Planck intermediate results. XXII. Frequency dependence of thermal emission from Galactic dust in intensity and polarization


ABSTRACT

Planck has mapped the intensity and polarization of the sky at microwave frequencies with unprecedented sensitivity. We use these data to characterize the frequency dependence of dust emission. We make use of the Planck 353 GHz I, Q, and U Stokes maps as dust templates, and cross-correlate them with the Planck and WMAP data at 12 frequencies from 23 to 353 GHz, over circular patches with 10° radius. The cross-correlation analysis is performed for both intensity and polarization data in a consistent manner. The results are corrected for the chance correlation between the templates and the anisotropies of the cosmic microwave background. We use a mask that focuses our analysis on the diffuse components of interstellar dust (e.g., carbon versus silicate grains). Our observational results provide inputs to quantify and optimize the spectral dependence of the dust polarization fraction. The polarization fraction (p) of the dust emission decreases by (21 ± 6)% from 353 to 70 GHz. We discuss this result within the context of existing dust models. The decrease in p could indicate differences in polarization efficiency among components of interstellar dust (e.g., carbon versus silicate grains). Our observational results provide inputs to quantify and optimize the separation between Galactic and cosmological polarization.


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1. Introduction

Planck\(^1\) (Tauber et al. 2010; Planck Collaboration I 2011) has mapped the polarization of the sky emission in seven channels at microwave frequencies from 30 to 353 GHz. The data open new opportunities for investigating the astrophysics of Galactic polarization. In this paper, we use these data to characterize the frequency dependence of dust polarization from the diffuse interstellar medium (ISM).

At microwave frequencies, dust emission components include the long-wavelength tail of thermal dust emission (Draine & Li 2007; Meny et al. 2007; Compiègne et al. 2011; Jones et al. 2013), the anomalous microwave emission (AME, Kogut et al. 1996; Leitch et al. 1997; de Oliveira-Costa et al. 1999; Banday et al. 2003; Lagache 2003; Davies et al. 2006; Dobler & Finkbeiner 2008; Miville-Deschênes et al. 2008; Ysard et al. 2010; Planck Collaboration XX 2011), and possibly dipolar magnetic emission of ferromagnetic particles (Draine & Lazarian 1999; Draine & Hensley 2013).

Thermal dust emission is known to be polarized, but to a different degree for each dust component, owing to differences in the shape and alignment efficiency of grains (Hildebrand et al. 1999; Martin 2007; Draine & Fraisse 2009). The polarization of the 9.7 µm absorption from silicates is direct evidence that silicate grains are aligned (Smith et al. 2000). The lack of polarization of the 3.4 µm absorption from aliphatic hydrocarbons (along lines of sight towards the Galactic centre with strong polarization in the 9.7 µm silicate absorption) indicates that dust comprises carbon grains that are much less efficient at producing interstellar polarization than silicates (Chiar et al. 2006). Observational signatures of these differences in polarization efficiency among components of interstellar dust are expected to be found in the polarization fraction \( \rho \) of the far infrared (FIR) and sub-mm dust emission. Spectral variations of polarization fraction have been reported from observations of star-forming molecular clouds (Hildebrand et al. 1999; Vaillancourt 2002; Vaillancourt et al. 2008; Vaillancourt & Matthews 2012). However, these data cannot be unambiguously interpreted as differences in the intrinsic polarization of dust components (Vaillancourt 2002); they can also be interpreted as correlated changes in grain temperature and alignment efficiency across the clouds. The sensitivity of Planck to low-brightness extended-emission allows us to carry out this investigation for the diffuse ISM, where the heating and alignment efficiency of grains are far more homogeneous than in star-forming regions.

AME is widely interpreted as dipole radiation from small carbon dust particles. This interpretation, first proposed by Erickson (1957) and modelled by Draine & Lazarian (1998), has been developed into detailed models (Ali-Haïmoud et al. 2009; Silsbee et al. 2011; Hoang et al. 2011) that provide a good spectral fit to the data (Planck Collaboration XX 2011; Planck Collaboration Int. XV 2014). The intrinsic polarization of this emission must be low, owing to the weakness or absence of polarization of the 220 nm bump in the UV extinction curve (Wolff et al. 1997), which is evidence of the poor alignment of small carbon particles. The polarization fraction of the AME could be up to a few percentage (Lazarian & Draine 2000; Hoang et al. 2013). The Wilkinson Microwave Anisotropy Probe (WMAP, hereafter) data have been used to search for polarization in a few sources with bright AME, for example the \( \rho \) Ophiuchus and Perseus molecular clouds (Dickinson et al. 2011; López-Caraballo et al. 2011), yielding upper limits in the range of 1.5 % to a few percent on polarization fraction (Rubiano-Martín et al. 2012).

Magnetic dipolar emission (MDE) from magnetic grains was first proposed by Draine & Lazarian (1999) as a possible interpretation of the AME. Draine & Hensley (2013) have recently revived this idea with a new model where the MDE could be a significant component of dust emission at frequencies from 50 to a few hundred GHz (Planck Collaboration Int. XIV 2014) and Planck Collaboration Int. XVII (2014), relevant to cosmic microwave background (CMB) studies. Recently, Liu et al. (2014) have argued that MDE may be contributing to the microwave emission of Galactic radio loops, in particular Loop I. This hypothesis may be tested with the Planck polarization observations. The polarization fraction of MDE is expected to be high for magnetic grains. If the magnetic particles are inclusions within silicates, the polarization directions of the dipolar magnetic and electric emissions are orthogonal. In this case the models predict a significant decrease in the polarization fraction of dust emission at frequencies below 350 GHz.

WMAP provided the first all-sky survey of microwave polarization. Galactic polarization was detected on large angular scales at all frequencies from 23 to 94 GHz. The data have been shown to be consistent with a combination of synchrotron and dust contributions (Kogut et al. 2007; Page et al. 2007; Miville-Deschênes et al. 2008; Macelli et al. 2011), but they do not constrain the spectral dependence of dust polarization.

The spectral dependence of the dust emission at Planck frequencies has been determined in the Galactic plane and at high Galactic latitudes by Planck Collaboration Int. XIV (2014) and Planck Collaboration Int. XVII (2014). In this paper, we use the high signal-to-noise 353 GHz Planck Stokes \( I, Q, U \) maps as templates to characterize the spectral dependence of dust emission in both intensity and polarization. Our analysis also includes the separation of dust emission from CMB anisotropies. We extract the dust-correlated emission in intensity \( I \) and polarization \( P \) by cross-correlating the 353 GHz maps with both the Planck and WMAP data. For the intensity, we also use the Hz and 408 MHz maps as templates of the free-free and synchrotron emission. The \( I \) and \( J \) spectra are compared and discussed in light of the present understanding and questions about microwave dust emission components introduced in Planck Collaboration Int. XVII (2014). We aim to characterize the spectral shape and the relative amplitude of Galactic emission components in polarization. In doing so we test theoretical predictions about the nature of the dust emission in intensity and polarization. We also provide information that is key to designing and optimizing the separation of the polarized CMB signal from the polarized Galactic dust emission.

The paper is organised as follows. In Sect. 2, we introduce the data sets used in this paper. Our methodology for the data analysis is described in the following three sections. We define the part of the sky we analyse in Sect. 3. We describe how we apply the cross-correlation analysis (hereafter CC) to the intensity and polarization data in Sect. 4. Section 5 explains the separation of the dust and CMB emission after data correlation. The scientific results are presented in Sects. 6 and 7 for intensity, and Sects. 8 and 9 for polarization. The dust SEDs, \( I \) and \( P \), are compared and discussed with relation to models of dust emission in Sect. 10. Section 11 summarizes the main results of our

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\(^1\) Planck (http://www.esa.int/Planck) is a project of the European Space Agency (ESA) 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 by a collaboration between ESA and a scientific consortium led and funded by Denmark.
work. We detail the derivation of the correlation coefficients in Appendix A. Appendix B describes the Monte Carlo simulations we have performed to show that our data analysis is unbiased. Appendix C describes the dependence of the dust $I$ SED on the correction of the $H\alpha$ map, used as template of the free-free emission, for dust extinction and scattering. The power spectra of the maps used as templates of dust, free-free and synchrotron emission are presented in Appendix D for a set of Galactic masks.

2. Data sets used

Here we discuss the Planck, WMAP, and ancillary data used in the paper and listed in Table 1.

2.1. Planck data

2.1.1. Sky maps

Planck is the third generation space mission to characterize the anisotropies of the CMB. It observed the sky in seven frequency bands from 30 to 353 GHz for polarization, and in two additional bands at 545 and 857 GHz for intensity, with an angular resolution from 31’ to 5’ (Planck Collaboration I 2014). The in-flight performance of the two focal plane instruments, the HFI (High Frequency Instrument) and the LFI (Low Frequency Instrument), are given in Planck HFI Core Team (2011) and Mennella et al. (2011), respectively. The data processing and calibration of the HFI and LFI data used here are described in Planck Collaboration VIII (2014) and Planck Collaboration II (2014), respectively. The data processing specific to polarization is given in Planck Collaboration VI (2014) and Planck Collaboration III (2014).

For intensity, we use the full Planck mission (five full-sky surveys for HFI and eight full-sky surveys for LFI) data sets between 30 and 857 GHz. The LFI and HFI frequency maps are provided in HEALPix format (Górski et al. 2005) with resolution parameters $N_{\text{side}} = 1024$ and 2048, respectively. The Planck sky maps between 30 and 353 GHz are calibrated in CMB temperature units, $K_{\text{CMB}}$, so that the CMB anisotropies have a constant spectrum across frequencies. The two high frequency maps of Planck, 545 and 857 GHz, are expressed in MJy sr$^{-1}$, calibrated for a power-law spectrum with a spectral index of $\sim$1, following the IRAS convention. We use Planck maps with the zodiacal light emission (ZLE) subtracted (Planck Collaboration XIV 2014) at frequencies $\nu \geq 353$ GHz, but maps not corrected for ZLE at lower frequencies because the extrapolation of the ZLE model is uncertain at microwave frequencies. Further it has not been estimated at frequencies smaller than 100 GHz. We do not correct for the zero offset, nor for the residual dipole identified by Planck Collaboration XI (2014) at HFI frequencies because it is not necessary for our analysis based on local correlations of data sets.

For polarization, we use the same full Planck mission data sets, as used for intensity, between 30 and 353 GHz. The Planck polarization that we use in this have been generated in exactly the same manner as the data publicly released in March 2013, described in Planck Collaboration I (2014) and associated papers. Note, however, that the publicly available data includes data include only temperature maps based on the first two surveys. Planck Collaboration XVI (2014) shows the very good consistency of cosmological models derived from intensity only with polarization data at small scale scales (high CMB multipoles). However, as detailed in Planck Collaboration VI (2014) (see their Fig. 27), the 2013 polarization data are known to be affected by systematic effects at low multipoles which were not yet fully corrected, and thus these data were not used for cosmology. In this paper, we use the latest Planck polarization maps (internal data release ’DX11d’), which are corrected from known systematics. The full mission maps for intensity as well as for polarization will be described and made publicly available in early 2015.

2.1.2. Systematic effects in polarization

Current Planck polarization data are contaminated by a small amount of leakage from intensity to polarization, mainly due to bandpass mismatch (BPM) and calibration mismatch between detectors (Planck Collaboration Int. XIX 2015; Planck Collaboration VI 2014; Planck Collaboration III 2014). The BPM results from slight differences in the spectral response to Galactic emission of the polarization sensitive bolometers (PSB) (Planck Collaboration VI 2014). In addition, the signal differences leak into polarization. The calibration uncertainties translate into a small mismatch in the response of the detectors, which produces a signal leakage from intensity to polarization. As the microwave sky is dominated by the large scale emission from the Galaxy and the CMB dipole, systematics affect the polarization maps mainly on large angular scales. We were only able to correct the maps for leakage of Galactic emission due to bandpass mismatch.

The observed Stokes $Q^\text{obs}_\nu$ and $U^\text{obs}_\nu$ maps at a given frequency $\nu$ can be written as,

$$Q^\text{obs}_\nu = Q + Q^G + Q^\text{inc} + L(I \rightarrow Q),$$

$$U^\text{obs}_\nu = U + U^G + U^\text{inc} + L(I \rightarrow U),$$

where the term $L$ corresponds to the BPM leakage map for Galactic emission, offset, and residual dipole. All of them are computed using the coupling coefficient of each detector to the sky emission spectrum together with the actual sky scanning strategy. The superscript $c$ represents the CMB polarization, $n$ represents the noise and the index $G$ incorporates all the Galactic emission components in intensity at Planck frequencies. We restrict our analysis to intermediate Galactic latitudes where the dominant Galactic emission at HFI frequencies is dust emission. The polarized HFI maps we used are corrected for the dust, CO, offset and residual dipole, to a first approximation, using sky measurements of the spectral transmission of each bolometer (Planck Collaboration IX 2014). At LFI frequencies, we correct for BPM coming from the low frequency Galactic components, i.e., the AME, synchrotron and free-free emission (Planck Collaboration III 2014), using sky measurements of the spectral transmission of each bolometer.

To test the results presented in this paper for systematic effects, we use multiple data sets that include the maps made with two independent groups of four PSBs (detector sets “DS1” and “DS2”, see Table 3 in Planck Collaboration VI 2014), the half-ring maps (using the first or second halves of the data from each stable pointing period, “HR1” and “HR2”) and maps made with yearly surveys (“YR1”, “YR2”, etc.). The HR1 and HR2 maps are useful to assess the impact on our data analysis of the noise and systematic effects on scales smaller than 20’. The YR1 map is a combination of first two surveys S1 and S2, and YR2 is a combination of surveys S3 and S4, and so on. The maps

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http://healpix.jpl.nasa.gov
two for Q band, two for V band, and four for W band. WMAP used differencing assemblies (DAs), one for both K and Ka bands.

