The polarization of the CMB with Planck

and the reionization of the universe

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For the Planck team

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2015 was the *Jubilaeus Annus* for the discovery of the Cosmic Microwave Background. We have been enormously privileged to have seen the success of 3 satellite missions and a number of remarkable suborbital experiments dedicated to exploration of the CMB sky.
The observational challenge

To clearly separate a primordial signal from more local sources we must

Constrain spectral energy distribution — Verify statistical isotropy — Probe all angular scales

CLASS

LSPE

BICEP2
BICEP3

SPIDER

Keck Array

PIPER

CLASS

LSPE

BICEP2
BICEP3

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From Jon’s talk
Planck 2015
full sky maps of
linear polarization

Nordita, July 2017
Fig. 16. Maximum posterior amplitude polarization maps derived from the Planck observations between 30 and 353 GHz. Left and right columns show the Stokes $Q$ and $U$ parameters, and rows show, from top to bottom, CMB, synchrotron polarization at 30 GHz and thermal dust polarization at 353 GHz. The CMB map has been highpass-filtered with a cosine-apodized filter between $f = 20$ and 40, and the Galactic plane has been replaced with a constrained Gaussian realization (Planck Collaboration A11 2014). The two top rows employ linear color scales, and the bottom row employs the non-linear HDR color scale. 

Short frequency lever arm, and it is from algebraic considerations expected to be the cleanest solution in terms of systematics. However, it also suffers from significantly higher statistical noise compared to the other types. Type-2 attempts to improve on this situation by fitting for all CO line maps simultaneously, using the same algebra and implementation as Type-1, but additionally using multi-frequency observations and imposing a simple (spatially constant) frequency model for thermal dust. Finally, in the 2013 release a Type-3 map also provided, which was a Commander solution, as described above, but assuming a rigid CO scaling between any two frequency maps, leaving only one free CO amplitude parameter per pixel, and one free overall line ratio per frequency map. This approach results in the highest signal-to-noise ratio, effectively by compressing all information into one map, but it is also relies directly on the accuracy of the overall model to avoid foreground leakage into the CO map. As described above, the Commander CO model has been generalized in the current release, and is now in principle very similar to Type-2, with the main difference being a different effective signal model to account for other components. No new Type-3 map is delivered in the 2014 data release, but this has been superceded by the new Commander $J = 2!1$ map, which Planck Collaboration X 2015 Planck Collaboration IX 2015
Total intensity encoded in colours
Polarization encoded in shaded striations.
Polarization orientation is at 90° from the striations, which indicate the direction of the magnetic field projected on the sky.
Four Color Composite Image of the Foreground Sky

Blue—synchrotron; Green—free-free; Yellow—CO; Red—thermal dust
Small signal confined to low multipoles => accurate control of instrumental systematics and Polarised foreground emission.
Measuring the Optical depth of reionized universe ($\tau$) with the CMB – Planck 2015

Commander T map

70GHz pol. Foreground cleaned with 30GHz and 353GHz

93% sky fraction

BR

BolPol

$\Omega_{\Delta}$

Power spectrum, $D_\ell [\mu K^2]$

Multipole $\ell$

Planck 2013

Planck 2015

LCDM 2013

LCDM 2015

WMAP 9-yr
Measuring the Optical depth of reionized universe (τ) with the CMB – Planck 2015

• Planck low-ell (T,P) Likelihood with all parameters but τ, A_s and n_s fixed to Planck 2015
Best Fit Model

An example with all parameters but τ, A_s fixed to Planck 2015 BFM

30/70/353 polarization (low-ell) $\rightarrow$ $\tau = 0.067 \pm 0.022$
Measuring the Optical depth of reionized universe ($\tau$) with the CMB

- Planck 2015: 
  30/70/353 polarization: 
  $$\tau = 0.067 \pm 0.022$$

- Planck 2015 polarization (low-ell) + TT (high-ell) 
  $$\tau = 0.078 \pm 0.019$$

- Planck 2015 TT + lensing 
  $$\tau = 0.070 \pm 0.024$$

- + BAO 
  $$\tau = 0.067 \pm 0.016$$

  $$\tau = 0.089 \pm 0.014$$

- WMAP9 Dust-cleaned with Planck 353 
  $$\tau = 0.075 \pm 0.013$$

Planck 2015 polarization (low-ell) + TT (high-ell) $$\Rightarrow \tau = 0.078 \pm 0.019$$
Planck/HFI data and large scale polarization

• In principle, lower noise level in 100, 143, 217 GHz data can improve Planck $\tau$ measurement.

• Polarization power spectra in 2015 release dominated by systematic errors at low multipoles ($\ell < 30$)

• New effort:
  • improved understanding of large angular scale systematics in both HFI and LFI instruments -> improved maps -> improved $\tau$ measurement
  • Simulation effort to characterize systematics remaining in the data
  • New mapmaking procedure

2 papers:
*Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth’*
2016A&A...596A.107P

'Planck intermediate results. XLVII. Planck constraints on reionization history’
2016A&A...596A.108P
Planck-HFI ’s polarization measurement

\[ m_t = I(\vec{n}) + \rho \left[ Q(\vec{n}).\cos(2\psi) + U(\vec{n}).\sin(2\psi) \right] \]

No instrumental polarization modulation: I,Q,U solved by combining sky measurements from polarization sensitive bolometers at different angles → differencing detector signals and by sky modulation.

