Cosmological parameters and constraints on inflation from Planck

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28 May 2013
The Cosmic Microwave Background (CMB)

• A snapshot of the early universe from the time of “last scattering”, 380,000 years after the big bang

• The universe is very simple this young, so any lumps seen then must have been there at the Big Bang (unless there are cosmic strings; see paper XXV… )
Simplified description of the Universe often suffices…

• We have distributions of:
  – Matter (Normal and “dark”)
  – Radiation (set by $T_{\text{CMB}}$)
  – Dark Energy

• “Optical depth $\tau$, due to reionization”
  – I.e. how much CMB gets “lost” on its way to us

• Initial gaussian, adiabatic, “growing” perturbations described by
  – Amplitude
  – Scale dependence (“spectral index”, $n_s$)
The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA) and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
• Planck 2013 results. XV. CMB power spectra and likelihood
• Planck 2013 results. XVI. Cosmological parameters
• Planck 2013 results. XVII. Gravitational lensing by large-scale structure
• Planck 2013 results. XXII. Constraints on inflation
Planck CMB map

(ESA)
Actually, what we really see is...
How to analyze?

• Low-l (multipoles $2 \leq l \leq 49$)
  – Use a “Gibbs sampler” on low-res maps
    • More or less equivalent to a pixel-based approach, also handles foregrounds and is faster to use
    • Uses 91% of the sky

• High-l (multipoles $50 \leq l \leq 2500$)
  – …
At high-$l$ we have to deal with *unresolved* foregrounds…

- “Point Sources”
  - Synchroton and dust emission from galaxies

- **SZ** (Sunyaev-Zeldovich) Effect
  - Hot gas in clusters of galaxies interacts with CMB on its way to us

- **CIB** (Cosmic Infrared Background)
  - Structured Emission from dusty galaxies
...and instrumental systematics

- Relative calibration factors
- Beam errors
In fact we use the just cleanest channels and apply big masks...
We use “pseudo” power spectra...
But these don’t come from the frequency maps!

• One would see the noise contribution
  – And have to model it just right to trust subtracting it out!
Planck actually makes multiple maps at each frequency...
We can make many “fine-grained” cross spectra, e.g. …
And take weighted averages of them...
Left with four effective spectra...

- 100x100: 50 \leq l \leq 1200
- 143x143: 50 \leq l \leq 2000
- 217x217: 500 \leq l \leq 2500
- 143x217: 500 \leq l \leq 2500
Unresolved components

• Model them at the power spectrum level
  – Simple templates in $l$
  – Various coefficients to describe amplitudes
    and (cross-) correlations

![Graph showing $P_l$ vs $l$ with data points and a curve fitting line, labeled Planck and with specified frequencies 100, 143, and 217.](image)
Beam errors

• We parameterize uncertainties in our understanding of the beams with “beam eigenmodes”
• Different theories lead to different predictions about what the CMB map should statistically look like
• Gives us a way to figure out what the universe is like
Compare theories to data using Bayes’ Theorem:

\[ P(\text{theory}|\text{data}) = \frac{P(\text{data|theory}) \cdot P(\text{theory})}{P(\text{data})} \]
Planck alone

• Seven peaks give us the acoustic scale really well:
  \[ \theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ. \]

• Turns out the following is also really well constrained:
  \[ \Omega_m h^3 = 0.0959 \pm 0.0006 \]

• 2% constraint on \( H_0 \):
  \[ H_0 = (67.4 \pm 1.4) \text{ km s}^{-1} \text{ Mpc}^{-1} \]
Also add in other data sets

- CMB
  - WMAP polarization data (helps for tau)
  - High-l experiments, ACT & SPT, looking at small regions of the sky at high-resolution

- Non-CMB
  - Planck lensing map (DM distribution deduced from CMB deflections)
  - BAO ("baryon acoustic oscillation") measurements
    - wiggles in the matter power spectrum
  - (SN and HST)
Planck Lensing (1)
Planck Lensing (2)
Get nice parameter constraints, e.g.:

Planck 2013 results. XVI. Cosmological parameters
BAO

\[ \frac{(\tau_s/D_V)/(\tau_s/D_V)_{\text{Planck}}}{z} \]

- \( \tau_s \) is the sound horizon
- \( D_V \) is the comoving distance
- \( z \) is the redshift
HST
But what of plausible extensions? Nothing!

- Curvature, neutrino masses, varying number of neutrinos...
• Helium fraction, running, tensors, dark energy...
Illustration of effects of tensions on extended models:
• Check out our full “grid” of models and data combinations online:
  – http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive
Still questions about LCDM…

• What is the dark matter?
• What is the dark energy?

• Why is the Universe neither totally chaotic nor perfectly uniform? (The Horizon Problem…)
Therefore, inflation! (perhaps...)

- Gives us more time...

- And quantum fluctuations stretch and grow into the “primordial” fluctuations in the hot big bang epoch
Details of the inflaton potential affect the perturbations...

- Puts pressure on large-field models
Nb. more complicated scenarios are possible

- Multifield inflation,
- non-canonical kinetic terms,
- non-standard vacuum,
- ...
There are some “curiosities”…

• Features in the power spectra
  – low-l dip
  – High-l dip

• Power asymmetries
Low-l dip...
High-l dip...
Some constraints on model-inspired modified power spectra...

<table>
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<th>Model</th>
<th>$-2\Delta \ln L_{\text{max}}$</th>
<th>$\ln B_{0X}$</th>
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Power-spectrum reconstruction...
What’s coming…

• Full temperature data, more aggressive analysis
  – Should help understand the power spectra features

• Polarization maps
  – At high-l, complement the temperature power spectra; not much foreground contamination!
“Teaser” plot...
Moreover, tensor fluctuations imprint a distinct “B-mode” pattern into the polarization maps at low-$l$

Hard to disentangle from systematics but if convincingly found or bounded will rule in or out many inflationary and other models
Conclusions

• Six-parameter LCDM fits the high-l data as well as any other plausible model
• Some “curiosities” that merit further investigation
• Stay tuned!