The Legacy Archive for Microwave Background Data Analysis (LAMBDA)3 provided the HEALPix pixelization scheme with a resolution $N_{side} = 512$. WMAP observed the sky in five frequency bands, denoted K, Ka, Q, V, and W, centred at the frequencies 23, 33, 41, 61, and 94 GHz, respectively. WMAP has ten differencing assemblies (DAs), one for both K and Ka bands, two for Q band, two for V band, and four for W band. WMAP has frequency-dependent resolution, ranging from 52′ (K band) to 12′ (W band). Multiple DAs at each frequency for Q, V and W bands are combined using simple average to generate a single map per frequency band.

2.2. WMAP data

We use the WMAP nine year data (Bennett et al. 2013) from the Legacy Archive for Microwave Background Data Analysis (LAMBDA)3 provided in the HEALPix pixelization scheme with a resolution $N_{side} = 512$. WMAP observed the sky in five frequency bands, denoted K, Ka, Q, V, and W, centred at the frequencies 23, 33, 41, 61, and 94 GHz, respectively. WMAP has ten differencing assemblies (DAs), one for both K and Ka bands, two for Q band, two for V band, and four for W band. WMAP has frequency-dependent resolution, ranging from 52′ (K band) to 12′ (W band). Multiple DAs at each frequency for Q, V and W bands are combined using simple average to generate a single map per frequency band.

2.3. Ancillary data

We complement the Planck and WMAP data with several ancillary sky maps. We use the 408 MHz map from Haslam et al. (1982), and Hα map from Dickinson et al. (2003) (hereafter DDD) as tracers of synchrotron and free-free emission, respectively. No dust extinction correction ($f_d = 0.0$) has been applied to the DDD Hα map, which is expressed in units of Rayleigh (R). For our simulations we use the Leiden/Argentine/Bonn (LAB) survey of Galactic H I column density (Kalberla et al. 2005) as a tracer of dust emission (Planck Collaboration XXIV 2011; Planck Collaboration Int. XVII 2014). Finally, we use the DIRBE 100 μm sky map to determine the dust temperature, like in Planck Collaboration XI (2014).

The 408 MHz, LAB H I, and DIRBE 100 μm data are downloaded from LAMBDA. We use the DIRBE data corrected for ZLE. We project the DIRBE 100 μm map on a HEALPix grid at $N_{side} = 512$ with a Gaussian interpolation kernel that reduces the angular resolution to 50′. Both the 408 MHz and the DDD Hα maps are provided at 1° resolution. The LAB H I survey and DIRBE 100 μm data have angular resolutions of 36′ and 50′, respectively.

3. Global mask

In the data analysis we use a global mask, shown in Fig. 1, which selects regions of dust emission from the ISM at intermediate Galactic latitudes. We only want to study polarization in regions where thermal dust emission dominates. This means that we need to remove the area around the Galactic plane, where other Galactic contributions are significant, and remove the high latitude regions, where the anisotropies of the cosmic infrared background (CIB) are important with respect to dust emission. The global mask combines thresholds on several sky emission components (in intensity): carbon monoxide (CO) line emission;
free-free; synchrotron; the CIB anisotropies; and point sources. We now detail how the global mask is defined.

In the regions of lowest dust column density at high Galactic latitudes, brightness fluctuations from the CIB are significant. To define the CIB mask, we apply a threshold on the ratio between the root mean square (rms) of the total Galactic emission and of the CIB at 353 GHz:

$$\left| \frac{\sigma_G}{\sigma_{\text{CIB}}} \right| < 9,$$

where $\sigma_G$ and $\sigma_{\text{CIB}}$ are defined as

$$\sigma_G^2 = \sum_{\ell} \frac{4\ell+1}{4\pi} C_\ell^G b_\ell^G w_\ell^G,$$

$$\sigma_{\text{CIB}}^2 = \sum_{\ell} \frac{4\ell+1}{4\pi} C_\ell^{\text{CIB}} b_\ell^{\text{CIB}} w_\ell^{\text{CIB}},$$

$$\sigma_G^2 = \sigma^2(\ell_{353}) - \sigma^2 - \sigma_{\text{CIB}}^2.$$

For this threshold, the CIB contribution to the CC coefficients in Sect. 4.2 is smaller than about 1 % (1/92) of that of the total Galactic emission at 353 GHz. The summation is over the multipole range $15 < \ell < 300$ (corresponding to an effective range of angular scales from $1^\circ$ to $10^\circ$). $C_\ell^{\text{CIB}}$ is the best-fit CIB power spectrum at 353 GHz (Planck Collaboration XXX 2014), $C_\ell^G$ is the best-fit CMB power spectrum (Planck Collaboration XIV 2014), $\ell_{353}$ represents the Planck 353 GHz map, $b_\ell$ is the beam function and $w_\ell$ is the HEALPix pixel window function. We measure the Galactic to CIB emission ratio over patches with $10^\circ$ radius centred on HEALPix pixels at a resolution $N_{\text{side}} = 32$.

The CO, free-free, and synchrotron emission are more important close to the Galactic plane. The first three CO line transitions $J=1\rightarrow 0$, $J=2\rightarrow 1$, and $J=3\rightarrow 2$ at 115, 230, and 345 GHz, respectively, are significant emission components in the Planck intensity maps (Planck Collaboration XIII 2014). The CO mask is defined by applying a threshold of 0.5 K km s$^{-1}$ on the “Type 2” CO $J=1\rightarrow 0$, which is extracted using the Planck data between 70 and 353 GHz (Planck Collaboration XIII 2014).

The free-free emission is weak compared to the CO line emission at 100GHz for most molecular clouds. In massive star-forming regions and for the diffuse Galactic plane emission, the free-free emission is significant (Planck Collaboration Int. XIV 2014). We take the WMAP maximum entropy method free-free map (Bennett et al. 2013) at 94GHz and apply a threshold of 10 $\mu$K (in Rayleigh-Jeans temperature units) to define the free-free mask. In addition, we use the Galactic mask (CS-CR75) from the Planck component separation results (Planck Collaboration XII 2014) to exclude the synchrotron emission from the Galactic plane and the Galactic “haze” (Planck Collaboration Int. IX 2013). We also apply the Planck point source mask (Planck Collaboration XV 2014).

Our mask focuses on the part of the sky where dust is the dominant emission component at HFI frequencies. This choice makes the spectral leakage from free-free and CO line emissions to polarization maps negligible. After masking we are left with 39 % of the sky at intermediate Galactic latitudes ($10^\circ < |b| < 60^\circ$). The same global mask is used for both intensity and polarization correlation analysis to compare results over the same sky.

### 4. Cross-correlation method

We use the CC analysis adopted in many studies (Banday et al. 1996; Gorski et al. 1996; Davies et al. 2006; Page et al. 2007; Ghosh et al. 2012; Planck Collaboration Int. XII 2013) to extract the signal correlated with the 353 GHz template in intensity and polarization. The only underlying assumption is that the spatial structure in the 353 GHz template and in the map under analysis are locally correlated. To reduce this assumption, we apply the CC analysis locally over patches of sky of $10^\circ$ radius (Sect. 4.4). Our choice for the dust template is presented in Sect. 4.1. The methodology is introduced for intensity in Sect. 4.2 and for polarization in Sect. 4.3. The practical implementation of the method is outlined in Sect. 4.4.

#### 4.1. 353 GHz template

We perform the CC analysis locally in the pixel domain using the Planck 353 GHz maps of Stokes parameters as representative internal templates for dust emission in intensity ($I$ with the ZLE subtracted) and polarization ($Q$ and $U$). Our choice of a Planck map as a dust template addresses some of the issues plaguing alternative choices. First, unlike the HI map, the 353 GHz map traces the dust in both HI and H$_2$ gas (Reach et al. 1998; Planck Collaboration XXIV 2011; Planck Collaboration Int. XVII 2014). Second, unlike the full-sky Finkbeiner et al. (1999) 94 GHz (hereafter FDS) map, the 353 GHz map does not rely on an extrapolation over a large frequency range, from 100 $\mu$m to the Planck bands. The main drawback of the 353 GHz template is that it includes CMB and CIB anisotropies. By introducing the global mask, we work with the sky region where the CIB anisotropies are small compared to dust emission. However, the contribution of the CMB to the CC coefficients, most significant at microwave frequencies, needs to be subtracted.

#### 4.2. Intensity

##### 4.2.1. Correlation with the 353 GHz template

For the intensity data, the CC coefficient ($\alpha^I_s$) is obtained by minimizing the $\chi^2$ expression given by,

$$\chi^2_I = \sum_{k=1}^{N_{\text{pix}}} \left[ I_s(k) - \left[ \alpha^I_s \right]_{353} \ell_{353}(k) - \alpha^I \right]^2,$$
where $I_r$ and $I_{353}$ denote the data and the 353 GHz template maps, respectively. This is a linear fit and the solution is computed analytically. Here the CC coefficient is a number in $K_{\text{CMB}}$, $K_{\text{CMB}}^{-1}$, as both $I_r$ and $I_{353}$ are expressed in $K_{\text{CMB}}$ units. The constant offset, $a$, takes into account the local mean present in the template as well as in the data. The sum is over the unmasked pixels, $k$, within a given sky patch. We are insensitive to the residual dipole present at Planck frequencies because we perform local correlation over 10° radius patches. The index ‘1T’ represents the 353 GHz correlated coefficient at a given frequency $\nu$ that we obtained using one template only.

The CC coefficient at a given frequency includes the contribution from all the emission components that are correlated with $\nu$ and computed analytically. Here the CC coefficient is a number in $K_{\text{CMB}}$, $K_{\text{CMB}}^{-1}$, perform local correlation over 10° Planck masked pixels, a constant offset, $a$, from Faraday rotation (Gardner & Whiteoak 1966), we cannot due to the absence of any polarized synchrotron template free from noise, but the Planck 353 GHz polarization templates do contain noise, which may bias the CC coefficients. To circumvent this problem, we use two independent $Q$ and $U$ maps made with the two detector sets DS1 and DS2 at 353 GHz as templates (Sect. 2.1.2). The maps made with each of the two detector sets have independent noise and dust BPM. Using two polarization detector sets at 353 GHz with independent noise realizations reduces the noise bias in the determination of the 353 GHz CC coefficients. We use the detector set maps rather than the half-ring maps because the removal of glitches induces some noise correlation between the two half-ring maps that affects the data at all multipoles (Planck Collaboration VI 2014; Planck Collaboration X 2014).

The polarization CC coefficient ($a_i^p$) is derived by minimizing the $\chi^2$ expression given by

$$
\chi^2_p = \sum_{i=1}^{N_{\text{pix}}} \left[ Q_i(k) - [a_i^{\text{IT}}_{353} Q_{353}(k) - a] \right]^2 + \left[ U_i(k) - [a_i^{\text{IT}}_{353} U_{353}(k) - b] \right]^2 ,
$$

where the index $i$ takes the values 1 and 2, which correspond to the DS1 and DS2 maps at 353 GHz. The summation $k$ is over the unmasked pixels within a given sky patch. The constant offsets $a$ and $b$ take into account the local mean present in the template as well as in the data Stokes $Q$ and $U$ maps, respectively. At 353 GHz, we cross-correlate the DS1 and DS2 maps of $Q$ and $U$ among themselves, minimizing

$$
\chi^2_p = \sum_{i=1}^{N_{\text{pix}}} \sum_{i,j=1}^{N_{\text{pix}}} \left[ Q_{353}(k) - [a_{353}^p Q_{353}(k) - a] \right]^2 + \left[ U_{353}(k) - [a_{353}^p U_{353}(k) - b] \right]^2 .
$$

The CC coefficients, $a_i^p$, comprise the contributions of CMB, dust, synchrotron and possibly AME polarization. The free-free polarization is expected to be negligible theoretically (Rybicki & Lightman 1979) and has been constrained to a few percent observationally (Macellari et al. 2011). The polarization decomposition is given by

$$
[a_{353}^p]_i = a_i^p (c_{353}^1) + a_i^p (d_{353}^1) + a_i^p (f_{353}) + a_i^p (a_{353}) .
$$

The indices ‘2T’ and ‘3T’ are used here to distinguish the CC coefficients for the fit with two and three templates, respectively. The use of additional templates removes the corresponding terms from the right hand side of these equations. Equation (12) is used to derive the mean dust SED in intensity. Equations (8), (11), and (12) may be combined to derive $a_i^p (s_{353})$ and $a_i^p (a_{353})$.

4.3. Polarization

For the polarization data, we cross-correlate both the Stokes $Q$ and $U$ 353 GHz templates with the $Q$ and $U$ maps for all Planck and WMAP frequencies. Ideally in CC analysis, the template is free from noise, but the Planck 353 GHz polarization templates do contain noise, which may bias the CC coefficients. To circumvent this problem, we use two independent $Q$ and $U$ maps made with the two detector sets DS1 and DS2 at 353 GHz as templates (Sect. 2.1.2). The maps made with each of the two detector sets have independent noise and dust BPM. Using two polarization detector sets at 353 GHz with independent noise realizations reduces the noise bias in the determination of the 353 GHz CC coefficients. We use the detector set maps rather than the half-ring maps because the removal of glitches induces some noise correlation between the two half-ring maps that affects the data at all multipoles (Planck Collaboration VI 2014; Planck Collaboration X 2014).