Much of the sky is poorly sampled in polarization angles: vulnerable to T→P leakage

• Characterization of detector-to-detector relative properties + long time scale stability of measurement is critical for large angular scales.
Simulated systematics propagated to EE-spectra for HFI

Systematics at low ell in HFI channels dominated by ADC nonlinearity

Purely instrumental -> Analog-to-Digital Converter (ADC) nonlinearity; Time response residuals; Relative gain between detectors; Possible time-variable gain
Scan-strategy related -> Far sidelobe pickup; Zodiacal light emission; Bandpass mismatch T → P leakage
ADC nonlinearity: Can be (mostly) corrected by applying a time-variable linear gain correction.
ADC nonlinearity in HFI

Nonlinearity near mid-range

A perfectly linear device would be a horizontal line at zero

Huge effort during HFI warm mission to characterize ADCs.
✦ Major improvements between 2013 and 2015 releases
✦ But some residual effects remain
Simulated effects of residual ADC nonlinearity

Can be (mostly) corrected by applying a time-variable linear gain correction. However dipole signal is distorted: signal leaked from $\ell=1$ to higher $\ell$ (affects mostly $\ell=2$ and 3)

Efficiency of the new mapmaking residual gain variation correction
Simulated LFI systematics in EE spectra

Systematics at low $\ell$ are mostly dominated by

- **calibration uncertainty**
- **far sidelobe pickup at 30 GHz**
Removal of Systematic Errors

Extend data model to solve for systematic effects while also solving for I, Q, U on the sky:

\[ d_t = g_r \left( I_P + \rho Q_P \cos 2\phi_t + \rho U_P \sin 2\phi_t + D_t + \sum f_i T_p^{(fg)i} + \sum c_i T_t^{(TF)i} \right) + o_r + n_t \]

- **Time variable gain** (mostly corrects ADC nonlinearity)
- **Residual dipole**
- **Bandpass mismatch**: leaks foreground T to P
- **Residual transfer function templates**.
- **Zodi templates**
- **Destriper offset**: remove 1/f noise
Null tests: great improvement in self-consistency of maps

2015 data set

2016 data set

Noise
Forefront removal

ILC with 30 GHz for synchrotron and 353 GHz for dust

50% sky fraction
Ell=4 EE power
100x143 spectra

- Main results: Use 100 x 143 (foreground cleaned)
- Cross checks from 100 x 70 and 143 x 70, 100x100 and 143x143 autospectra for crosschecks.
- Use multiple spectral estimator techniques
  - Pseudo-Cl (PCL) - Lollipop
  - Quadratic Maximum Likelihood (QML)
- Use instrumental simulations to compute and subtract bias due to systematics (very small), and to construct pixel-pixel noise covariance
- Simulation based Likelihood - SimBal

Black lines - Model for \( \tau = 0.05 \) (dotted), 0.07(solid) and 0.09 (dashed)

QML computed with two different simulation sets
Tau results

Instrumental cross-check: HFI x LFI

QML spectra: $0.055^{+0.009}_{-0.009}$

$\tau = 0.049^{+0.015}_{-0.019}$ for the 70x100 cross-spectra
$\tau = 0.053^{+0.012}_{-0.016}$ for the 70x143 cross-spectra
Summary of tau results

Given lower limit from astrophysics (Gunn-Peterson), $z_{re} \sim 6$, ie, $\tau \sim 0.038$

New Planck/HFI result has 95% CL upper limit $\tau < 0.072$

$z_{re} \sim 7.7$ to 8.8 (depending on the model of reionization)

The Universe is ionized at less than the 10% level above $z \sim 10$
Timeline of tau results

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Effects on other $\Lambda$CDM cosmological parameters

- Impact on scalar amplitude of the spectra, $A_s$, and tilt, $n$:
  - Main degeneracy is with primordial scalar $A_s \rightarrow \sigma_8$ comes down (by 1 $\sigma$)
  - *but not enough to resolve discrepancy with Planck cluster abundance measurement*
  - Slight degeneracy with $n_s$, which shifts down slightly

![Graph showing $\ln(10^{10} A_s)$ vs. $\sigma_8$ and $n_s$ for Planck 2015 and Planck 2016.]
Impact on models of early galaxy evolution and star formation

Left: Evolution of the ionization fraction for several functions with same $\tau=0.06$
Green and Blue are for redshift-symmetric instantaneous ($z = 0.05$) and extended reionization ($z = 0.7$), respectively;
Red is an example of a redshift asymmetric parameterization;
Light Blue and Magenta are examples of an ionization fraction defined in redshift bins, with two bins inverted between these two examples.
Right: correspondingly $EE$ power spectra with cosmic variance in grey.

All models have the same optical depth $\tau = 0.06$ and are essentially indistinguishable at the reionization bump scale.
Impact on models of early galaxy evolution and star formation

redshift-symmetric parameterization

Green after imposing prior $z_{\text{end}} > 6$

redshift-asymmetric parameterization
Conclusions

• The Planck team has made huge improvements in understanding and cleaning of systematic errors in HFI and LFI instruments:
  • Internal consistency of maps on large angular scales is much improved
  • Improved simulations and removal of systematic effects allow detection of signature of reionization in large scale E-mode angular power spectrum.

• Reionization optical depth $\tau$ lower than previous measurements:
  • $\tau = 0.055 \pm 0.009$ based on 100x143, foreground-cleaned with 30 and 353 GHz
  • Still limited by systematics:
    • cosmic variance limited error bars over 50% of the sky: 0.006 $\rightarrow$ some room for improvement in final 2017 release or beyond..

• Two papers on:
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