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Planck intermediate results. IX. Detection of the Galactic haze with *Planck*

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ABSTRACT

Using precise full-sky observations from *Planck*, and applying several methods of component separation, we identify and characterize the emission from the Galactic "haze" at microwave wavelengths. The haze is a distinct component of diffuse Galactic emission, roughly centered on the Galactic centre, and extends to $|b| \sim 35^\circ$ in Galactic latitude and $|l| \sim 15^\circ$ in longitude. By combining the *Planck* data with observations from the *Wilkinson Microwave Anisotropy Probe* we are able to determine the spectrum of this emission to high accuracy, unhindered by the large systematic biases present in previous analyses. The derived spectrum is consistent with power-law emission with a spectral index of -2.55 ± 0.05, thus excluding free-free emission as the source and instead favouring hard-spectrum synchrotron radiation from an electron population with a spectrum (number density per energy) $dN/dE \propto E^{-2.1}$. At Galactic latitudes $|b| < 30^\circ$, the microwave haze morphology is consistent with that of the *Fermi* gamma-ray "haze" or "bubbles," indicating that we have a multi-wavelength view of a distinct component of our Galaxy. Given both the very hard spectrum and the extended nature of the emission, it is highly unlikely that the haze electrons result from supernova shocks in the Galactic disk. Instead, a new mechanism for cosmic-ray acceleration in the centre of our Galaxy is implied.

Key words. Galaxy: nucleus – ISM: structure – ISM: bubbles – radio continuum: ISM

1. Introduction

The initial data release from the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) revolutionised our understanding of both cosmology (Spergel et al. 2003) and the physical processes at work in the interstellar medium (ISM) of our own Galaxy (Bennett et al. 2003). Some of the processes observed were expected, such as the thermal emission from dust grains, free-free emission (or thermal bremsstrahlung) from electron/ion scattering, and synchrotron emission due to shock-accelerated electrons interacting with the Galactic magnetic field. Others, such as the anomalous microwave emission now identified as spinning dust emission from rapidly rotating tiny dust grains (Draine & Lazarian 1998a,b; de Oliveira-Costa et al. 2002; Finkbeiner et al. 2004; Hinshaw et al. 2007; Boughn & Pober 2007; Dobler & Finkbeiner 2008b; Dobler et al. 2009), were more surprising. But perhaps most mysterious was a "haze" of emission discovered by Finkbeiner (2004a) that was centred on the Galactic centre (GC), appeared roughly spherically symmetric in profile, fell off roughly as the inverse distance from the GC, and was of unknown origin. This haze was originally characterised as free-free emission by Finkbeiner (2004a) due to its apparently very hard spectrum, although it was not appreciated at the time how significant the systematic uncertainty in the measured spectrum was.

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An analysis of the 3-year *WMAP* data by Dobler & Finkbeiner (2008a, hereafter DF08) identified a source of systematic uncertainty in the determination of the haze spectrum that remains the key to determining the origin of the emission. This uncertainty is due to residual foregrounds contaminating the cosmic microwave background (CMB) radiation estimate used in the analysis, and arises as a consequence of chance morphological correlations between the CMB and the haze itself. Nevertheless, the spectrum was found to be both significantly softer than free-free emission, and also significantly harder than the synchrotron emission observed elsewhere in the Galaxy as traced by the low-frequency synchrotron measurements of Haslam et al. (1982) (see also Reich & Reich 1988; Davies et al. 1996; Kogut et al. 2007; Strong et al. 2011; Kogut 2012). Finally, it was noted that this systematic uncertainty could be almost completely eliminated with data from the *Planck*[1] mission, which would produce estimates of the CMB signal that were significantly less contaminated by Galactic foregrounds.

The synchrotron nature of the microwave haze was substantially supported by the discovery of a gamma-ray counterpart to this emission by Dobler et al. (2010) using data from the *Fermi Gamma-Ray Space Telescope*. These observations were consistent with an inverse Compton (IC) signal generated by electrons with the same spectrum and amplitude as would yield the microwave haze at *WMAP* wavelengths. Further work by Su et al. (2010) showed that the *Fermi* haze appeared to have sharp edges and it was renamed the "*Fermi* bubbles." Subsequently, there has been significant theoretical interest in determining the origin of the very hard spectrum of progenitor electrons. Suggestions include enhanced supernova rates (Biermann et al. 2010), a Galactic wind (Crocker & Aharonian 2011), a jet generated by accretion onto the central black hole (Guo & Mathews 2011; Guo et al. 2011), and co-annihilation of dark matter (DM) particles in the Galactic halo (Finkbeiner 2004b; Hooper et al. 2007; Lin et al. 2010; Dobler et al. 2011). However, while each of these scenarios can reproduce some of the properties of the haze/bubbles well, none can completely match all of the observed characteristics (Dobler 2012).