The polarization CC coefficient ($a_i^p$) is derived by minimizing the $\chi^2$ expression given by

$$
\chi^2_p = \sum_{i=1}^{N_{\text{pix}}} \left[ Q_i(k) - [a_i^{\text{IT}}_{353} Q_{353}(k) - a] \right]^2 + \left[ U_i(k) - [a_i^{\text{IT}}_{353} U_{353}(k) - b] \right]^2 ,
$$

where the index $i$ takes the values 1 and 2, which correspond to the DS1 and DS2 maps at 353 GHz. The summation $k$ is over the unmasked pixels within a given sky patch. The constant offsets $a$ and $b$ take into account the local mean present in the template as well as in the data Stokes $Q$ and $U$ maps, respectively. At 353 GHz, we cross-correlate the DS1 and DS2 maps of $Q$ and $U$ among themselves, minimizing

$$
\chi^2_p = \sum_{i=1}^{N_{\text{pix}}} \sum_{i,j=1}^{N_{\text{pix}}} \left[ Q_{353}(k) - [a_{353}^p Q_{353}(k) - a] \right]^2 + \left[ U_{353}(k) - [a_{353}^p U_{353}(k) - b] \right]^2 .
$$

The CC coefficients, $a_i^p$, comprise the contributions of CMB, dust, synchrotron and possibly AME polarization. The free-free polarization is expected to be negligible theoretically (Rybicki & Lightman 1979) and has been constrained to a few percent observationally (Macellari et al. 2011). The polarization decomposition is given by

$$
[a_{353}^p]_i = a_i^p (c_{353}^1) + a_i^p (d_{353}^1) + a_i^p (f_{353}) + a_i^p (a_{353}) .
$$

The indices ‘2T’ and ‘3T’ are used here to distinguish the CC coefficients for the fit with two and three templates, respectively. The use of additional templates removes the corresponding terms from the right hand side of these equations. Equation (12) is used to derive the mean dust SED in intensity. Equations (8), (11), and (12) may be combined to derive $a_i^p (s_{353})$ and $a_i^p (a_{353})$.
4.4. Implementation

Here we describe how we implement the CC method. The Planck, WMAP, HI and DIRBE sky maps are smoothed to a common resolution of 1°, taking into account the effective beam response of each map, and reduced to a HEALPix resolution \( N_{\text{side}} = 128 \). For the Planck and WMAP maps, we use the effective beams defined in multipole space that are provided in the Planck Legacy Archive\(^4\) (PLA) and LAMBDAsite (Planck Collaboration VII 2014; Planck Collaboration IV 2014; Bennett et al. 2013). The Gaussian approximation of the average beam widths for Planck and WMAP maps are quoted in Table 1. For the HI and DIRBE maps, we also use Gaussian beams with the widths given in Table 1. For the polarization data, we use the “isomoothing” routine of HEALPix that decomposes the \( Q \) and \( U \) maps into \( E \) and \( B \) maps, and applies Gaussian smoothing of 1° in harmonic space (after deconvolving the effective azimuthally symmetric beam response for each map), and transforms the smoothed \( E \) and \( B \) maps back into \( Q \) and \( U \) maps at \( N_{\text{side}} = 128 \) resolution.

We divide the intermediate Galactic latitudes into sky patches with 10° radius centred on HEALPix pixels for \( N_{\text{side}} = 8 \). For a much larger radius we would have too few independent sky pixels within a given sky patch to measure the mean dust SED. For a much smaller radius we would have too few sky patches to estimate the statistical uncertainty on the computation of the mean dust SED. Each sky patch contains roughly 1500 pixels at \( N_{\text{side}} = 128 \) resolution. We only consider 400 sky patches (\( N_{\text{bins}} \)), which have 500 or more unmasked pixels. We then cross-correlate the 353 GHz Planck internal template with the WMAP and Planck maps between 23 and 353 GHz, locally in each sky patch to extract the 353 GHz correlated emission in intensity, along with its polarization counterpart. The sky patches used are not strictly independent. Each sky pixel is part of a few sky patches, which is required to sample properly the spatial variations of the CC coefficients. The mean number of times each pixel is used in CC coefficients \((N_{\text{vis}})\) is estimated with the following formula:

\[
N_{\text{vis}} = \frac{N_{\text{bins}} \times \langle N_{\text{pixels}} \rangle}{0.39 \times N_{\text{total}}} \sim 5,
\]

where \( N_{\text{total}} = 12 \times N_{\text{side}}^2 \) is the total number of pixels at 1° resolution, 0.39 is the fraction of the sky used in our analysis and \( \langle N_{\text{pixels}} \rangle = 1000 \) is the average number of pixels per sky patch after masking.

5. Component separation methodology

At the highest frequencies \((\nu \geq 100 \text{ GHz})\) within our mask, the two main contributors to the CC coefficient are the CMB and dust emission. In this section, we detail how we separate them and estimate the spectral index of the dust emission \( (\beta_d) \) in intensity and polarization.

5.1. Separation of dust emission for intensity

The CC coefficients at \( \nu \geq 100 \text{ GHz} \) can be written as

\[
[a_1^{\nu T}]_{353} = a_1^{(c_1^{353})} + a_1^{(d_1^{353})},
\]

where \( c_1^{353} \) and \( d_1^{353} \) are the 353 GHz correlated CMB and dust emission, respectively. The CMB CC coefficient is achromatic in \( K_{\text{CMB}} \) units, i.e., in temperature units relative to the CMB blackbody spectrum. To remove the CMB contribution, we work with the differences of CC coefficients between two given frequencies. To measure the dust spectral index both in intensity and polarization, we choose to work with colour ratios defined between two given frequencies \( \nu_2 \) and \( \nu_1 \) as

\[
R_{\nu_1}(\nu_2, \nu_1) = \frac{[a_1^{\nu_2 T}]_{353} - [a_1^{\nu_1 T}]_{353}}{[a_1^{\nu_2 T}]_{353} - [a_1^{\nu_1 T}]_{353}}
\]

\[
= \frac{a_1^{\nu_2}(d_{353}) - a_1^{\nu_1}(d_{353})}{a_1^{\nu_2}(d_{353}) - a_1^{\nu_1}(d_{353})},
\]

where \( \nu_0 \) represents the reference CMB frequency which is chosen to be 100 GHz in the present analysis. To convert the measured colour ratio into \( \beta_d \) we follow earlier studies (Planck Collaboration Int. XVII 2014; Planck Collaboration XI 2014) by approximating the SED of the dust emission with a modified blackbody (MBB, hereafter) spectrum (Planck Collaboration XXV 2011; Planck Collaboration XXIV 2011; Planck Collaboration XI 2014) given by

\[
a_1^{\nu_2}(d_{353}) = F_2 C_2 A_2 \nu^{\beta_d} B_2(T_d)
\]

\[
a_1^{\nu_1}(d_{353}) = F_1 C_1 A_1 \nu^{\beta_d} B_1(T_d)
\]

where \( T_d \) is the colour temperature and \( \beta_d \) is the spectral index of the dust emission. The factor \( F_2 \) takes into account the conversion from MJy sr\(^{-1}\) (with the photometric convention \( J L_d=\text{constant} \)) to \( K_{\text{CMB}} \) units, while \( C_\nu \) is the colour correction that depends on the value of \( \beta_d \) and \( T_d \). The colour correction is computed knowing the bandpass filters at the HFI frequencies (Planck Collaboration IX 2014) and the spectrum of the dust emission. Using Eq. (19), the colour ratio can be written as a function of \( \beta_d \) and \( T_d \):

\[
R_{\nu_1}(\nu_2, \nu_1) = \frac{F_2 C_2 \nu^{\beta_d} B_2(T_d) - F_1 C_1 \nu^{\beta_d} B_1(T_d)}{F_2 C_2 \nu^{\beta_d} B_2(T_d) - F_1 C_1 \nu^{\beta_d} B_1(T_d)}
\]

\[
= g(\beta_d, T_d).
\]

In Sect. 6.1, we use the three Planck maps, at 100, 217, and 353 GHz, to compute \( R_{\nu_1}(353, 217) \) and measure the dust spectral index \( (\beta_d) \) at microwave frequencies (or mm wavelengths), for each sky patch. In the next section, we explain how we determine \( T_d \).

5.2. Measuring colour temperatures in intensity

The dust temperatures inferred from an MBB fit of the Planck at \( \nu \geq 353 \text{ GHz} \) and the IRAS 100 μm sky maps at 5° resolution (Planck Collaboration XI 2014) cannot be used to compute mean temperatures within each sky patch because the fits are nonlinear. The two frequencies, Planck 857 GHz and DIRBE 100 μm (3000 GHz), which are close to the dust emission peak, are well suited to measure \( T_d \) for each sky patch. We use the Planck 353 GHz map as a template to compute the colour ratio \( R^0(3000, 875) \) over each sky patch, as described in Eq. (18). The superscript 0 on the colour ratio and \( \beta_d \) denote intensity. As the CMB signal is negligible at these frequencies, we work directly with the ratio \( R^0(3000, 875) \), without subtracting the 100 GHz CC measure. We assume a mean dust spectral index at submm frequencies, \( \beta_{d, \text{submm}} \), of 1.50. The choice of \( \beta_{d, \text{submm}} \) value is based on the MBB fit to the dust emissivities at 100 μm and the Planck 353, 545 and 857 GHz frequencies, for each sky patch. Due to the \( \beta_{d, \text{submm}} - T_d \) anti-correlation, the variations of the \( \beta_{d, \text{submm}} \) value just increases the scatter of the \( T_d \) values by about

\(^4\) http://archives.esac.esa.int
20\% as compared to $T_d$ values derived using fixed $\beta^{t}_{d,\text{submm}}$. However, the $T_d$ values from the MBB fits are closely correlated with $T_d$ values determined using the ratio $R(3000, 857)$ and a fixed spectral index. We use the colour ratio $R(3000, 857)$ and mean $\beta^{t}_{d,\text{submm}} = 1.50$ to estimate $T_d$ values for each sky patch by inverting the relation given in Eq. (20).

In Fig. 2, we plot the derived $T_d$ versus the local brightness dispersion of the Planck 353 GHz intensity template, $\sigma^2_{353}$. The mean $T_d$ is 19.6 K, with the 1$\sigma$ dispersion of 0.8 K across sky patches (shaded area).

5 These values are derived from a grey-body fit of dust SED at $\nu \geq 353$ GHz. The error-bar on the dust temperature is associated with that on the spectral index.

the 1$\sigma$ dispersion on the mean value of $\beta^{p}_{d,\text{submm}}$ is 0.16 (syst.). The new value of $\beta^{p}_{d,\text{submm}} = 1.50$ is well within the range of values and systematic uncertainties quoted in Table 3 of Planck Collaboration XI 2014 (using 2013 Planck data) for the same region of the sky.

5.3. Separation of CMB emission in intensity

The CC coefficient, derived in Eq. (8), contains the CMB contribution that is achromatic in $K_{\text{CMB}}$ units. We determine this CMB contribution assuming that the dust emission is well approximated by a MBB simulation from 100 to 353 GHz. For each sky patch, we use the values of $\beta^{t}_{d,\text{mm}}$ and $T_d$ from Sects. 6.1 and 5.2. We solve for two parameters, the CMB contribution, $a^r(c^{3}_{353})$, and the dust amplitude, $A^r_d$, by minimizing

$$\chi^2 = \sum_{\nu} \left( \frac{[a^r_{353}]^{\nu} - a^r(c^{3}_{353}) - F_{\nu} C_{\nu} A^r_d v^{\beta^{t}_{d,\text{mm}}} B_{\nu}(T_d)}{\sigma_{d}^{\nu}} \right)^2,$$

where $\sigma_{d}^{\nu}$ is the uncertainty on the CC coefficient, determined using the Monte Carlo simulations (Appendix B). The joint spectral fit of $a^r(c^{3}_{353})$, $\beta^{t}_{d,\text{mm}}$, $T_d$, and $A^r_d$ leads to a degeneracy between the fitted parameters. To avoid this problem, we fix the values of $\beta^{t}_{d,\text{mm}}$ and $T_d$ for each sky patch based on the colour ratios, independent of the value of $a^r(c^{3}_{353})$. The CMB contributions are subtracted from the CC coefficients at all frequencies, including the LFI and WMAP data not used in the fit. After CMB subtraction, the CC coefficient ($\alpha^r$) for the 353 GHz template is

$$[\alpha^r_{353}] = [a^r_{353}]^{\nu} - a^r(c^{3}_{353}) = a^r_d(d_{353}).$$

We perform the same exercise on the one- and two-template fits to derive the CMB subtracted CC coefficients.

5.4. Separation of dust emission for polarization

As for our analysis of the intensity data, we write the 353 GHz correlated polarized CC coefficients at $\nu \geq 100$ GHz as

$$a^p_{353} = a^p(c^{3}_{353}) + a^p_d(d_{353}),$$

where $c^{3}_{353}$ and $d_{353}$ are the CMB and dust polarization correlated with the 353 polarization templates. The contributions from synchrotron and AME to the polarized CC coefficients are assumed to be negligible at HFI frequencies. Like for intensity in Eq. (20), we compute $R^p_{100}(353, 217)$ combining the three polarized CC coefficients at 100, 217 and 353 GHz. We assume that the temperature of the dust grains contributing to the polarization is the same as that determined for the dust emission in intensity (Sect. 5.2), and derive $\beta^{p}_{d,\text{mm}}$ at microwave frequencies.

To separate the contribution of dust and the CMB to the polarized CC coefficients, we follow the method described in Sect. 5.3, and rely on the Monte Carlo simulations described in Appendix B to estimate uncertainties. The CMB contribution is subtracted at all frequencies, including the LFI and WMAP data.

6. Dust spectral index for intensity

Here we estimate the dust spectral index $\beta^{p}_{d,\text{mm}}$ at microwave frequencies ($\nu \leq 353$ GHz) and mm wavelengths. We present the results of the data analysis and estimate the uncertainties, including possible systematic effects.
6.1. Measuring $\beta_{d,\text{mm}}$

![Graph showing the variation of $\beta_{d,\text{mm}}$ with $\sigma_{353}$](image)

**Fig. 3.** Top: Colour ratio $R_{100}^{353}(353, 217)$ versus dispersion of the 353 GHz template $\sigma_{353}^1$ for each sky patch. The 1$\sigma$ dispersion of the $R_{100}^{353}(353, 217)$ values is shown as the shaded grey area. The mean ratio corresponds to a spectral index of 1.51 (solid line) for a mean $T_d$ = 19.6 K. Bottom: probability distribution function (PDF) of the $\beta_{d,\text{mm}}$ values derived from $R_{100}^{353}(353, 217)$ using the specific value of $T_d$ for each sky patch. The measured 1$\sigma$ dispersion of $\beta_{d,\text{mm}}$ is 0.07.

