COrE+ foreground removal with COMMANDER

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Bayesian parametric fitting

COMMANDER - Eriksen et al (2008)

Parametric model of the sky

$$\boldsymbol{m}(\boldsymbol{p}, \boldsymbol{v}) = \boldsymbol{a}(\boldsymbol{v}) \, \boldsymbol{s}^{cmb}(\boldsymbol{p}) \\ + \left(\frac{\boldsymbol{v}}{\boldsymbol{v}_0^s}\right)^{\beta_s(\boldsymbol{p})} \, \boldsymbol{s}^{sync}(\boldsymbol{p}) \\ + \left(\frac{\boldsymbol{v}}{\boldsymbol{v}_0^d}\right)^{\beta_d(\boldsymbol{p})} B_{\boldsymbol{v}}\left(T_d(\boldsymbol{p})\right) \, \boldsymbol{s}^{dust}(\boldsymbol{p}) \\ + \boldsymbol{n}(\boldsymbol{p}, \boldsymbol{v})$$

- pixel space
- low multipoles

Joint CMB-foreground posterior ?

$$P\left(s,\beta,C_{\ell}\middle|d\right) \propto P\left(d\middle|s,\beta,C_{\ell}\right)P\left(s,\beta,C_{\ell}\right)$$

Methodology

Eriksen et al, ApJ 2008 Remazeilles et al, MNRAS 2016

1. Separation of components (COMMANDER Gibbs sampling) :

$$egin{aligned} oldsymbol{s}^{(i+1)} &\leftarrow P\left(oldsymbol{s}|C_\ell^{(i)},oldsymbol{eta}^{(i)},oldsymbol{d}
ight),\ C_\ell^{(i+1)} &\leftarrow P\left(C_\ellig|oldsymbol{s}^{(i+1)}
ight),\ oldsymbol{eta}^{(i+1)} &\leftarrow P\left(oldsymbol{eta}ig|oldsymbol{s}^{(i+1)},oldsymbol{d}
ight), \end{aligned}$$

amplitudes

CMB power spectrum

spectral indices

2. Likelihood estimation of r and A $_{lens}$:

$$-2\ln\mathcal{L}\left[\widehat{C}_{\ell}|C_{\ell}^{th}\left(r,A_{lens}\right)\right] = \sum_{\ell} (2\ell+1)\left[\ln\left(\frac{C_{\ell}^{th}}{\widehat{C}_{\ell}}\right) + \frac{C_{\ell}^{th}}{\widehat{C}_{\ell}} - 1\right]$$

$$C_{\ell}^{th} = r C_{\ell}^{tensor}(r=1) + A_{lens} C_{\ell}^{lensing}(r=0),$$

Challenging sky simulation

M. Remazeilles, J. Delabrouille, C. Dickinson

Modified version of the public Planck Sky Model :

- CMB r = 0.001, τ = 0.066
- Lensing
- Synchrotron with varying β
- Thermal dust with varying β and T
- AME 1% polarized
- Point-sources (radio and IR)
- white noise / COrE+ and LiteBIRD specs

Challenging sky simulation M. Remazeilles,

J. Delabrouille, C. Dickinson



Case 1. constant spectral indices







Case 1. constant spectral indices



Case 2. constant spectral indices + lensing





We do need to control foregrounds at $\ell < 12$ (Reionization bump) to disentangle tensor B-modes and lensing B-modes !



That's also why we need a satellite mission ! (large angular scales, broad frequency range)

Why r is biased ?

- Incorrect foreground modelling ?

 i.e., too challenging polarized sky
 (low r, low τ, complex foregrounds)
- Lack of low / high frequency channels ?

Correct foreground modelling



Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Impact of foreground mis-modelling : omitting one dust greybody



Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Do we need extra channels < 60 GHz ?



Index curvature can make synchrotron spectrum less orthogonal to CMB spectrum

<u>Over a restricted frequency range</u>, spectral flattening may prevent component separation techniques from distinguishing between CMB and synchrotron B-modes

i.e. global sky is correctly fitted ($\chi^2 \sim 1$) but individual synchrotron and CMB components not correctly splitted (r biased)

Impact of mis-modelling synchrotron : neglecting index curvature



→ lack of low-frequency channels

Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Impact of mis-modelling synchrotron : neglecting index curvature



Remazeilles, Dickinson, Eriksen, Wehus, MNRAS 2016

Main questions we intend to address

- Can we reconstruct the CMB B-mode at r = 0.001 ?
 What are the bias and the error at Reionization bump ?
 - with complex polarized foregrounds,
 - with gravitational lensing effect,
 - with COrE+ and LiteBIRD specs.
- Are 1% polarized foregrounds (e.g. AME) relevant for r = 0.001 ?
- Impact of the variation of foreground spectral indices ?
- Impact of polarized point-sources ?

current simulation

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current simulation

• What is the impact of systematics on the foreground removal ?