Moreover, despite the significant observational evidence, there have been suggestions in the literature that the microwave haze is either an artefact of the analysis procedure (Mertsch & Sarkar 2010) or not synchrotron emission (Gold et al. 2011). The former conclusion was initially supported by alternative analyses of the *WMAP* data that found no evidence of the haze (Eriksen et al. 2006; Dickinson et al. 2009). However, more recently Pietrobon et al. (2012) showed that these analyses, while extremely effective at cleaning the CMB of foregrounds and identifying likely contaminants of a known morphology (e.g., a low-level residual cosmological dipole), typically cannot separate the haze emission from a low-frequency combination of free-free, spinning dust, and softer synchrotron radiation. The argument of Gold et al. (2011) that the microwave haze is not synchrotron emission was based on the lack of detection of a polarised component. This criticism was addressed by Dobler (2012) who showed that, even if the emission is not depolarised by turbulence in the magnetic field, such a polarised signal is not likely to be seen with *WMAP* given the noise in the data.

With the *Planck* data, we now have the ability not only to provide evidence for the existence of the microwave haze with an independent experiment, but also to eliminate the uncertainty in the spectrum of the emission which has hindered both observational and theoretical studies for nearly a decade. In Sect. 2 we describe the *Planck* data as well as some external templates we use in our analysis. In Sect. 3 we describe the two most effective component separation techniques for studying the haze emission in temperature. In Sect. 4 we discuss our results on the morphology and spectrum of the haze, before summarising in Sect. 5.

2. *Planck* data and templates

Planck (Tauber et al. 2010; Planck Collaboration I 2011) is the third generation space mission to measure the anisotropy of the cosmic microwave background (CMB). It observes the sky in nine frequency bands covering 30–857 GHz with high sensitivity and angular resolution from 31′ to 5′. The Low Frequency Instrument (LFI; Mandolesi et al. 2010; Bersanelli et al. 2010; Mennella et al. 2011) covers the 30, 44, and 70 GHz bands with amplifiers cooled to 20 K. The High Frequency Instrument (HFI; Lamarre et al. 2010; Planck HFI Core Team 2011a) covers the 100, 143, 217, 353, 545, and 857 GHz bands with bolometers cooled to 0.1 K. Polarisation is measured in all but the highest two bands (Leahy et al. 2010; Rosset et al. 2010). A combination of radiative cooling and three mechanical coolers produces the temperatures needed for the detectors and optics (Planck Collaboration II 2011). Two data processing centres (DPCs) check and calibrate the data and make maps of the sky (Planck HFI Core Team 2011b; Zacchei et al. 2011). *Planck*'s sensitivity, angular resolution, and frequency coverage make it a powerful instrument for galactic and extragalactic astrophysics as well as cosmology. Early astrophysics results are given in Planck Collaboration VIII–XXVI 2011, based on data taken between 13 August 2009 and 7 June 2010. Intermediate astrophysics results are now being presented in a series of papers based on data taken between 13 August 2009 and 27 November 2010.

We take both the *WMAP* and *Planck* bandpasses into account when defining our central frequencies. However, throughout we refer to the bands by the conventional labels of 23, 33, 41, 61, and 94 GHz for *WMAP* and 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz for *Planck*; the central frequencies are 22.8, 33.2, 41.0, 61.4, and 94.0 GHz, and 28.5, 44.1, 70.3, 100.0, 143.0, 217.0, 353.0, 545.0, and 857.0 GHz respectively. In each case, the central frequency represents the convolution of the bandpass response with a CMB spectrum and so corresponds to the effective frequency for emission with that spectrum. For emission with different spectra, the effective frequency is slightly shifted, but the effects are at the few percent level and do not significantly affect our conclusions.

Our analysis also requires the use of external templates to morphologically trace emission mechanisms within the *Planck* data. All the data are available in the HEALPix [2] scheme (Górski et al. 2005). In each case, we use maps smoothed to 1° angular resolution.