We use the three full mission Planck maps, at 100, 217, and 353 GHz, to derive a mean $\beta_{d,\text{mm}}$ using the three-template fit, assuming an MBB spectrum for the dust emission (Sect. 5.1). The 217 and 353 GHz maps have the highest signal-to-noise ratio for dust emission at microwave frequencies, whereas the 100 GHz map is used as a reference frequency to subtract the CMB contribution at the CC level. We estimate $R_{100}^{353}(353, 217)$ for each sky patch using the relation given by Eq. (18). The values of $R_{100}^{353}(353, 217)$ are plotted in top panel of Fig. 3 as a function of $\sigma_{353}^1$, which allows us to identify the statistical noise and systematic effects due to uncertainties on the CC coefficients. Our Monte Carlo simulations (Appendix B) show that the uncertainties on $R_{100}^{353}(353, 217)$ scale approximately as the inverse square-root of $\sigma_{353}^1$, and that the scatter in the measured $R_{100}^{353}(353, 217)$ for sky patches with low $\sigma_{353}^1$ is due to data noise.

For each sky patch, we derive $\beta_{d,\text{mm}}$ from $R_{100}^{353}(353, 217)$ by inverting Eq. (20) for the values of $T_d$ derived in Sect. 5.2. The histogram of $\beta_{d,\text{mm}}$ for all sky patches is presented in the bottom panel of Fig. 3. The mean value of $\beta_{d,\text{mm}}$ from the 400 sky patches is 1.514 (round-off to 1.51) with 1$\sigma$ dispersion of 0.065 (round-off to 0.07). The statistical uncertainty on the mean $\beta_{d,\text{mm}}$ is 0.01, which is computed from the 1$\sigma$ deviation divided by the square root of the number of independent sky patches (400/$N_{\text{sky}}$) used. This estimate of the statistical error bar on $\beta_{d,\text{mm}}$ takes into account the uncertainties associated with the chance correlation between the dust template and emission components (CO lines, point sources, the CIB anisotropies and the ZLE) not fitted with templates. It also includes uncertainties on the subtraction of the CMB contribution.

**Table 2.** Dust spectral indices for intensity derived applying the three-template fit on distinct subsets of the Planck data (Sect. 2.1.2). Here the index “Full” refers to the full mission Planck 2014 data, which is used in Sect. 6.1 to produce Fig. 3. The scatter of the seven measurements for the subsets of the Planck data is within the 1$\sigma$ statistical uncertainty on the mean $\beta_{d,\text{mm}}$.

<table>
<thead>
<tr>
<th>Data sets</th>
<th>$\beta_{d,\text{mm}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>1.514</td>
</tr>
<tr>
<td>YR1</td>
<td>1.514</td>
</tr>
<tr>
<td>YR2</td>
<td>1.519</td>
</tr>
<tr>
<td>HR1</td>
<td>1.515</td>
</tr>
<tr>
<td>HR2</td>
<td>1.518</td>
</tr>
<tr>
<td>DS1</td>
<td>1.514</td>
</tr>
<tr>
<td>DS2</td>
<td>1.520</td>
</tr>
</tbody>
</table>

![Graph showing the comparison of $\beta_{d,\text{mm}}$ for different subsets](image)

**Fig. 4.** Same plot as in the bottom panel of Fig. 3, including our results for the subsets of the Planck data listed in Table 2. The bin per bin measurements of $\beta_{d,\text{mm}}$ using subsets of the Planck data are compatible with the one obtained using the full mission data (Sect. 6.1).
6.2. Uncertainties on $\beta_{d,\text{mm}}$

We use the full mission Planck intensity maps as a reference data for the mean dust spectral index value. To assess the systematic uncertainties on the mean spectral index, we repeat our CC analysis on maps made with subsets of the Planck data (Sect. 2.1.2), keeping the same ZLE-subtracted Planck 353 GHz map as a template. For each set of maps, we compute the mean $\beta_{d,\text{mm}}$ from $R_{100}^l(353, 217)$ values. Table 2 lists the $\beta_{d,\text{mm}}$ values derived from the three-template fit applied to each data sub-set. The six measurements of $\beta_{d,\text{mm}}$ from various data splits are within the 1σ statistical uncertainties on the mean intensity dust spectral index. We find a mean dust spectral index $\beta_{d,\text{mm}} = 1.51 \pm 0.01$ (stat.). This spectral index is very close to the mean index of 1.50 at sub-mm wavelengths we derived from MBB fits to the Planck data at $\nu \geq 353$ GHz in Sect. 5.2.

6.3. Dependence of $\beta_{d,\text{mm}}$ on the choice of $\beta_{d,\text{submm}}$

In Fig. 5 we plot $R_{100}^l(353, 217)$ as a function of $\beta_{d,\text{mm}}$ and $T_d$. The central black line corresponds to the median value of $R_{100}^l(353, 217)$ obtained using the CC analysis. Figure 5 shows that varying $T_d$ by $\pm 2$ K, a $\pm 2.5\sigma$ deviation from the mean value, changes $\beta_{d,\text{mm}}$ by $\pm 0.05$. To estimate $\beta_{d,\text{mm}}$ we use $T_d$, which in turn depends on $\beta_{d,\text{submm}}$. We repeat our analysis with two different starting values of $\beta_{d,\text{submm}}$, which are within 1σ systematics uncertainties derived in Sect. 5.2. For the values of $\beta_{d,\text{submm}} = 1.34$ and 1.66, we find $\beta_{d,\text{mm}} = 1.50$ and 1.53, respectively. This is due to the fact that in Rayleigh-Jeans limit, the effect of $T_d$ is low, and the shape of the spectrum is dominated by $\beta_{d,\text{mm}}$. Our determination of mean $\beta_{d,\text{mm}}$ is robust and independent of the initial choice of $\beta_{d,\text{submm}}$ used for the analysis.

![Fig. 5. Variation of $\beta_{d,\text{mm}}$ with $T_d$ for constant values of $R_{100}^l(353, 217)$](image)

To derive the dust spectral index from $R_{100}^l(353, 217)$, we assume an MBB spectrum for the dust emission between 100 and 353 GHz (Sect. 5.1). To validate this assumption, we repeat our CC analysis with Planck maps corrected for CMB anisotropies using the CMB map from the spectral matching independent component analysis (SMICA, Planck Collaboration XII 2014). We infer $\beta_{d,\text{mm}}$ (SMICA) directly from the ratio between the 353 and 217 GHz CC coefficients without subtracting the 100 GHz CC coefficient, i.e.,

$$R_{100}^l(353, 217) = \frac{[\alpha'_{353} T_{353-\text{SMICA}}]}{[\alpha'_{217} T_{353-\text{SMICA}}]},$$

(24)

where $\alpha'$ refers to the CC coefficients computed with maps corrected for CMB anisotropies using the SMICA map. The histogram of the difference between the two sets of spectral indices $\beta_{d,\text{mm}}$ and $\beta_{d,\text{mm}}$ (SMICA) is presented in Fig. 6. The mean difference between the two estimates is zero.

![Fig. 6. Histogram of the difference between the spectral indices $\beta_{d,\text{mm}}$ from Eq. (20) and $\beta_{d,\text{mm}}$ (SMICA) from Eq. (24), where we applied the CC analysis to Planck maps corrected for CMB anisotropies with the SMICA CMB map.](image)

6.5. Comparison with other studies

Our determination of the spectral index $\beta_{d,\text{mm}}$ of the dust emission in intensity at intermediate Galactic latitudes may be compared with the results from similar analyses of the Planck data. In Planck Collaboration Int. XVII (2014), the CC analysis has been applied to the Planck data at high Galactic latitudes ($b < -30^\circ$) using an HI map as a dust template free from CIB and CMB anisotropies. This is a suitable template to derive the spectral dependence of dust emission at high Galactic latitudes. The same methodology of colour ratios has been used in that work. The mean dust spectral index, $\beta_{d,\text{mm}} = 1.53 \pm 0.03$, from Planck Collaboration Int. XVII (2014) agrees with the mean value we find in this paper. In an analysis of the diffuse emission in the Galactic plane, the spectral index of dust at millimetre wavelengths is found to increase from $\beta_{d,\text{mm}} = 1.54$, for lines of sight where the medium is mostly atomic, to $\beta_{d,\text{mm}} = 1.66$, where
the medium is predominantly molecular (Planck Collaboration Int. XIV 2014). The three studies indicate that the spectral index $\beta_{d,mn}$ is remarkably similar over the diffuse ISM observed at high and intermediate Galactic latitudes, and in the Galactic plane.

7. Spectral energy distribution of dust intensity

In this section, we derive the mean SED of dust emission for intensity with its uncertainties from our CC analysis. The detailed spectral modelling of the dust SED is discussed in Sect. 7.2.

7.1. Mean dust SED

We use the full mission Planck maps for the spectral modeling of the dust SED in intensity. The mean SED is obtained by averaging the CC coefficients after CMB subtraction (see Sect. 5.3) over all sky patches. The mean SED is expressed in K$_{\nu}$ units, normalized to 1 at 353 GHz. The three SEDs obtained from the fits with one, two, and three templates are shown in Fig. 7. The SED values obtained with the three templates fit are listed in Table 3. The three SEDs are identical at the highest frequencies. They differ at $\nu < 100$ GHz due to the non-zero correlation between the 353 GHz dust template with synchrotron and free-free emission. At 23 GHz, after CMB correction the CC coefficient from the fit with three templates is lower by 9 and 35 % from those derived from the fits with two and one template, respectively. The 9 % difference accounts for the free-free emission correlated with dust and the 35 % difference for the combination of both synchrotron and free-free emission correlated with dust. At these low frequencies, the fit with three templates provides the best separation of the dust from the synchrotron and free-free emission. It is this SED that we call the dust SED hereafter.

Our dust SED is similar to that measured for the Gould Belt system (Planck Collaboration Int. XII 2013) and at high Galactic latitudes (Planck Collaboration Int. XVII 2014). It shows the thermal dust emission at $\nu \geq 70$ GHz and is dominated by AME at lower frequencies. At WMAP frequencies, our dust SED is similar to that obtained using the FDS 94 GHz map as a dust template in Davies et al. (2006) and Ghosh et al. (2012). The mean dust SED derived using the three-template fit depends on the correction of the DDD H$_{\alpha}$ map for dust scattering and extinction (Dickinson et al. 2003; Witt et al. 2004; Brandt & Draine 2012; Bennett et al. 2013). In Appendix C, we study the impact of both assumptions on the mean dust SED, which are within a few percent at frequencies below 70 GHz and have no impact on frequencies above 100 GHz.

The total uncertainty on the dust SED includes the inter-calibration uncertainties on the data, the statistical uncertainties estimated from the variations of the CC coefficients across the sky patches, and the uncertainties due to the CMB subtraction, as discussed for $\beta_{d,mn}$ in Sect. 6.1. The inter-calibration uncertainties ($c_{\nu}$) for Planck and WMAP data are given in Table 3. The statistical uncertainties are computed from the 1$\sigma$ dispersion of the CC coefficients over the 400 sky patches divided by the square root of the number of independent sky patches (400/N$_{\text{sky}}$). All three types of uncertainty, listed in Table 3, are added together in quadrature to compute the total uncertainty on the mean dust SED. They are shown in Fig. 7, but most do not appear because they are smaller than the size of the symbols.

7.2. Parametric modelling for intensity dust SED

A spectral fit of the dust SED is required to separate the thermal dust emission from the AME. We continue to use an MBB spectrum for the thermal dust emission, and consider two models with different spectra for the AME.

- Model $\text{Di+AI}$: In this first approach, we use the analytical model of the AME (AI) introduced by Bonaldi et al. (2007), which is a parabola in the log $I_{\nu}$ – log $\nu$ plane, parameterized by the peak frequency ($\nu_{p}$) and the slope $-m_{\nu_{p}}$ at 60 GHz. The AME model ($M_{\nu}$) normalized at 23 GHz (in K$_{\nu}$ units)
Table 3. Mean microwave SEDs obtained from the fit with one, two, and three templates using the CC analysis.