 How COrE+, LiteCOrE, LiteBIRD perform in this respect ? <u>we still need a simulation mixing both</u> <u>systematics (beams, bandpass, etc) and foregrounds</u>

Actions for the paper

- Compare comp sep results between COrE+, LiteBIRD, LiteCOrE on the challenging sky simulation (non-uniform T and β, point-sources, AME polarization)
- Optimal Galactic masking ?
- Optimal frequency range ? # of channels ? Do we need extra frequencies ?
- Add systematics to the sky simulation ? Impact of systematics on foreground removal ?
 - asymmetric beams
 - bandpass mismatch
 - correlated noise
- Improve PSM simulation ?
 - GNILC foreground Q / U maps from Planck observations (Remazeilles, Karakci, Delabrouille)
 - non-uniform polarization fraction for AME
 - super-realistic foreground models: multi-layer galaxy emission J. Delabrouille, F. Boulanger's work

Also see talks from S. Basak, P. Vielva, C. Hervias, J. Errard



Impact on component separation of calibration errors



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J. Dick, M. Remazeilles and J. Delabrouille

Figure 2. Plot of the relative error of FastICA as a function of the galactic latitude. Generated using 128 simulations for each case. As expected, the relative error of FastICA has very little dependence upon the calibration error.



MNRAS 2010



ILC output



Figure 4. Input CMB- and ILC-estimated CMB plotted on a 0.2 mK scale for one realization at 1 per cent calibration error with particularly bad output (relative error near 1.0). Note that the variance of the ILC output is far below the input CMB, indicating that the input CMB was largely cancelled.

performed especially poorly, compared with the input CMB plotted on the same scale. The variance of the ILC output is much lower

ILC weights discrepant with actual CMB calibration \rightarrow variance minimization kills the CMB !





Large scale polarized foregrounds

Component	Spectrum	Polarization fraction	References
Synchrotron	- Power-law β ~-3, variations $\Delta\beta$ ~0.2 - In theory, curvature C=-0.3 - Flattening from multiple power-laws / populations of electrons	~15-20% (up to ~50%)	Page et al (2007), Kogut et al (2007), Macellari et al (2011) Vidal et al (2015)
Thermal dust	- Modified black-body - Possibly 2 components/flattening at frequencies <300 GHz	~5% - 10% (up to ~20+%)	Ponthieu et al (2005), Planck Collaboration, ESLAB conference (2013). Planck intermediate results. XIX
Magnetic dipole?	- Similar to thermal dust, but flatter index at frequencies ~100 GHz - Not yet detected (70GHz-300 GHz)	<i>Variable (up to ~35% ?)</i> <~5%	Draine & Lazarian (1999), Draine & Hensley (2013) Hoang & Lazarian (2015)
spinning dust	- Peaked spectrum ~10-60 GHz	<~1% Perseus:0.6+/-0.5%	Lazarian & Draine (2000), Dickinson (2011), Lopez-Caraballo et al. (2011), Macellari et al. (2011), Rubino- Martin et al. (2012) Planck 2015 results. XXV
Free-free	- Power-law β ~-2.14 with positive curvature (steepening at frequencies >~100 GHz)	<i>Intrisically zero, in practice <~1%</i>	Rybicki & Lightman (1979), Keating et al. (1998), Macellari et al. (2011)

Instrument specs

	COrE+ ext.			LiteBIRD ext.	
frequency	beam	P-noise	frequency	beam	P-noise
[GHz]	[arcminute]	$[\mu K.degree]$	[GHz]	[arcminute]	$[\mu K.degree]$
60	14.0	0.342	40.0	108.0	0.708
70	12.0	0.233	50.0	86.0	0.433
80	10.5	0.160	60.0	72.0	0.333
90	9.3	0.123	68.4	63.0	0.258
100	8.4	0.098	78.0	55.0	0.208
115	7.3	0.073	88.5	49.0	0.167
130	6.5	0.057	100.0	43.0	0.200
145	5.8	0.057	118.9	36.0	0.158
160	5.3	0.057	140.0	31.0	0.125
175	4.8	0.058	166.0	26.0	0.117
195	4.3	0.063	195.0	22.0	0.083
220	3.8 (4.0)	0.090	234.9	18.0	0.108
255	3.3 (4.0)	0.152	280.0	37.0	0.167
295	2.9 (4.0)	0.220	337.4	31.0	0.167
340	2.5 (4.0)	0.422	402.1	26.0	0.317
390	2.2 (4.0)	0.790			
450	1.9 (4.0)	1.982			
520	1.6 (4.0)	5.632			
600	1.4 (4.0)	20.050			
700	1.2 (4.0)	93.500			
800	1.1 (4.0)	203.333			