Dust polarization spectral dependence from Planck HFI data
Turning point on CMB polarization foreground modelling

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Alessia Ritacco (OAC - INAF, LPENS)
and Francois Boulanger, Vincent Guillet, Jean-Marc Delouis, Jean-Loup Puget, Jonathan Aumont, Léo Vacher
Outline

- Scientific context
- Constraints on CMB polarization detection accuracy
- CMB dust polarization foreground
  - Power spectra analysis of a recent release of Planck HFI data
  - Dust mean SED in polarization at very low multipoles
  - Spatial variations
  - Frequency dependence
- Conclusions and perspectives
Cosmic Microwave Background polarization provides a unique insight on the primordial Universe

Credits: ESA and Planck collaboration

**Cosmic Microwave Background polarization**

provides a unique insight on the primordial Universe

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### Cosmic Microwave Background polarization

- **E-modes**
- **B-modes**

**Sensitivity target**

- $r$ parameter $\sim 10^{-3}$

**Angular scales**

- $90^\circ$
- $2^\circ$
- $0.2^\circ$

**Amplitude**

- $[\mu K^2]$**

**Errard+2016**

**DUST + SYNCHROTRON FOREGROUND**

**LiteBIRD (space)**

**CMB-S4 (ground)**

and others

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**Alessia Ritacco** (OAC - INAF, LPENS)

CMB-France #3

June 21st - Paris
CMB $B$-modes detection as probe of the inflation

**Technical Challenges**

★ High sensitivity  
   (LiteBIRD satellite, CMB-S4 *under development*)

★ Systematic effects control

★ Precise absolute calibration of the polarization angle

★ Foreground emission subtraction
CMB $B$-modes detection as probe of the inflation

Technical Challenges

★ High sensitivity
   (LiteBIRD satellite, CMB-S4 under development)

★ Systematic effects control

★ Precise absolute calibration of the polarization angle

★ Foreground emission subtraction
To subtract the sky dust **polarization** we need to have a full-sky modelling
→ So we need to understand how dust polarization behaves
Dust Spectral Energy Distribution

The dust SED in polarization from Planck 2018 results is remarkably well fit by a single temperature modified black-body emission law from 353 GHz to 44 GHz.

This brought a significant advance in constraining dust models in astrophysics & for CMB foreground dust component separation methods.

⇒ Characterize spatial variations of polarization SEDs, i.e. the local frequency dependence of polarized intensity and angles)
Dust polarization low-\(\ell\) SED spatial variation
Planck HFI maps
SRoll2 release

http://sroll20.ias.u-psud.fr/sroll20_data.htm

Improved polarization maps w.r.t PR3

Check out Delouis et al. A&A 629, A38 (2019) for technical details
A synthetic model based on total intensity spatial SED variations

**Modified Black Body function**

\[ I_d(\nu) = \tau_{353} \times B(T, \nu) \times \left(\frac{\nu}{353 \text{ GHz}}\right)^\beta \]

**Extrapolation to polarization**

\[ Q_{\text{model}}(\nu) = \frac{I_d(\nu)}{I_d(\nu_0)} \cdot (Q_{\text{Planck}}(\nu_0) - Q_{\text{Planck}}(\text{CMB})) \]

\[ U_{\text{model}}(\nu) = \frac{I_d(\nu)}{I_d(\nu_0)} \cdot (U_{\text{Planck}}(\nu_0) - U_{\text{Planck}}(\text{CMB})) \]

We use T, \( \beta \) maps from Commander & GNILC

⇒ Dust polarization models commonly used by CMB community (models d1 & d11 of PySM)
A synthetic model based on total intensity spatial SED variations

Including instrumental systematics + noise and CMB

\[ Q_{\text{sim}}(\nu) = Q_{\text{model}}(\nu) + Q_{\text{noise}}(\nu) + Q_{\text{CMB}} \]

\[ U_{\text{sim}}(\nu) = U_{\text{model}}(\nu) + U_{\text{noise}}(\nu) + U_{\text{CMB}} \]