<table>
<thead>
<tr>
<th>Experiment Frequency [GHz]</th>
<th>WMAP 23</th>
<th>Planck 28.4</th>
<th>WMAP 33</th>
<th>Planck 44.1</th>
<th>WMAP 61</th>
<th>Planck 70.4</th>
<th>WMAP 94</th>
<th>Planck 100</th>
<th>Planck 143</th>
<th>Planck 217</th>
<th>Planck 353</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle I_{353}^{\nu,1} \rangle$</td>
<td>$1.1202$</td>
<td>$0.5813$</td>
<td>$0.3955$</td>
<td>$0.2223$</td>
<td>$0.1857$</td>
<td>$0.1335$</td>
<td>$0.1361$</td>
<td>$0.1745$</td>
<td>$0.2108$</td>
<td>$0.3058$</td>
<td>$0.5837$</td>
</tr>
<tr>
<td>$\sigma_{\text{stat}}$</td>
<td>$0.0319$</td>
<td>$0.0175$</td>
<td>$0.0126$</td>
<td>$0.0073$</td>
<td>$0.0056$</td>
<td>$0.0038$</td>
<td>$0.0023$</td>
<td>$0.0038$</td>
<td>$0.0023$</td>
<td>$0.0029$</td>
<td>$0.0045$</td>
</tr>
<tr>
<td>$e_{\nu}$ [%]</td>
<td>$1.0$</td>
<td>$1.0$</td>
<td>$1.0$</td>
<td>$1.0$</td>
<td>$1.0$</td>
<td>$1.0$</td>
<td>$0.5$</td>
<td>$1.0$</td>
<td>$0.5$</td>
<td>$1.0$</td>
<td>$0.5$</td>
</tr>
<tr>
<td>$\sigma_{\text{cmb}}$</td>
<td>$0.0086$</td>
<td>$0.0083$</td>
<td>$0.0085$</td>
<td>$0.0083$</td>
<td>$0.0081$</td>
<td>$0.0079$</td>
<td>$0.0077$</td>
<td>$0.0035$</td>
<td>$0.0026$</td>
<td>$0.0015$</td>
<td>$0.0007$</td>
</tr>
<tr>
<td>$\sigma_{\text{tot}}$</td>
<td>$0.0346$</td>
<td>$0.0201$</td>
<td>$0.0156$</td>
<td>$0.0113$</td>
<td>$0.0089$</td>
<td>$0.0044$</td>
<td>$0.0081$</td>
<td>$0.0043$</td>
<td>$0.0041$</td>
<td>$0.0055$</td>
<td>$0.0119$</td>
</tr>
<tr>
<td>$C$</td>
<td>$32.3$</td>
<td>$29.0$</td>
<td>$25.3$</td>
<td>$19.7$</td>
<td>$18.6$</td>
<td>$15.1$</td>
<td>$21.6$</td>
<td>$49.3$</td>
<td>$74.3$</td>
<td>$106.9$</td>
<td>$83.9$</td>
</tr>
<tr>
<td>$U$</td>
<td>$1.0732$</td>
<td>$1.0000$</td>
<td>$1.0270$</td>
<td>$1.0480$</td>
<td>$1.0000$</td>
<td>$1.0450$</td>
<td>$0.9810$</td>
<td>$0.9927$</td>
<td>$1.0877$</td>
<td>$1.0191$</td>
<td>$1.1203$</td>
</tr>
<tr>
<td>$\langle I_{353}^{\nu,2} \rangle$</td>
<td>$0.9864$</td>
<td>$0.9487$</td>
<td>$0.9723$</td>
<td>$0.9577$</td>
<td>$0.9328$</td>
<td>$0.9091$</td>
<td>$0.8484$</td>
<td>$0.7998$</td>
<td>$0.7942$</td>
<td>$0.5921$</td>
<td>$0.3343$</td>
</tr>
</tbody>
</table>

The predicted signal-to-noise ratio on the mean dust SED.

The total uncertainty on the mean dust SED in $K_{\text{RJ}}$ units, normalized to 1 at 353 GHz, from the fit with three templates. The values are not colour corrected.

$\sigma_{\text{tot}}$ is statistical uncertainty on the mean dust SED.

c$_{\nu}$ is uncertainties on the inter-calibration [%] between Planck and WMAP frequencies (Planck Collaboration I 2014; Bennett et al. 2013).

$\sigma_{\text{cmb}}$ is uncertainty on the mean dust SED introduced by the CMB subtraction multiplied by the inter-calibration factor $c_{\nu}$.

$\sigma_{\text{tot}}$ is total uncertainty on the mean dust SED.

$S/N$ is signal-to-noise ratio on the mean dust SED.

$C$ is colour-correction factors computed with a linear combination of the power-law model and the MBB parameters listed in Table 4.

$U$ is unit conversion factors from thermodynamic (KMB) to Rayleigh-Jeans (K$_{\text{RJ}}$) temperature.

$\langle I_{353}^{\nu,1} \rangle$ is mean dust SED in $K_{\text{RJ}}$ units, normalized to 1 at 353 GHz, from the correlation of the maps with the one-template fit. The values are not colour corrected.

$\sigma_{\text{tot}}^{\nu}$ is total uncertainty on the mean dust SED with the one-template fit.

$\langle I_{353}^{\nu,2} \rangle$ is mean dust SED in $K_{\text{RJ}}$ units, normalized to 1 at 353 GHz, derived from the correlation of the maps with the two-template fit. The values are not colour corrected.

$\sigma_{\text{tot}}^{\nu}$ is total uncertainty on the mean dust SED with the two-template fit.

is given by:

$$
\log M_s = -\left( \frac{m_{60} \log \nu_p}{\log(\nu_p/60 \, \text{GHz})} + 2 \right) \log \left( \frac{\nu}{23 \, \text{GHz}} \right) + \frac{m_{60}}{2 \log(\nu_p/60 \, \text{GHz})} \left[ (\log(\nu/1 \, \text{GHz}))^2 - (\log 23)^2 \right].
$$

This model is a good fit to spectra of dipole emission from small spinning dust particles computed with the SPUDUST code (Ali-Haïmoud et al. 2009; Silsbee et al. 2011). The second component is the MBB spectrum of the thermal dust emission (DI) with free parameter $\beta_{d,\text{mm}}^\theta$. The model is written in $K_{\text{RJ}}$ units normalized to 1 at the frequency $\nu_{\text{ref}} = 353$ GHz:

$$
\langle I_{353}^{\nu,1} \rangle = A_{1,d} M_s \left( \frac{\nu_{\text{ref}}}{\nu} \right)^{\beta_{d,\text{mm}}^\theta} B_s(T_d) B_\nu(T_d),
$$

where $A_{1,d}$ is the amplitude of AME and $\beta_{d,\text{mm}}^\theta$ is the spectral index of thermal dust emission at microwave frequencies. We fix $T_d = 19.6$ K from Sect. 5.2. The four free parameters of the model are $A_{1,d}, m_{60}, \nu_p$ and $\beta_{d,\text{mm}}^\theta$.

Model DI+AII: In this second approach, the AME component (All) is a linear combination of two spinning dust components arising from the typical cold neutral medium (CNM) and warm neutral medium (WNM). In our analysis, we use the predicted SPUDUST (v2) spectra (Ali-Haïmoud et al. 2009; Silsbee et al. 2011) of the CNM and WNM spinning dust components. Following the work of Hoang et al. (2011) and Ghosh et al. (2012), we shift both the WNM and CNM spectra in frequency space to fit the observed dust SED. The same DI model of the thermal dust emission is considered for this model. In this case, the spectral model is given in $K_{\text{RJ}}$ units, normalized to 1 at the frequency $\nu_{\text{ref}}$, by:

$$
\langle I_{353}^{\nu,1} \rangle = A_{1,w} D_{\text{WNM}}(\nu - \Delta \nu_{\text{WNM}}) + A_{1,c} D_{\text{CNM}}(\nu - \Delta \nu_{\text{CNM}}) + \left( \frac{\nu}{\nu_{\text{ref}}} \right)^{\beta_{d,\text{mm}}^\theta} B_s(T_d) B_\nu(T_d),
$$

where $A_{1,w}$ is the amplitude of WNM spectrum normalized at 23 GHz, $A_{1,c}$ is the amplitude of CNM spectrum normalized at 41 GHz, $D_{\text{WNM}}$ is the SPUDUST WNM spectrum, $D_{\text{CNM}}$ is the SPUDUST CNM spectrum, $\Delta \nu_{\text{WNM}}$ is the shift in the WNM spectrum, $\Delta \nu_{\text{CNM}}$ is the shift in the CNM spectrum, $\nu_{\text{ref}} = 353$ GHz is the reference frequency, $\beta_{d,\text{mm}}^\theta$ is the spectral index of the thermal dust emission. We fix $\beta_{d,\text{mm}}^\theta = 1.51$ from Sect. 6.2 and $T_d = 19.6$ K from Sect. 5.2. The four free parameters of the model are the WNM amplitude, the WNM frequency shift, the CNM amplitude and the CNM frequency shift.

The fits of the dust SED with models DI+AI and DI+AII are shown in Fig. 8. The best fit model parameters are listed in Table 4.

8. Dust spectral index for polarization

We now move to the analysis of the polarization data. Like in Sect. 6, we estimate the polarized dust spectral index ($\beta_{d,\text{mm}}^\theta$) at microwave frequencies ($\nu \leq 353$ GHz). We present the results of
Fig. 8. Mean dust SED in K$_{AB}$ units, normalized to 1 at 353 GHz, with different spectral fits and the respective residuals. The two parametric model fits are DI+AI (top left), and DI+All (bottom left), as presented in Sect. 7.2. Right: residuals after removing the best fit model listed in Table 4, from the mean dust SED. The two spectral models provide good fit to the data, with residuals compatible with zero.

Table 4. Results of the spectral fits to the mean dust SED in intensity using Planck and WMAP maps.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DI+AI</th>
<th>Parameters</th>
<th>DI+All</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{d,mm}^{\text{in}}$ . . . . .</td>
<td>1.52 ± 0.01</td>
<td>$A_{\text{WMN}}^{\text{in}}$ . . . . .</td>
<td>1.12 ± 0.04</td>
</tr>
<tr>
<td>$A_p^{\text{in}}$ [GHz]</td>
<td>1.14 ± 0.04</td>
<td>$\nu_{\text{WMN}}^{\text{in}}$ [GHz]</td>
<td>−1.7 ± 0.8</td>
</tr>
<tr>
<td>$m_{350}^{\text{in}}$ . . . . .</td>
<td>9.5 ± 6.9</td>
<td>$A_{\text{CNM}}^{\text{in}}$ . . . . .</td>
<td>0.07 ± 0.01</td>
</tr>
<tr>
<td>$\Delta T^{\text{in}}$ [GHz]</td>
<td>1.81 ± 0.38</td>
<td>$\Delta T_{\text{CNM}}^{\text{in}}$ [GHz]</td>
<td>22.2 ± 1.6</td>
</tr>
<tr>
<td>$\chi^2/N_{\text{tot}}$ . . . . .</td>
<td>2.4/8</td>
<td>$\chi^2/N_{\text{tot}}$ . . . . .</td>
<td>8.7/8</td>
</tr>
</tbody>
</table>

The parameters listed in this table are described in Eqs. (26) and 27, where the dust SED is expressed in K$_{AB}$ units and normalized to 1 at 353 GHz. The fixed model parameter is $T_d = 19.6$ K for two intensity models.

8.1. Measuring $\beta_{d,mm}^{\text{pol}}$

Here we use the full mission Planck polarization maps, keeping the polarized detector set maps (DS1 and DS2) at 353 GHz as fixed templates, to derive a mean $\beta_{d,mm}^{\text{pol}}$ using the one-template fit. Using the polarization CC coefficients, $[\alpha_{P}^{\text{in}}]_{353}$, we compute $R_{100}^{\text{p}}(353, 217)$ for each sky patch using Eq. (18). Fig. 9 shows the values of $R_{100}^{\text{p}}(353, 217)$ versus the local dispersion of the polarized map at 353 GHz ($\sigma_{P}^{353}$) for all the sky patches. To compute $\sigma_{P}^{353}$, we use a 1° smoothed map of $P_{353}$ derived in Planck Collaboration Int. XIX (2015). We derive $\beta_{d,mm}^{\text{pol}}$ for each sky patch from $R_{100}^{\text{p}}(353, 217)$, taking into account the local estimate of $T_d$ derived from $R_{100}^{\text{p}}(3000, 857)$ (Sect. 5.2). We assume that the temperature of the dust grains contributing to the polarization is the same as that determined for the dust emission in intensity. This is not necessarily true if the polarization is associated with specific dust grains, e.g., the silicates versus carbon dust (Martin 2007; Draine & Fraisse 2009). This should be kept in mind in thinking of physical interpretations. Here we use the spectral indices $\beta_{d,mm}^{\text{pol}}$ and $\beta_{d,mm}^{\text{int}}$ as a mathematical way to quantify the difference between the dust SED for intensity and polarization.
The scatter on the $R_{100}^P(353, 217)$ values increases for $\sigma_{353}^P < 20 \mu K$ due to data noise. The histogram of $\beta_{d,mm}^P$ from the 400 sky patches is presented in Fig. 9. The distribution of $\beta_{d,mm}^P$ has a mean value of 1.592 (round-off to 1.59), with a 1σ dispersion of 0.174 (round-off to 0.17). This dispersion is the same if we use the mean dust temperature of 19.6 K for all sky patches. The statistical uncertainty on the mean $\beta_{d,mm}^P$ is computed from the 1σ dispersion divided by the square root of the number of independent sky patches (400/$N_{visit}$) used, which is 0.02.

The mean value of the dust spectral index for polarization is different from that for intensity, $1.51 \pm 0.01$ (Sect. 6) over the same sky area. In the next section, we check whether the difference of spectral indices in intensity and polarization is a robust result against systematics present in the polarization data.

Table 5. Polarized dust spectral indices derived using multiple subsets and templates of the Planck data. The full mission Planck polarization data along with the DS1 and DS2 templates (first entry in the Table below) is used in Sect. 8.1 to produce Fig. 9. The scatter of the 20 measurements is consistent with the 1σ statistical uncertainty on the mean value of $\beta_{d,mm}^P$.