Thermal and spinning dust For a template of the combined thermal and spinning dust emission, we use the 100 μm all-

[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.

[2] see http://healpix.jpl.nasa.gov

sky map from Schlegel et al. (1998) evaluated at the appropriate *Planck* and *WMAP* frequencies using Model 8 from Finkbeiner et al. (1999, FDS99). This is a sufficiently good estimate of the thermal emission for our purposes, although it is important to note that the morphological correlation between thermal and spinning dust is not well known.

Free-free The free-free template adopted in our analysis is the Hα map assembled by Finkbeiner (2003)[3] from three surveys: the Wisconsin Hα Mapper (Haffner et al. 2003), the Southern Hα Sky Survey Atlas (Gaustad et al. 2001), and the Virginia Tech Spectral-Line Survey (Dennison et al. 1998). The map is corrected for line-of-sight dust absorption assuming uniform mixing between gas and dust, although we mask some regions based on the predicted total dust extinction where the correction to the Hα emission is deemed unreliable.

Soft Synchrotron Since synchrotron intensity rises with decreasing frequency, the 408 MHz full-sky radio continuum map (Haslam et al. 1982) provides a reasonable tracer of the soft synchrotron emission. While there is a very small contribution from free-free emission to the observed intensity, particularly in the Galactic plane, the bulk of the emission traces synchrotron radiation from supernova shock-accelerated electrons that have had sufficient time to diffuse from their source. In addition, as pointed out by Dobler (2012), the propagation length for cosmic-ray electrons in the disk is energy-dependent and therefore the 408 MHz map (which is dominated by synchrotron emission from lower energy electrons compared to the situation at 20–100 GHz) will be more spatially extended than the synchrotron at *Planck* frequencies (see Mertsch & Sarkar 2010). This can result in a disk-like residual when using the 408 MHz map as a tracer of synchrotron at higher frequencies that could be confused with the haze emission. We use an elliptical Gaussian disk template ($\sigma_l = 20°$ and $\sigma_b = 5°$) for this residual, though in practice this results in only a very small correction to our results, which use a larger mask than Dobler (2012) (see below).

The Haze Although a measurement of the precise morphology of the microwave haze is to be determined, an estimate of the morphology is necessary to reduce bias in template fits for the following reason: when using templates to separate foregrounds, the amplitudes of the other templates may be biased to compensate for the haze emission present in the data unless an appropriate haze template is used to approximate the emission. Following Dobler (2012), we use an elliptical Gaussian template with $\sigma_l = 15°$ and $\sigma_b = 25°$. Note that a map of the *Fermi* gamma-ray haze/bubbles cannot be used to trace the emission for two reasons. First, as pointed out by Dobler et al. (2011), the morphology of the gamma-ray emission is uncertain at low latitudes. Second, the synchrotron morphology depends sensitively on the magnetic field while the gamma-ray morphology depends on the interstellar radiation field. Therefore, while the same cosmic-ray population is clearly responsible for both, the detailed morphologies are not identical.[4]

[3] Our specific choice of the Finkbeiner (2003) Hα template does not have a strong impact on results. We have repeated our analysis using the Dickinson et al. (2003) Hα map and find differences at the few percent level that are not spatially correlated with haze emission.

[4] We have performed our fits using the uniform "bubbles" template given in Su et al. (2010) and the morphology of the haze excess (see Sect. 4) is not significantly changed.

Mask As noted above, the effect of dust extinction requires careful treatment of the Hα map when using it as a tracer of free-free emission. Therefore, we mask out all regions where dust extinction at Hα wavelengths is greater than 1 mag. We also mask out all point sources in the *WMAP* and *Planck* ERCSC (30–143 GHz) catalogs. Several larger-scale features where our templates are likely to fail are also masked: the LMC, SMC, M31, Orion–Barnard's Loop, NGC 5128, and ζ Oph. Finally, since the Hα to free-free ratio is a function of gas temperature, we mask pixels with Hα intensity greater than 10 rayleigh to minimise the bias due to strong spatial fluctuations in gas temperatures. This mask covers 32% of the sky and is shown in Fig. 1.

