid at last scattering and are the only fluctuations which can form structure though gravitational instability.
Vector perturbations represent vortical motions of the matter, similar to "eddies" in water. There is no associated density variation, and these modes are not expected to be observable in the CMB.

Wayne Hu
Tensor fluctuations are transverse-traceless perturbations to the metric, which can be viewed as gravitational waves.
$P_S(k) \approx \left( \frac{H^2}{16\pi^3 k^2} \right)_{(k=\alpha H)}$ (scalar perturbations),

$P_T(k) \approx \left( \frac{H^2}{4\pi^2 m_{pl}^2} \right)_{(k=\alpha H)}$ (tensor perturbations),
Each of these polarization patterns on the sky can be separated into "electric" (E) and "magnetic" (B) components.
Planck will measure the polarization of the CMB at high angular resolution, hopefully with sufficient sensitivity to measure both E and B modes.
Unsolved mysteries:

What is the nature of this dark energy?

Why is the density of dark energy, or “lambda,” apparently so much less by cosmological observations, than is predicted by quantum mechanical considerations – by about 120 orders of magnitude?

What is the dark matter made of?

Are there effects of “physics beyond the Standard Model” that can be found in the CMB power spectrum?

What can we learn about the future expansion of the Universe?
Conclusion: Exciting times ahead!