<table>
<thead>
<tr>
<th>Templates</th>
<th>Data sets</th>
<th>$\beta_{d,mm}^P$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.592</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.595</td>
</tr>
<tr>
<td>DS1 and DS2</td>
<td>HR2</td>
<td>1.595</td>
</tr>
<tr>
<td></td>
<td>YR1</td>
<td>1.619</td>
</tr>
<tr>
<td></td>
<td>YR2</td>
<td>1.592</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.602</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.603</td>
</tr>
<tr>
<td>YR1 and YR2</td>
<td>HR2</td>
<td>1.606</td>
</tr>
<tr>
<td></td>
<td>DS1</td>
<td>1.564</td>
</tr>
<tr>
<td></td>
<td>DS2</td>
<td>1.627</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.613</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.579</td>
</tr>
<tr>
<td>HR1 and HR2</td>
<td>DS2</td>
<td>1.639</td>
</tr>
<tr>
<td></td>
<td>YR1</td>
<td>1.639</td>
</tr>
<tr>
<td></td>
<td>YR2</td>
<td>1.614</td>
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<td></td>
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<td>1.578</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.560</td>
</tr>
<tr>
<td>S1+S3 and S2+S4</td>
<td>HR1</td>
<td>1.590</td>
</tr>
<tr>
<td></td>
<td>HR2</td>
<td>1.581</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.588</td>
</tr>
</tbody>
</table>

8.2. Uncertainties in $\beta_{d,mm}^P$

For the mean polarized dust spectral index, we use the results from full mission Planck polarization maps with the two detector set maps as fixed templates (Sect. 8.1). To estimate the systematic uncertainty for the mean $\beta_{d,mm}^P$, we apply the CC analysis on multiple subsets of the Planck data, including the combination of yearly maps (YR1 and YR2), the full mission half-ring maps (HR1 and HR2), the combination of odd surveys (S1+S3) and even surveys (S2+S4), and the detector set maps (DS1 and DS2) (see Sect. 2.1.2 for more details). We use these subsets of the data as maps and templates at 353 GHz. Table 5 lists the derived mean $\beta_{d,mm}^P$, for all the sky patches from each combination of the data subsets. The dispersion of the $\beta_{d,mm}^P$ values in Table 5, 0.02, is consistent with the 1σ dispersion on the mean polarization spectra index from statistical uncertainties estimated in Sect. 8.1, making it difficult to separate the contributions from the statistical noise and the data systematics. Therefore, we use the 1σ dispersion from the subsets of the Planck data, as listed in Table 5, as a combine statistical and systematic uncertainties on the mean value of $\beta_{d,mm}^P$. Thus, we find $\beta_{d,mm}^P = 1.59 \pm 0.02$ (stat+syst.).

The small difference, 0.08, between $\beta_{d,mm}^P$ and $\beta_{d,mm}^I$, has a 3.6σ significance, taking into account the total uncertainty on both $\beta_{d,mm}^P$ and $\beta_{d,mm}^I$.

9. Spectral energy distribution of dust polarization

We now derive the mean SED for the dust polarization and extend to polarization the parametric modelling already made on the dust SED in intensity (Sect. 7.2).

![Fig. 9. Top: Colour ratio $R_{100}^P(353, 217)$ against the local dispersion of the polarization template at 353 GHz. Bottom: Histogram of the $\beta_{d,mm}^P$ values inferred from $R_{100}^P(353, 217)$ for all sky patches. The mean value of the spectral index for polarization is 1.59 ± 0.02, which is different from that for intensity 1.51 ± 0.01 (Fig. 3).](image-url)
9.1. Mean polarized SED

We use the full mission Planck maps for the spectral modelling of the dust SED in polarization. Like in Sect. 7.1 for dust emission in intensity, the mean SED for polarization is obtained by averaging the polarization CC coefficients after CMB subtraction (see Sect. 5.3) over all sky patches and is expressed in $K_B$ units. The polarization SED is derived from the one-template fit, keeping the templates fixed to the polarized detector set maps (DS1 and DS2) at 353 GHz (see Sect. 4.3 for more details). We compute the mean polarization SED and its uncertainties in a similar manner to that discussed in Sect. 7. The mean polarized SED and associated uncertainties are listed in Table 6, and is shown in Fig. 11.

The polarization SED first decreases with decreasing frequency, then turns up below 60 GHz. This is the first time that such a behavior has been observed for polarized emission correlated with dust polarization, though it has been seen before for the total sky polarization (Bennett et al. 2013).

9.2. Low frequency rise of the polarization SED

In this section, we show that a synchrotron component correlated with dust is the most likely interpretation for the low frequency rise of the polarization SED.

9.2.1. Synchrotron polarization correlated with dust

The polarized dust and synchrotron emissions may be written as

\[ Q^p, U^p = p_s I_s^p \cos 2\psi_s, \sin 2\psi_s, \]

\[ Q^d_{353}, U^d_{353} = p_d I_d^d_{353} \cos 2\psi_d, \sin 2\psi_d, \]

where $p_s$ and $p_d$ are the polarization fractions, and $\psi_s$ and $\psi_d$ are the polarization angles, for synchrotron and dust, respectively. After correlation with the 353 GHz $I, Q$ and $U$ templates, we have

\[ \langle \alpha^s_{\nu}(353) \rangle \leq \frac{p_s}{p_d} \langle \alpha^d_{\nu}(353) \rangle, \]

where $\langle \alpha^s_{\nu}(353) \rangle$ and $\langle \alpha^d_{\nu}(353) \rangle$ are the mean SEDs of the synchrotron emission correlated with dust in intensity and polarization. The upper limit in Eq. (30) is obtained when the synchrotron and dust polarization angles are identical, which is not what is observed comparing the Planck 353 GHz $I, Q$ and $U$ templates data (Planck Collaboration Int. XIX 2015).

Both emission processes trace the same large-scale Galactic magnetic field (GMF), but they give different weights to different parts of the line of sight. The CC analysis only keeps the synchrotron emission that arises from the same volume of interstellar space as the dust emission. For example, it is expected to filter out the synchrotron emission from the Galactic halo, where there is little dust. Thus, to validate our interpretation of the low frequency rise of the polarization SED with synchrotron and no AME polarization, we need to show that the upper limit in Eq. (30) holds.

The intrinsic polarization of synchrotron emission is about 75% for typical relativistic electron spectra (Rybicki & Lightman 1979; Longair 1994), whereas the analysis of Planck polarization maps indicates that the intrinsic polarization of dust at 353 GHz can reach about 20% (Planck Collaboration Int. XIX 2015; Planck Collaboration Int. XX 2015). To compute the synchrotron SED in intensity, $\langle \alpha^s_{\nu}(353) \rangle$, we combine the 353 GHz correlated CC coefficients, corrected for the CMB (Sect. 5.3), obtained from the fits with one and two templates (Sect. 4.2).

The SED of the synchrotron emission correlated with dust is then obtained by taking the difference between the CC coefficients in Eqs. (8) and (11), and averaging over all sky patches. It is shown in Fig. 10. We fit this synchrotron SED with a power-law (PL) model. The normalized amplitude of synchrotron emission at 23 GHz is $A_1 = 0.30$. This is the ratio between the 23 and 353 GHz emission in units of $K_B$. The mean synchrotron spectral index derived from the fit is $\beta_1 = -3.04 \pm 0.36$. The uncertainty on $\beta_1$ is overestimated as the uncertainties on the synchrotron SED are highly correlated across all WMAP and Planck frequencies. However, this is not critical for our study because we do not use the uncertainty on $\beta_1$ in the paper. The derived mean $\beta_1$ of the dust-correlated synchrotron emission is consistent with the spectral index of 408-MHz-correlated synchrotron emission obtained using WMAP data (Miville-Deschênes et al. 2008; Dickinson et al. 2009; Gold et al. 2011; Ghosh et al. 2012), and the spectral index of the polarized synchrotron emission (Fuskeland et al. 2014).

Using $\langle \alpha^d_{\nu}(353) \rangle$, we find the theoretical upper limit on $\langle \alpha^s_{\nu}(353) \rangle$ to be

\[ \langle \alpha^s_{\nu}(353) \rangle \leq \frac{0.75}{0.20} \times 0.30 = 1.1. \]

The measured value of $\langle \alpha^s_{\nu}(353) \rangle$ is 0.95 (shown in Fig. 11), which is within the upper limit. The difference between the measured and theoretical upper limit in Eq. (30) can be explained by the fact that polarization angles traced by synchrotron and dust emission are not perfectly aligned. We point out that this statement refers to the synchrotron emission correlated with the dust template in intensity, which is not one to one correlated with dust in polarization.

9.2.2. Upper limit on AME polarization

We can set an upper limit on the polarization fraction of AME by assuming that the synchrotron and dust polarization are totally uncorrelated. Within this hypothesis, the low frequency rise of the polarization SED is entirely due to polarized AME. Since
Table 6. Mean microwave SED for polarization computed using the CC analysis.

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>WMAP 23</th>
<th>Planck 28.4</th>
<th>WMAP 33</th>
<th>Planck 41</th>
<th>WMAP 44.1</th>
<th>Planck 61</th>
<th>WMAP 70.4</th>
<th>Planck 94</th>
<th>WMAP 100</th>
<th>Planck 143</th>
<th>Planck 217</th>
<th>Planck 353</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>WMAP</td>
<td>Planck</td>
<td>WMAP</td>
<td>Planck</td>
<td>WMAP</td>
<td>Planck</td>
<td>WMAP</td>
<td>Planck</td>
<td>WMAP</td>
<td>Planck</td>
<td>WMAP</td>
<td>Planck</td>
</tr>
<tr>
<td>⟨αPν⟩1T353</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>⟨[αPν⟩1T353⟩</td>
<td>0.9481</td>
<td>0.4038</td>
<td>0.3351</td>
<td>0.1793</td>
<td>0.1525</td>
<td>0.1179</td>
<td>0.1129</td>
<td>0.1852</td>
<td>0.1900</td>
<td>0.3029</td>
<td>0.5624</td>
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</tr>
<tr>
<td></td>
<td>0.1201</td>
<td>0.0538</td>
<td>0.0402</td>
<td>0.0292</td>
<td>0.0190</td>
<td>0.0118</td>
<td>0.0118</td>
<td>0.0261</td>
<td>0.0050</td>
<td>0.0048</td>
<td>0.0062</td>
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</tr>
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<td>cν [%]</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>σν/stat</td>
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<td>0.0006</td>
<td>0.0006</td>
<td>0.0006</td>
<td>0.0006</td>
<td>0.0000</td>
<td>0.0003</td>
<td>0.0005</td>
<td>0.0002</td>
<td>0.0002</td>
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</tr>
<tr>
<td>σtot</td>
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<td>0.0262</td>
<td>0.0051</td>
<td>0.0050</td>
<td>0.0067</td>
<td>0.0114</td>
</tr>
<tr>
<td>S/N</td>
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<td>7.5</td>
<td>8.3</td>
<td>6.1</td>
<td>8.0</td>
<td>5.9</td>
<td>9.6</td>
<td>7.1</td>
<td>37.1</td>
<td>60.4</td>
<td>83.6</td>
<td>87.7</td>
</tr>
</tbody>
</table>

⟨[αPν⟩1T353⟩ ≡ Mean polarization SED in K$_{RJ}$ units, normalized to 1 at 353 GHz, from the correlation with the 353 GHz templates. The values are not colour corrected.

σν/stat ≡ Statistical uncertainty on the mean polarization SED.

cν ≡ Uncertainties on the inter-calibration [%] between Planck and WMAP frequencies (Planck Collaboration I 2014; Bennett et al. 2013).

σν/tot ≡ Uncertainty on the mean polarized SED introduced by the CMB-subtraction multiplied by the inter-calibration factor cν.

σν/tot ≡ Total uncertainty on the mean polarized SED.

Fig. 11. Mean polarized SED in K$_{RJ}$ units, normalized to 1 at 353 GHz correlated with the Stokes $Q$ and $U$ 353 GHz maps. The polarized spectral model with and without the constraint on $\beta^P_s$ match the observed data points.

both AME and thermal dust emission are associated with interstellar matter, it is reasonable to assume that the polarization angles are the same for AME and dust. We obtain the 353 GHz correlated AME polarization at 23 GHz as,

$$\langle [\alpha^P_{23}]_{353} \rangle = \langle a^P_{23} (a_{353}) \rangle \approx p_a \langle a^I_{23} (a_{353}) \rangle,$$

i.e., $0.95 = p_a \langle a^I_{23} (a_{353}) \rangle$, so

$$p_a = \frac{0.95}{\langle a^I_{23} (a_{353}) \rangle} \approx \frac{p_a \times 0.95}{A^I_a}.$$

(32)
We use the mean AME amplitude, $A_\nu^p = 1.14$, from model DI+AI and Table 4, together with $\rho_d = 20\%$ (Planck Collaboration Int. XIX 2015; Planck Collaboration Int. XX 2015), to derive an upper limit on the intrinsic polarization fraction of AME of about 16%. This is much higher than upper limits reported from the analysis of compact sources (Dickinson et al. 2011; López-Caraballo et al. 2011; Rubiño-Martín et al. 2012) and theoretical predictions (Lazarian & Draine 2000; Hoang et al. 2013). Thus AME is unlikely to be the sole explanation for the low frequency rise of the polarization SED, even if we cannot exclude some contribution from AME.

### 9.3. Parametric modelling for polarized dust SED

In this section we present a spectral model that fits the observed polarization SED. We model the polarization SED with a combination of polarized synchrotron and dust components. This model does not include AME. We account for the rise of the SED towards the lowest frequencies with the synchrotron component. For the synchrotron component we use the PL model with two parameters: the amplitude; and the spectral index. The PL model does not include AME. We account for the rise of the SED for model with and without the constraint on $\beta_p^s$ are shown in Fig. 11. The parameters for the best-fit models are listed in Table 7. The two models provide very similar fits to the observed polarized SED. If we force the spectral indices of the synchrotron for intensity and polarization to be equal, we find an equally good fit to the polarization SED. These results are further discussed in the next section.

### 10. Comparison of the dust SEDs for intensity and polarization

We now compare the dust SEDs for intensity and polarization and discuss the frequency dependence of the polarization fraction within the context of existing dust models.