3. Component separation methods

In this paper, we apply two methods for separating the Galactic emission components in the *Planck* data. The first one, used in the original *WMAP* haze analyses, is a simple regression technique in which the templates described in the previous section are fit directly to the data. This "template fitting" method is relatively simple to implement and its results are easy to interpret. Furthermore, the noise characteristics are well understood and additional components not represented by the templates are readily identifiable in residual maps. The second technique, a powerful power-spectrum estimation and component-separation method based on Gibbs sampling, uses a Bayesian approach and combines pixel-by-pixel spectral fits with template amplitudes. One of the significant advantages of this approach is that, rather than assuming an estimate for the CMB anisotropy, a CMB map is generated via joint sampling of the foreground parameters and C_ℓs of cosmological anisotropies; this should reduce the bias in the inferred foreground spectra.

3.1. Template fitting

The rationale behind the simple template fitting technique is that there are only a few physical mechanisms in the interstellar medium that generate emission at microwave wavelengths, and these emission mechanisms are morphologically traced by maps at other frequencies at which they dominate. We follow the linear regression formalism of Finkbeiner (2004a), Dobler & Finkbeiner (2008a), and Dobler (2012) and solve the relation

$$\boldsymbol{d}_\nu = \boldsymbol{a}_\nu \cdot \mathbf{P}, \tag{1}$$

where $\boldsymbol{d}_\nu$ is a data map at frequency ν, $\mathbf{P}$ is a matrix of the templates defined in Sect. 2, and $\boldsymbol{a}_\nu$ is the vector of scaling amplitudes for this set of templates. The least-squares solution to this equation is

$$\boldsymbol{a}_\nu = (\mathbf{P}^{\mathrm{T}}\mathbf{N}_\nu^{-1}\mathbf{P})^{-1}(\mathbf{P}^{\mathrm{T}}\mathbf{N}_\nu^{-1}\boldsymbol{d}_\nu), \tag{2}$$

where $\mathbf{N}_\nu$ is the noise covariance matrix at frequency ν. In practice, for our template fits we use the mean noise per band (i.e., we set $\mathbf{N}_\nu = \langle \mathbf{N}_\nu \rangle$ for all pixels), which is appropriate in the limit where the dominant uncertainty is how well the templates trace the foregrounds, as is the case here. To the extent that the templates morphologically match the actual foregrounds, the solutions a_ν^i for template i as a function of frequency represent a reasonable estimate of the spectrum over the fitted pixels.

There are two important features of this approach to template fitting that must be addressed. First, there is an implicit assumption that the spectrum of a given template-correlated emission mechanism does not vary across the region of interest, and second, an estimate for the CMB must be pre-subtracted from the data. The former can be validated by inspecting a map of the residuals which can reveal where this assumption fails, and as a consequence of which the sky can easily be subdivided into regions that can be fitted independently. The latter involves the complication that no CMB estimate is completely clean of the foregrounds to be measured, which thereore introduces a bias (with the same spectrum as the CMB) in the inferred foreground spectra. As shown by DF08, this bias becomes increasingly large with frequency and renders an exact measurement of the haze spectrum impossible with *WMAP* alone. This "CMB bias" is the dominant source of uncertainty in all foreground analyses. However, DF08 also pointed out that, because the haze spectrum falls with frequency, the high-frequency data from *Planck* can be used to generate a CMB estimate that is nearly completely free from haze emission. Thus, pre-subtraction of this estimate should result in an essentially unbiased estimate of the haze spectrum. The CMB estimate that we use consists of a "*Planck* HFI internal linear combination" (PILC) map, formed from a minimum-variance linear combination of the *Planck* HFI 143–545 GHz data after pre-subtraction of the thermal dust model of FDS99 at each frequency.[5] Defining $\boldsymbol{p}_\nu$ and $\boldsymbol{t}_\nu$ to be the *Planck* maps and FDS99 prediction (respectively) at frequency ν, the PILC in $\Delta T_{\rm CMB}$ is given by

$$\begin{aligned}\mathrm{PILC} \;=\; & 1.39\times(\boldsymbol{p}_{143}-\boldsymbol{t}_{143}) \;-\; 0.36\times(\boldsymbol{p}_{217}-\boldsymbol{t}_{217}) \\ & -0.025\times(\boldsymbol{p}_{353}-\boldsymbol{t}_{353})+0.0013\times(\boldsymbol{p}_{545}-\boldsymbol{t}_{545}).\end{aligned} \quad (3)$$

The weights are determined by minimising the the variance over unmasked pixels of the PILC while maintaining a unity response to the CMB spectrum.