Two total intensity model considered:
- Commander (Planck Collaboration et al. 2016a)
- GNILC (Remazeilles+2011)
Dust polarized mean SED for low multipoles $\ell_{\text{min}}, \ell_{\text{max}} = [4, 32]$

SED computed for 100, 143, 217 GHz w.r.t $\nu_0 = 353$ GHz

\begin{align*}
\mathbf{Cross \ Power \ Spectra \ Analysis} \\
\gamma_p^{XX}(\nu) = \rho \left( \frac{D_{XX}^{XX}(\nu \times \nu_0) - D_{XX}^{XX}(\text{CMB})}{D_{XX}^{XX}(\nu_0 \times \nu_0) - D_{XX}^{XX}(\text{CMB})} \right)_{\ell_{\text{min}}, \ell_{\text{max}}} \\
\text{SED} \\
\text{Polarization efficiency} \\
\text{Planck Coll. et al. 2020b} \\
\text{Spectra} \\
XX = \text{EE, BB}
\end{align*}

$\gamma_p$ is computed for:
- Planck SRoll2 data
or
- Commander, GNILC models
Galactic masks used for the power spectra data analysis

- Mask $f_{\text{sky}}$ 80%
- Mask $f_{\text{sky}}$ 90%
- Mask $f_{\text{sky}}$ 97%

⇒ We extend earlier studies to brighter Galactic sky emission to gain signal-to-noise ratio
Dust *polarized mean* SED for low multipoles $\ell_{\text{min}}, \ell_{\text{max}} = [4, 32]$

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**Graphs:**

- **Upper Graph:**
  - $f_{\text{sky}} = 80\%$
  - $f_{\text{sky}} = 90\%$
  - $f_{\text{sky}} = 97\%$

- **Lower Graph:**
  - $f_{\text{sky}} = 80\%$
  - $f_{\text{sky}} = 90\%$
  - $f_{\text{sky}} = 97\%$

**Axes:**

- **Y-axis:** SED (Data, Model)
- **X-axis:** Frequency (GHz)

**Note:**

- MBB ($\beta_d = 1.53, T_d = 19.6\, \text{K}$)
Dust polarized mean SED for low multipoles $\ell_{\text{min}}, \ell_{\text{max}}=[4,32]$

- Mean polarization SED confirmed remarkably close to total intensity (confirming previous results)
- Also consistent within 5% with a Modified Black Body function with $T_d=19.6$ K and $\beta_d=1.53$
Spatial SED variation of the dust polarization

Residual maps

\[ R_Q(\nu) = Q_d(\nu) - \gamma_p(\nu) \cdot Q_{\text{Planck}}(\nu_0) \]
\[ R_U(\nu) = U_d(\nu) - \gamma_p(\nu) \cdot U_{\text{Planck}}(\nu_0). \]

Corrected for synchrotron at 100, 143 GHz

Mean SED
Residual polarization maps

Data

Model

Alessia Ritacco (OAC - INAF, LPENS)
CMB-France #3
June 21st - Paris
Cross power spectra analysis of residual maps

Correlation between Planck half-mission data sets

Correlation between data and the Commander model
Averaged cross-correlation between multipoles $\ell=[4,32]$.

At high latitudes $\rightarrow$ less $f_{\text{sky}}$ correlation with total intensity models is low.

These models do not reproduce spatial SED variations detected in polarization data.
Contribution from polarization angles

Planck intermediate results L. 2017

Decomposition of the LOS complex polarization vector into a random walk process through different coherent cells for two pixels at two frequencies, $\nu_1$ and $\nu_2$.

Frequency dependence of polarization angles introduced by the interplay between dust emission properties and the structure of the magnetized ISM

$\Rightarrow$ Decorrelation of the polarization pattern with frequency
Isolating polarization angle variation effect

We build synthetic Stokes Q and U parameters which depend on the polarization angle

\[
\begin{align*}
\tilde{Q}(\nu) &= \gamma_P(\nu) \cdot P(\nu_0) \times \cos 2\psi(\nu) \\
\tilde{U}(\nu) &= \gamma_P(\nu) \cdot P(\nu_0) \times \sin 2\psi(\nu)
\end{align*}
\]