#### 10.1. Spectral dependence of the polarization fraction

Figure 12 presents the dust SEDs for intensity and polarization derived from the spectral decomposition in emission components (Sects. 7.2 and 9.3). The SED for intensity, obtained after AME subtraction, is shown in the top panel of Fig. 12 from 70 to 353 GHz. The two sets of data points computed for each of the two AME models are very close to each other. The dust SED for polarization, obtained after subtraction of the synchrotron component, is shown in the middle panel of Fig. 12. The data points are plotted for the two spectral indices in Table 7, which differ by 0.4. The small difference between the corresponding points shows that the subtraction of the synchrotron component has a very small impact on the dust polarization SED even at 70 GHz. This indicates that our dust polarization SED is robust with respect to uncertainties on the spectral index of polarized synchrotron, including a possible steepening of the spectrum with increasing frequencies as discussed in Gold et al. (2011). The polarization fraction, shown in the bottom panel of Fig. 12, is normalized with respect to the data point at 353 GHz. The uncertainties on $p$ include the uncertainties from both $P$ and $I$. The data suggest that there is a small decrease in $p$ by 21 ± 6% from 353 to 70 GHz.

#### 10.2. The contribution of carbon dust and silicates to polarization

The results of this work set new observational constraints on dust models including silicate and carbon grains with possibly different polarization properties (Hildebrand et al. 1999; Martin 2007). We discuss the spectral dependence of $p$ using the models from Draine & Li (2007), Compiègne et al. (2011), and Jones et al. (2013). In these three models, the thermal dust emission is the electric dipole emission from two types of grains, silicates and carbon grains, with distinct optical properties and thereby temperatures. The first two models use the same optical properties for silicates, but distinct properties for carbon grains; Draine & Li (2007) use the optical properties of graphite, while Compiègne et al. (2011) use results from laboratory measurements of amorphous carbon. The spectral index for carbon grains is 2 in the Draine & Li (2007) model and 1.6 in Compiègne et al. (2011). Over microwave frequencies, the opacity of silicates scales as $\nu^{1.6}$ in both models. Jones et al. (2013) use optical properties of amorphous carbon grains, which depend on the hydrogen fraction and degree of aromatization (Jones 2012). The spectral index of the carbon dust at 353 GHz varies between 1.2 and 2.3, depending on the nature of the carbon grains (see Fig. 14 of Jones et al. 2013 for more details).

SEDs from the first two models have been compared to the Planck dust SED in intensity in Planck Collaboration Int. XVII (2014) and Planck Collaboration Int. XXIX (2014). The differences between the model and the data are within 5–15% at $\nu < 353$ GHz. Draine & Fraise (2009) have used the Draine & Li (2007) dust model to compute spectra for dust polarization. They predict a systematic increase of the polarization fraction $p$ at microwave frequencies when only silicates contribute to dust polarization. This prediction is not what we report in this paper.

### Table 7. Results of the spectral fits to the mean polarized dust SED obtained using Planck and WMAP data.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unconstrained $\beta_p^s$</th>
<th>Fixed $\beta_p^s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\nu^s$</td>
<td>0.97 ± 0.10</td>
<td>0.86 ± 0.06</td>
</tr>
<tr>
<td>$\rho_d^s$</td>
<td>−3.40 ± 0.28</td>
<td>−3.04</td>
</tr>
<tr>
<td>$\beta_d^s_{\text{mm}}$</td>
<td>1.57 ± 0.01</td>
<td>1.58 ± 0.01</td>
</tr>
<tr>
<td>$\chi^2$/N.D.O.</td>
<td>6.6/9</td>
<td>8.6/10</td>
</tr>
</tbody>
</table>

* The parameters of the model PSI+PDI are described in Eq. (33) for fixed $T_d = 19.6\,\text{K}$, where the dust SED is expressed in K$_\text{RJ}$ units and normalized to 1 at 353 GHz.
However, model predictions for the spectral dependency of $p$ are related to the difference in spectral index between carbon and silicate grains, which is not known. Thus, a difference between carbon and silicate polarization may be the correct physical interpretation of the spectral dependence of $p$, even if the data do not match the Draine & Fraisse (2009) model.

Calculations of the polarized SED for the Compiègne et al. (2011) and Jones et al. (2013) models are needed to assess quantitatively this interpretation. In the Compiègne et al. (2011) model, the spectra from silicates and carbon grains are very similar at long wavelengths and we do not expect $p$ to depend on wavelength when only silicates contribute to the polarization. In the Jones et al. (2013) model the contribution from carbon dust grains could be dominant at $\nu < 353$ GHz.

10.3. Microwave dust emission

The dust SED in polarization and the spectral dependence of $p$ allows us to discuss two possible interpretations of the dust microwave emission.

Meny et al. (2007) introduced a physical description of FIR/microwave dust emission, where the microwave dust opacity of amorphous grains is dominated by low energy transitions associated with disorder in the structure of the solids on atomic scales. This contribution is modelled by transitions in two-level systems (TLS). The TLS model is supported by experimental results on silicates (Agladze et al. 1996; Boudet et al. 2005; Coupeaud et al. 2011), which indicate that the opacity of amorphous silicate grains flattens towards long wavelengths. The TLS model has been used to model dust emission spectra by Paradis et al. (2011). It was also proposed as a possible interpretation of the flattening of the dust SED in intensity from FIR to mm wavelengths, which was reported in two earlier Planck papers on the diffuse dust emission in the Galactic plane in Planck Collaboration Int. XVII (2014) and at high Galactic latitudes in Planck Collaboration Int. XVII (2014). Our analysis based on new Planck data does not confirm this flattening, but does not dismiss it either because the error-bars on the submm spectral index from calibration uncertainties remain significant: 0.16 ($1\sigma$) from Sect. 5.2. Within the TLS model, a flattening of the dust SED in intensity would be due to a decrease in the spectral index of silicate grains at long wavelengths. Since silicate grains are polarized, the flattening of the dust SED should also be seen in polarization. This expectation is not supported by the results of our data analysis, namely the difference in spectral indices of the thermal dust emission in intensity and polarization ($\beta_{1,\text{mm}}^{\text{mm}}$ and $\beta_{2,\text{mm}}^{\text{mm}}$) reported in Sect. 8.2.

MDE has been introduced by Draine & Hensley (2012) to explain the flattening of the dust SED at sub-mm wavelengths in the Small Magellanic Cloud (Planck Collaboration XVII 2011). MDE could also contribute to the long wavelength emission of Galactic dust. Model spectra of MDE are presented in Draine & Hensley (2013) for Galactic dust. The contribution of MDE could be significant at frequencies smaller than a few hundred GHz and increasing towards smaller frequencies. If the magnetic particles are inclusions randomly-oriented within interstellar grains, their emission is polarized in a direction perpendicular to that of the dipolar electric emission (Draine & Hensley 2013). In this case, we expect this emission component to reduce the polarization of the dust emission. This could possibly account for the observed decrease in $p$ from 353 to 70 GHz.

Fig. 12. Frequency dependence of the dust SED in intensity without AME (top), in polarization without synchrotron (middle), and the polarization fraction (bottom) for the four different combinations of dust models. The SEDs are plotted in units of $K_{\text{Bd}}$ and normalized to 1 at 353 GHz. The shaded areas represent $1\sigma$ (green), $2\sigma$ (yellow), and $3\sigma$ (grey) statistical uncertainty on the mean normalized polarization fraction. We used the mean spectra from the same 400 sky patches for both the intensity and polarization analysis.
A fit of the SEDs in polarization and intensity with the models of Paradis et al. (2011) and Draine & Hensley (2013) would be necessary to test these two interpretations quantitatively.

11. Conclusion

We have characterized the frequency dependence of dust emission in intensity and polarization by analysing Planck data over 39% of the sky at intermediate Galactic latitudes. We use the Planck 353 GHz $I$, $Q$, and $U$ maps as templates for dust emission in intensity and polarization. We cross-correlate them with the Planck and WMAP data, at 12 frequencies from 23 to 353 GHz. The main results of the data analysis are as follows.

- The mean spectral index of the dust emission measured between 100 and 353 GHz is $\beta_{d,mm} = 1.51 \pm 0.01$. This value agrees with that reported by Planck Collaboration Int. XVII (2014) for the high Galactic latitude sky and Planck Collaboration Int. XIV (2014) for diffuse emission in the Galactic plane. The microwave spectral index $\beta_{d,mm}$ is close to that at submm wavelengths, which is derived from fits to the Planck data at $\nu \geq 353$ GHz with the full-mission Planck data.

- We determine the mean dust SED in intensity from 23 to 353 GHz. We separate the dust and AME contributions to the SED. The dust contribution is well fit by combining the modified blackbody spectrum with a spectral index of 1.51 with the mean temperature of 19.6 K. The two parametric models we use for the AME yield the same SED for the dust for frequencies $\nu \geq 70$ GHz.

- The mean spectral index for dust polarization, measured between 100 and 353 GHz, is $\beta_{P,mm} = 1.59 \pm 0.02$, assuming the temperature of aligned dust grains contributing to the polarization is the same as that determined from the dust emission in intensity. We show that the small difference with $\beta_{d,mm}$, the spectral index measured in a similar way for dust intensity, is a robust result against systematic uncertainties estimated comparing results of our data analysis obtained on various subsets of the Planck data.

- We determine the SED of the dust-correlated polarized emission from 23 to 353 GHz. This SED decreases with decreasing frequency and turns up below 60 GHz, very much like the dust SED in intensity due to AME. We show that the low frequency rise of the polarization SED may be explained by synchrotron polarization correlated with dust.

- We use a parametric model to separate the synchrotron and dust polarization and to characterize the spectral dependence of the dust polarization fraction. The polarization fraction $p$ of the dust emission decreases by $(21 \pm 6)$% from 353 to 70 GHz. We discuss this result within the context of evolving dust models. It could indicate differences in polarization efficiency among components of interstellar dust (e.g., carbon and silicate grains).

Our observational results provide inputs to quantify and optimize the separation between Galactic and CMB polarization (Planck Collaboration Int. XXX 2014). Our CC analysis yields a spectral decomposition of the diffuse emission into its main components: thermal emission from dust; free-free; synchrotron; and AME. This spectral decomposition may be combined with power spectra of the templates, as discussed in Appendix D, to quantify the Galactic emission in intensity as a function of the observed frequency and multipole (see Figs. 27 and 28 in Planck Collaboration I (2014)). For our polarization, we are currently missing a synchrotron polarization template that is free from Faraday rotation. Polarized synchrotron templates, which are expected from C-BASS (King et al. 2010) at 5 GHz and QUIJOTE (Hoyland et al. 2012) between 10 and 20 GHz, will be important for future correlation analyses.

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References


Ackermann, M., Ajello, M., Atwood, W. B., et al., Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV. 2010, Phys. Rev. D, 82, 092004, arXiv:1008.3999


This appendix details how we compute the dust SED using the CC analysis in Sect. 4.2. For simplicity, we present the simplest effects: characterization, removal, and simulation. 2014, A&A, 571, A10, arXiv:1303.5071


Appendix A: Derivation of the CC coefficients
In the ratio the scaling between the $a^d_d$ and $a^d_\ell$ goes away. The colour ratio only depends on the dust spectral properties and not on the CMB signal. The extension of Eq. (A.5) in the presence of AME, synchrotron, and free-free emission at the WMAP and LFI frequencies is given by Eq. (8).

The CMB contribution, $a(c_{353})$, in the presence of inverse noise-weighting can be written as

$$a(c_{353}) = \frac{\sum_{k=1}^{N} w_k(k) \tilde{F}(k) \left( \tilde{F}(k) + \tilde{P}_{353}(k) \right)}{\sum_{k=1}^{N} w_k(k) \tilde{I}_{353}(k)^2},$$

where $w_k$ is a weighting factor given by $w_k = (1/\sigma_k^2)$. If the weighting factor depends on the frequency, the CMB contribution is not strictly constant in $K_{\text{CMB}}$ units. This effect can reach up to 2%, as the weighting factors for the WMAP and Planck maps are quite different. This is not negligible compared to the instrumental noise which we use for inverse noise-weighting in our $\chi^2$ minimization.

In Sect. 9.2.1 we compute the frequency dependence of synchrotron emission correlated with dust. The mean spectrum of this component is given by

$$\langle a^s_i(\nu_{353}) \rangle = N \left( \sum_{k=1}^{N} \tilde{I}_{353}(k) \left( \tilde{I}_{353}(k) + \tilde{P}_s(k) \right) \right),$$

assuming the CMB chance correlation term with synchrotron emission is zero over all the sky patches. We detect $\langle a^s_i(\nu_{353}) \rangle$ with high-significance in our analysis (Sect. 9.2.1), which cannot be just a chance correlation term. One would expect such a correlation, since synchrotron emission arises from the same ISM as dust emission.

Similarly for polarization, we minimize $\chi^2_P$ between the data and 353 GHz Stokes $Q$ and $U$ maps, as given by Eq. (13). The polarization CC coefficient is then given by

$$[a^P_i(\nu_{353})] = N \left( \sum_{k=1}^{N} \tilde{Q}_c(k) \cdot \tilde{Q}_533(k) + \tilde{U}_c(k) \cdot \tilde{U}_533(k) \right),$$

where $NP$ is the normalization factor for polarization. Following the same logic as described for intensity, the polarization CC coefficient in the HFI frequencies can be written as

$$[a^P_i(\nu_{353})] = a^P_i(c_{353}) + N \sum_{i=1}^{N} \sum_{k=1}^{N} \left[ \tilde{Q}_c(k) \left( \tilde{Q}_c(k) + \tilde{Q}_{353}(k) + \tilde{Q}_{533}(k) \right) \right] + N \sum_{i=1}^{N} \sum_{k=1}^{N} \left[ \tilde{U}_c(k) \left( \tilde{U}_c(k) + \tilde{U}_{353}(k) + \tilde{U}_{533}(k) \right) \right],$$

assuming the dust polarization at a given frequency is a scaled version of 353 GHz dust polarization yields $\tilde{Q}_c(k) = a^P_i \tilde{Q}_{353}(k)$ and $\tilde{U}_c(k) = a^P_i \tilde{U}_{353}(k)$. Putting this back into Eq. (A.10) gives

$$[a^P_i(\nu_{353})] = a^P_i(c_{353}) + a^P_i(d_{353}) .$$

The polarized CMB contribution $a^P_i(c_{353})$ is strictly constant in $K_{\text{CMB}}$ units if we do not apply any noise weighting, similar to the intensity analysis. To deal with the noise, we first smooth all the maps to 1° resolution and then perform correlation over local patches on the sky. To compute the uncertainty on the CC coefficients, we rely on Monte Carlo simulations, as discussed in Appendix B.