Although no constraint is made on the spectral dependence of the template coefficients in Eq. 2, the fit does assume that the spectrum is constant across the sky. While this assumption is actually quite good outside our mask (as we show below), it is known to be insufficient in detail. As such, in addition to full (unmasked) sky fits, we also perform template fits on smaller sky regions and combine the results to form a full composite map. The subdivisions are defined by hand to separate the sky into regions with particularly large residuals in a full-sky fit and are listed in Table 1.

3.2. Gibbs sampling: Commander

An alternative method for minimising the CMB bias is to generate a CMB estimate from the data while simultaneously solving for the parameters of a Galactic foreground model. Within the Bayesian framework it is possible to set stronger priors on the CMB parameterisation (i.e., C_ℓs), taking advantage not only of the frequency spectrum of the CMB (a blackbody), but also of the angular power spectrum of the fluctuations. Even for relatively simple foreground models, the dimensionality of parameter space is quite large so uniform sampling on a grid is not feasible.

[5] Pre-subtracting the FDS99 prediction for the thermal dust is not meant to provide a perfect model for the thermal dust, but rather a reasonable model. The goal is to minimise variance in the PILC and it is more effective to do so by pre-subtracting the dust model. This allows the fit to manage the CO contamination present at various HFI frequency channels more effectively (although there is still some leakage however, see Sect. 4.1). We have tested a PILC which does not subtract the thermal dust and the morphology and amplitude of the recovered haze signal are similar.

Table 1. Regions used for the multi-region (RG) template fits.

Region	Sky Coverage	
1	$-125° \le l < -104°$	$-30° \le b < 0°$
2	$-104° \le l < -80°$	$-30° \le b < 0°$
3	$-125° \le l < -104°$	$0° \le b < 30°$
4	$-104° \le l < -80°$	$0° \le b < 30°$
5	$-37° \le l < 42°$	$0° \le b < 90°$
6	$-80° \le l < -25°$	$-30° \le b < 0°$
7	$70° \le l < 180°$	$-90° \le b < 0°$
8	$12° \le l < 70°$	$-90° \le b < 0°$
9	Unmasked pixels outside regions 1–8 and $b \le 0$	
10	Unmasked pixels outside regions 1–8 and $b > 0$	

Jewell et al. (2004) and Wandelt et al. (2004) first discussed the application of Gibbs sampling algorithms (a variant of MCMC sampling) in this context. These algorithms have been further improved (Eriksen et al. 2004; O'Dwyer et al. 2004; Eriksen et al. 2007; Chu et al. 2005; Jewell et al. 2009; Rudjord et al. 2009; Larson et al. 2007) and packaged into the `Commander` code.

Gibbs sampling is particularly suitable for component separation since it samples from the conditional distribution along perpendicular directions in parameter space, updating the distribution with each sample. This approach has been advocated by Eriksen et al. (2007, 2008a) and Dickinson et al. (2009) and has been applied recently to the *WMAP* 7-year data by Pietrobon et al. (2012). A detailed description of the algorithm and its validation on simulated data is provided by Eriksen et al. (2008b, and references therein).

The outputs of the sampling are a map-based CMB estimate and the parameters of a foreground model, which can either be template-based, pixel-based, or a combination of the two. We perform the analysis at HEALPix resolution $N_{\rm side} = 128$. The choice of the foreground model is limited by the number of frequency channels observed since it sets the number of constraints on the model when fitting spectra for each pixel. We separate our results in the following section into two categories, fits using *Planck* data only and fits using *Planck* data plus ancillary data sets.