Residual maps:

\[
\begin{align*}
R_{\tilde{Q}}(\nu) &= \tilde{Q}(\nu) - \gamma_P(\nu) \cdot \tilde{Q}(\nu_0) \\
R_{\tilde{U}}(\nu) &= \tilde{U}(\nu) - \gamma_P(\nu) \cdot \tilde{U}(\nu_0)
\end{align*}
\]

Polarization angle maps:

\[\psi_\nu = 0.5 \times \text{atan}(U/Q)\]
Isolating polarization angle variation effect

Amplitudes of residuals due to polarization angle spatial variation
Isolating polarization angle variation effect

Converting the residual amplitudes due to variations of the polarization angle to effective angle variation $\delta \psi$:

$$\sin \delta \psi(\nu) = 0.5 \cdot (\tilde{A}_{\text{res}}^{EE}(\nu) + \tilde{A}_{\text{res}}^{BB}(\nu))^{0.5} \cdot (\gamma_P(\nu) \cdot P(\nu_0))^{-1}$$

<table>
<thead>
<tr>
<th>$f_{\text{sky}}$</th>
<th>100 GHz</th>
<th>143 GHz</th>
<th>217 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>$3.1° \pm 0.4°$</td>
<td>$1.4° \pm 0.2°$</td>
<td>$0.8° \pm 0.2°$</td>
</tr>
<tr>
<td>90%</td>
<td>$2.7° \pm 0.3°$</td>
<td>$1.1° \pm 0.1°$</td>
<td>$0.6° \pm 0.1°$</td>
</tr>
<tr>
<td>97%</td>
<td>$2.6° \pm 0.2°$</td>
<td>$0.8° \pm 0.1°$</td>
<td>$0.5° \pm 0.1°$</td>
</tr>
</tbody>
</table>

Decorrelation due to polarization angle variation along LOS

Uncertainty on absolute angle calibration $< 1°$

(Rosset et al. 2010)
Frequency dependance
Taylor expansion of the MBB emission law

Introduced by Chluba et al. 2017, Mangilli et al. 2021, Azzoni et al. 2021, Vacher et al. 2022a

\[ D_\ell(v) = \gamma P(v)^2 \cdot \left\{ \begin{array}{l}
1^{\text{st}} \text{ order } \beta \\
1^{\text{st}} \text{ order } T \\
1^{\text{st}} \text{ order } T \times \beta
\end{array} \right. \]

\[ + D_\ell^{\omega^\beta \times \omega^\beta} \ln \left( \frac{v}{v_0} \right)^2 \]

\[ + D_\ell^{\omega_T \times \omega_T} \left( \Theta_v(T_d) - \Theta_v(T_0) \right)^2 \]

\[ + 2 D_\ell^{\omega^\beta \times \omega_T} \ln \left( \frac{v}{v_0} \right) \cdot \left( \Theta_v(T_d) - \Theta_v(T_0) \right) \]

(18)
Frequency dependance

Taylor expansion of the MBB emission law

- Dust polarization $EE$ SED variation well described by MBB deriv. in $\beta$
- $BB$ SED tends to flat towards high angular latitudes
- Residual maps between the three frequencies are not fully correlated
Conclusions and Perspectives

Power spectra to characterise spatial variations of polarized dust SED for $\ell = [4, 32]$

– Mean polarization SED confirmed Planck 2018 results.

– Residual maps at 100, 143 and 217 GHz quantifies spatial variations of the dust polarization.

– Residual maps correlated with reference models account for fraction of the total SED variation.
Conclusions and Perspectives

– We detect **variations in the polarization angle**.
  They dominate variations of polarized intensity for $f_{\text{sky}} = 80\%$ and $90\%$

⇒ **It is essential to consider in simulations of Galactic foregrounds and component separation**

– EE power of residuals is well fit by MBB 1st order $\beta$-derivative of MBB.

⇒ **It suggests SED variations follow from small variations of MBB parameters within the beam**

– This conclusion is challenged by BB results, in particular for $f_{\text{sky}} = 80\%$, and by cross-spectra that show that the residuals maps at the three frequencies are not fully correlated.


This work sets new requirements for CMB dust polarized foreground modelling