### Appendix B: Simulations

This appendix presents the simulations of the sky emission in intensity and polarization at HFI frequencies that we use to test the CC analysis. The intensity and polarization emission components are listed in Table B.1. The simulations use a simplified model of dust emission in intensity and polarization that is good enough to provide a realistic framework to test the CC analysis. They are computed on HEALPix pixels at $N_{\text{side}} = 128$ with a 1° Gaussian beam. The Monte Carlo simulations serve two specific purposes. First, we use them to check that the CC analysis does not introduce any bias on our estimations of the mean dust spectral indices in intensity and polarization. Second, they provide realistic uncertainties on the CC coefficients, which we use in the spectral fit to separate out the dust and the CMB emission (Sect. 5.3).

#### B.1. Intensity

At HFI frequencies, the main diffuse emission components are the thermal dust, free-free, CMB, and CIB emission. The simulations also include instrumental noise. We now describe how we simulate each of these components.

The HI column density from the LAB survey (Kalberla et al. 2005) is taken as a proxy for thermal dust emission. We normalize the HI data to a suitable amplitude to match the observed Planck data at 353 GHz and extrapolate to the other HFI frequencies using an MBB spectrum with a fixed spectral index $\beta_d = 1.5$ and temperature $T_d = 19.6 \text{ K}$ over the whole sky. The HI data provide only a partial description of the thermal dust emission, as quoted in Planck Collaboration Int. XVII (2014). We include an additional dust component, spatially uncorrelated with the HI data, to mimic the residuals present after adopting the IR-HI correlation at 857 GHz. The additional dust-like emission is assumed to have an $\ell^{-\beta_d}$ power spectrum, with a normalized amplitude of $4\pi\sigma_{RJ}^2$ for $\ell = 2$, where $\sigma_{RJ}$ is the residual at 857 GHz after applying the IR-HI correlation and removing the CIB contribution (Planck Collaboration Int. XVII 2014). The amplitude of the uncorrelated HI emission is normalized at 857 GHz, taken from Planck Collaboration Int. XVII (2014), and scaled to the HFI frequencies assuming $\beta_d = 2.0$ for a dust temperature of $T_d = 19.6 \text{ K}$. We use the DDD Hα map as a proxy for free-free emission, which we compute at HFI frequencies for a spectral index $\beta_f = -2.14$ (in $K_{\text{RJ}}$ units) (Planck Collaboration Int. XIV 2014) and an electron temperature $T_e = 7000 \text{ K}$ (Dickinson et al. 2003). No dust extinction correction is applied to the DDD Hα map.

For the CMB, we compute Gaussian realizations of the CMB sky from the theoretical power spectrum of the Planck best-fit model (Planck Collaboration XV 2014). The CIB emission is generated using the best-fit model of CIB anisotropies at 353 GHz obtained directly from the Planck data (Planck Collaboration XXX 2014). We assume 100% correlated CIB across all the HFI frequencies, assuming an MBB spectrum with $\beta_{\text{CIB}} = 1.3$ and $T_{\text{CIB}} = 18.4 \text{ K}$. The Gaussian realizations of the instrumental noise are obtained at each frequency, using the noise variance maps (Planck Collaboration VI 2014). The noise
realizations are simulated at the full resolution of the Planck data, before smoothing to 1° resolution and reducing the pixelization from $N_{\text{side}} = 2048$ to 128.

We compute 1000 realizations of sky maps of the additional dust component, together with the CMB and CIB anisotropies. Independent realizations of the instrumental noise are generated for each sky simulation at a given frequency. The dust component computed from the HI map and the free-free emission traced by the Hα map are kept fixed.

We analyse the 1000 simulated maps with the CC method applied to the Planck intensity data. We compute the mean and standard deviation of the $R_{100}^I(353, 217)$ values for each sky patch. Both are plotted in Fig. B.1 versus the local dispersion of the 353 GHz template, $\sigma_{353}$. There is no bias on the estimation of the mean dust spectral index $\beta_d$. We recover a mean value equal to the index of 1.5 we used for the main HI-correlated dust component. The uncertainties on $R_{100}^I(353, 217)$, and hence on $\beta_d$, are associated with noise, CIB anisotropies, free-free emission, and the additional dust component. The 1σ dispersion of $\beta_d$ across sky patches for a given Monte Carlo realization is 0.02. This is smaller than the scatter of 0.07 measured for the Planck data. We interpret the difference as evidence for a small intrinsic dispersion in the spectral index of the dust emission.

### B.2. Polarization

The simulations of the polarized sky at HFI frequencies include polarized CMB, thermal dust emission, and noise. We compute 1000 realizations of the CMB Stokes $Q$ and $U$ maps using the best-fit Planck model (Planck Collaboration XV 2014), smoothed to 1° resolution at HEALPix resolution $N_{\text{side}} = 128$. Random realizations of Gaussian noise $Q$ and $U$ maps are generated at each pixel using the $3 \times 3$ noise covariance matrix defined at $N_{\text{side}} = 2048$. The noise maps are then smoothed to 1° resolution and projected on to a HEALPix map at $N_{\text{side}} = 128$. We generate independent realizations of the instrumental noise to mimic the detector sets at 353 GHz (Sect. 2.1.2).

For polarized thermal dust emission, we use the following model:

$$[Q_d^\nu, U_d^\nu] = p_d \left( \frac{v}{v_{\text{ref}}} \right)^{\beta_{d,\text{mm}}} \frac{B_{\nu}(T_d)}{B_{v_{\text{ref}}}(T_d)} f_{\text{ref}}^\nu \cos 2\psi_d \sin 2\psi_d .$$

(B.1)

Here $p_d$, $f_{\text{ref}}^\nu$, and $\psi_d$ are the polarization fraction, the dust intensity at reference frequency, and the polarization angle, respectively. The reference frequency is $v_{\text{ref}} = 353$ GHz. We fix $p_d$ to a constant value of 10% over the whole sky. The $f_{\text{ref}}^\nu$ map is that obtained by Planck Collaboration XI (2014) from the spectral fit to the high frequency Planck and IRAS 100 μm data, with an MBB model. For the dust polarization, we use an MBB spectrum with $\beta_{d,\text{mm}} = 1.6$ and $T_d = 19.6$ K, constant over the whole sky. We derive $\psi_d$ from the 1° smoothed Planck Stokes maps using the relation

$$\psi_d = -0.5 \times \tan(2\left(U_{v_2}^{\text{obs}} - U_{v_1}^{\text{obs}} + Q_{v_1}^{\text{obs}} - Q_{v_2}^{\text{obs}} \right)) .$$

(B.2)

We choose $v_1$ and $v_2$ as the 143 and 353 GHz, respectively. The difference between the two frequencies removes the CMB contribution.

We analyse 1000 polarized simulated maps using the CC analysis as applied to the Planck data. We compute the mean and the standard deviation of the $R_{100}^P(353, 217)$ for each sky patch. The plot of $R_{100}^P(353, 217)$ versus $\sigma_{353}^P$ is shown in Fig. B.1. We find no bias in the estimation of $R_{100}^P(353, 217)$ and hence in the measurement of $\beta_{d,\text{mm}}^P$. The 1σ dispersion of $\beta_{d,\text{mm}}^P$ across sky patches for a given simulation is 0.07. The 1σ dispersion of $\beta_{d,\text{mm}}^P$ from the simulations is smaller compared than that measured from the Planck data, because we use a simplified white noise model. However, some of the dispersion may come from the intrinsic dispersion of the polarized dust spectral index, and also additional Galactic polarized emission components, which we neglect in the simulations.

### Appendix C: Mean dust SED with dust extinction and scattering correction on the Hα template

The mean dust SED for intensity presented in this paper is obtained using the three-template fit with no extinction and dust scattering correction from the DDD Hα template. The effect of dust extinction ($f_d$) on the Hα template is described in equation 3 of Dickinson et al. (2003), whereas the effect of dust scattering ($s_d$) on the Hα template is described in equation 26 of Bennett et al. (2013). The mean measured value of $s_d$ is 0.11.
Table B.1. The ancillary data sets and models used in the Monte Carlo simulations.

<table>
<thead>
<tr>
<th>Components</th>
<th>Tracer</th>
<th>Model</th>
<th>Parameters</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB</td>
<td>TT spectrum</td>
<td>MBB</td>
<td>Planck best-fit parameters</td>
<td>Planck Collaboration XV (2014)</td>
</tr>
<tr>
<td>Thermal dust</td>
<td>Hα template</td>
<td>MBB</td>
<td>Planck Collaboration Int. XVII (2014)</td>
<td></td>
</tr>
<tr>
<td>IR-He excess</td>
<td>Residual at 857 GHz</td>
<td>MBB</td>
<td>Planck Collaboration Int. XVII (2014)</td>
<td></td>
</tr>
<tr>
<td>Free-free</td>
<td>Hα map</td>
<td>PL</td>
<td>(βα, Tα) = (-2.14, 7000 K)</td>
<td>Dickinson et al. (2003)</td>
</tr>
<tr>
<td>CIB</td>
<td>CIB spectrum</td>
<td>MBB</td>
<td>(βCIB, T_CIB) = (1.3, 18.4 K)</td>
<td>Planck Collaboration XXX (2014)</td>
</tr>
<tr>
<td>Statistical noise</td>
<td>Variance maps</td>
<td>(H, I, Q, U, QQ, QU, UU)</td>
<td>Planck Collaboration VI (2014)</td>
<td></td>
</tr>
<tr>
<td>Polarized thermal dust</td>
<td>Model</td>
<td>MBB</td>
<td>(βα, Tα) = (1.6, 19.6 K)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. C.1. Fractional change in the mean dust SED with respect to the reference dust SED presented in this paper, for different combinations of \( f_d \) and \( s_d \) corrections on the DDD Hα template.

\[
\begin{align*}
R(\text{MJy sr}^{-1}) & \text{ in high Galactic latitude regions (Lehtinen et al. 2010; Witt et al. 2010; Seon \& Witt 2012; Brandt \& Draine 2012; Bennett et al. 2013). To check the impact of the } f_d \text{ and } s_d \text{ corrected Hα template on the mean dust SED, we repeat the analysis with different combinations of } f_d \text{ and } s_d. \text{ The three different combinations of } f_d \text{ and } s_d \text{ corrected Hα templates we choose are: } f_d = 0.3 \text{ and } s_d = 0.0, f_d = 0.0 \text{ and } s_d = 0.11, \text{ and } f_d = 0.3 \text{ and } s_d = 0.11 (\text{R(MJy sr}^{-1})\text{). The fractional change in the mean dust SED with respect to the reference dust SED (} f_d = 0.0 \text{ and } s_d = 0.0 \text{ R(MJy sr}^{-1})\text{) is presented in Fig. C.1. At higher frequencies (> 100 GHz), the impact of both dust extinction and scattering is negligible. However at frequencies < 50 GHz, the fractional change on the mean SED can go as high as ± 4%. The } f_d \text{ and } s_d \text{ parameters are degenerate, although their effect on the derived best-fit parameter of models DI+AI and DI+AI11, listed in Table 4, is very small.}
\end{align*}

Appendix D: Power spectra of the templates

In this section, we compute the temperature power spectra of the three templates at 1° resolution: 408 MHz; DDD Hα; and 353 GHz dust template. The Planck 353 GHz map contains a significant component of CMB anisotropies. Taking the SMICA map (Planck Collaboration XII 2014) as a proxy for the CMB map, we remove its contribution from the 353 GHz total map. These spectra are combined with the SEDs from this paper to compute the contributions of each emission component to the microwave sky emission as a function of angular scales in Planck Collaboration I (2014) (see their Figs. 27 and 28).
Eqs. (26) and (27). The derived analytical model of these power spectra are valid in the frequency range 20 to 353 GHz, and for $f_{\text{sky}}$ between 0.4 and 0.8.

![Power spectra](image)

**Fig. D.1.** Power spectra of the 408 MHz, DDD Hz, and SMICA-subtracted 353 GHz templates, smoothed to 1° resolution for different Galactic masks (or $f_{\text{sky}}$).

<table>
<thead>
<tr>
<th>Galactic masks</th>
<th>$A_{0.408}$</th>
<th>$A_{0.60}$</th>
<th>$A_{353-\text{SMICA}}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$[10^0 \mu K^2_\ell]$</td>
<td>$[\mu K^2_\ell]$</td>
<td>$[\mu K^2_\ell]$</td>
</tr>
<tr>
<td>$f_{\text{sky}}$</td>
<td>$\alpha = -2.5$</td>
<td>$\alpha = -2.2$</td>
<td>$\alpha = -2.4$</td>
</tr>
<tr>
<td>G40</td>
<td>0.40</td>
<td>1.913 ± 0.492</td>
<td>0.011 ± 0.002</td>
</tr>
<tr>
<td>G60</td>
<td>0.60</td>
<td>3.223 ± 0.314</td>
<td>0.051 ± 0.003</td>
</tr>
<tr>
<td>G70</td>
<td>0.70</td>
<td>4.187 ± 0.379</td>
<td>0.271 ± 0.016</td>
</tr>
<tr>
<td>G80</td>
<td>0.80</td>
<td>6.139 ± 0.489</td>
<td>0.536 ± 0.026</td>
</tr>
</tbody>
</table>

**Table D.1.** Amplitudes of the power spectra, normalized at $\ell = 100$, as a function of $f_{\text{sky}}$. 

---

1. APC, AstroParticule et Cosmologie, Universit\'e Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
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