For the *Planck*-only fits, our model consists of a single power law $T \propto \nu^{\beta_{\rm S}}$ describing the effective low-frequency emission (with a prior on spectral index, $\beta_{\rm S} = -3.05 \pm 0.3$), a greybody for the thermal dust emission that dominates at high frequencies (with a temperature and emissivity prior given by the results of Planck Collaboration XIX 2011, where mean values of $T_{\rm D} \simeq 18$ K and $\epsilon_{\rm D} = 1.8$ were measured), and a CO spectrum. The CO spectrum is assumed constant across the sky and normalised to 100 GHz. The relative strength of the J=2→1 ($\sim$ 217 GHz) and J=3→2 ($\sim$ 353 GHz) transition lines with respect to the J=1→0 transition were computed by taking into account the specifications of the HFI detectors and calibrated by means of the available survey (Dame et al. 2001). The relative ratios in the 100, 217, and 353 GHz bands are 1.0, 0.35, and 0.12 respectively. We checked the robustness of the result against a plausible variation of the line ratios of $\sim$ 10%. (A more detailed discussion of the CO analysis that we performed can be found in Planck Collaboration XIX 2011). We normalise the thermal dust component at 353 GHz and the low-frequency power law at 33 GHz. Hence, we solve for two spectral indices together with the corresponding amplitudes as well as a CO amplitude, with the dust temperature fixed at a value of 18 K. The current `Commander` implementation allows for the determination of residual monopole and dipole contributions, as may result from the calibration and map-making procedures. This fit is referred to as CMD1 throughout. It is interesting to note that, given the noise in the data, this highly over-simplified model is sufficient to describe the total Galactic emission (see Sect. 4.1). However, it is well established that the low-frequency emission actually consists of several components. Following Pietrobon et al. (2012), our procedure for separating these components is to perform a template fit as specified in Eq. 2 on the `Commander` solution for the low-frequency amplitude (i.e., replacing $\boldsymbol{d}_\nu$ with the low-frequency amplitude map). Pietrobon et al. (2012) showed that applying this "post-processing" template regression procedure is effective in extracting the haze from the `Commander` solution.

The addition of the *WMAP* channels allows us to refine the foreground model further, separating the multiple contributions in the frequency range 23–70 GHz. Moreover, the inclusion of the 408 MHz data improves the characterisation of the synchrotron component and will allow us to investigate the spatial variations of its spectral index (see Sect. 4.2). The `Commander` fit, CMD2, is then based on 14 frequency maps (eight *Planck* channels from 30 to 353 GHz, five from *WMAP*, and Haslam 408 MHz), and allows a modification of the foreground model to encompass two low-frequency power-law components – one soft component with a fixed spectral index $\beta_{\rm S} = -3.05$ to describe the soft synchrotron emission[6] and one with a spectral index $\beta_{\rm H}$ with prior $\beta_{\rm H} = -2.15 \pm 0.3$ to capture both the hard synchrotron haze and the free-free emission. With this model, the low-frequency part of the spectrum is more easily resolved into physically meaningful components.

In addition, we parameterise a joint thermal and spinning-dust model by

$$D_{\rm jd}(\nu) = \left(\frac{\nu}{\nu_0}\right)^{1+\epsilon} \frac{B(\nu, T)}{B(\nu_0, T)} + {\rm e}^{\alpha} {\rm e}^{-[(\nu-\nu_1)/b]^2/2}. \qquad (4)$$

This is the sum of a grey-body spectrum for the thermal dust, and a Gaussian profile to mimic the spinning dust SED. The latter is a purely phenomenological model selected on the basis of its straightforward numerical implementation. However, we have established its effectiveness in describing well-known spinning dust regions in the Gould Belt (*Planck* Intermediate Paper, in preparation). The thermal dust pivot frequency ν_0 is set to 545 GHz and the spinning dust peak frequency ν_1 to 20 GHz. The remaining parameters (the amplitude of the joint spectrum, the relative amplitude of the spinning dust contribution, and the width of the spinning dust bump) are constrained by the Gibbs sampling procedure. As before we also adopt a spectrum for the CO emission.

4. Results

In what follows, we perform four different types of haze extraction:

1. A masked full-sky (FS) template fit for each input frequency band.
2. Template fits over subsections of the sky (RG) that are combined to give a full-sky haze map for each input frequency band.
3. A `Commander` fit (CMD1) with a simple two-component foreground model, using *Planck* 30–353 GHz data.
4. A comprehensive `Commander` fit (CMD2) including thermal and spinning dust models, a soft power-law component, and a hard power-law component, using *Planck* 30–545 GHz, *WMAP* 23–94 GHz, and Haslam 408 MHz data sets.

[6] This value represents the spectral index of the large Loop I feature that is a prominent supernova remnant visible at both 408 MHz and microwave frequencies in the northern Galactic hemisphere. We have repeated our analysis varying this index by $\delta\beta = 0.1$ and find no significant difference in our results.

We first discuss our results from the template fitting and Gibbs sampling analyses derived from the *Planck* data alone, then proceed to include external data sets in the analysis. A direct comparison of the results between the template fits and `Commander` haze extraction methods boosts confidence that, not only are components being appropriately separated, but the spectrum is relatively free from bias.

4.1. *Planck*-only results

4.1.1. Template fitting

Figure 1 presents the templates and mask used for the *Planck* analysis, together with the CMB-subtracted data and best fit template model at 30 GHz. We also show the full-sky (i.e., unrestricted in l and b) haze residual, defined as

$$\mathcal{R}^{\rm H}_\nu = \boldsymbol{d}_\nu - \boldsymbol{a}_\nu \cdot \mathbf{P} + a^{\rm H}_\nu \cdot \boldsymbol{h}, \qquad (5)$$

where $\boldsymbol{h}$ is the haze template defined in Sect. 2. The haze is clearly present in the *Planck* data set and, as illustrated in Fig. 2 (left column), scaling each residual by $\nu^{2.5}$ yields roughly equal brightness per frequency band indicating that the spectrum is approximately $T^{\rm H}_\nu \propto \nu^{-2.5}$. A more detailed measurement of the spectrum will be given in Sect. 4.3. It is also interesting to note that the morphology does not change significantly with frequency (although striping in the *Planck* HFI maps used to form the CMB estimate is a significant contaminant at frequencies above ~ 40 GHz) indicating that the spectrum of the haze emission is roughly constant with position.

The haze residual is most clearly visible in the southern GC region, but we note that our assumption of uniform spectra across the sky does leave some residuals around the edge of the mask and in a few particularly bright free-free regions. However, while our imperfect templates and assumptions about uniform spectra have done a remarkable job of isolating the haze emission (96% of the total variance is removed in the fit at *Planck* 30 GHz), we can more effectively isolate the haze by subdividing the sky into smaller regions as described in Sect. 3.1. The resultant full-sky haze residual is shown in Fig. 2. With this fit, the residuals near the mask are cleaner and we have done a better job in fitting the difficult Ophiucus region in the northern GC, though striping again becomes a major contaminant for frequencies above ~ 40 GHz.

4.1.2. `Commander`

Figure 3 presents the results of our CMD1 `Commander` fit and the subsequent post-processing. As noted previously, this very simple model provides an adequate description of the data with a mean χ^2 of 18.4 (7 d.o.f.) outside the mask, despite the fact that the low-frequency component is really an aggregate of several different emission mechanisms, as shown by Pietrobon et al. (2012). It is visually apparent that the low-frequency amplitude is highly correlated with thermal dust emission in some regions,

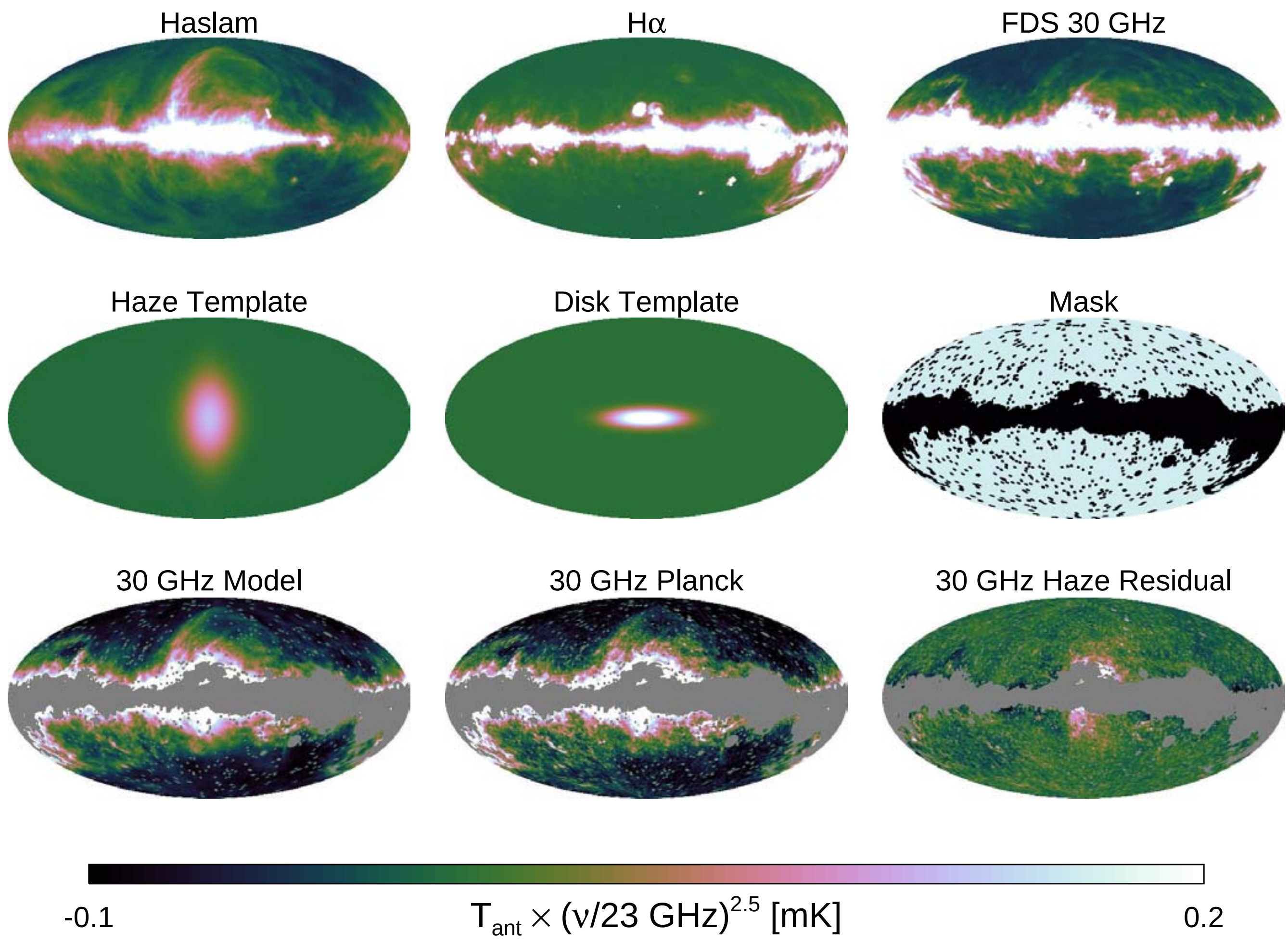

Fig. 1. The templates and full-sky template fitting model (see Sect. 4.1). *Top left*: the Haslam et al. (1982) 408 MHz map. *Top middle*: the Finkbeiner (2003) Hα map. *Top right*: the Finkbeiner et al. (1999) dust prediction at the *Planck* 30 GHz channel. *Middle left*: the elliptical Gaussian haze template. *Center*: the elliptical Gaussian disk template. *Middle right*: the mask used in the fit. *Bottom left*: the best fit template linear combination model at *Planck* 30 GHz. *Bottom middle*: the CMB-subtracted *Planck* data at 30 GHz. *Bottom right*: the *Planck* 30 GHz data minus the 30 GHz model with the haze template component added back into the map.

suggesting a dust origin for some of this emission (e.g., spinning dust). Finally, features that are well known from low-frequency radio surveys, such as Loop I, are also visible, implying a synchrotron origin, with a spectral index closer to $\beta_S = -3$. The coefficients of the post-processing template-based fit described in Sect. 3.2 are given in Table 2 and show a strong positive correlation with each template.

As with the template fitting case, we see from Fig. 3 that the post-processing residuals for the low-frequency CMD1 component are low except towards the Galactic centre where the haze is clearly present, implying that it is emission with a distinct morphology compared to the dust, free-free, and soft synchrotron emission. Furthermore, the morphology is strikingly similar to the template fitting indicating strong consistency between the results. Since an analogous regression cannot be performed on the spectral-index map, a more flexible foreground model must be implemented to isolate the haze spectrum. However, the additional model parameters require the use of external data sets.

4.2. Results from Planck plus external data sets

4.2.1. Template fitting

In order to further our understanding of the spectrum and morphology of the microwave haze component, we augment the *Planck* data with the *WMAP* 7-year data set (covering the frequency range 23–94 GHz) and the 408 MHz data. For the template-fitting method, the inclusion of the new data is trivial since Eq. 2 does not assume anything about the frequency dependence of the spectrum and each map is fit independently. The results for the full sky and for smaller regional fits are shown in Figs. 4 and 5. The haze residual is present in both the *WMAP* and *Planck* data, and the morphology and spectrum appear consistent between data sets. As before, scaling each residual by $\nu^{2.5}$ yields roughly equal brightness per band from 23 GHz to 61 GHz. Including the *WMAP* data also confirms that the morphology does not change significantly with frequency, thus implying a roughly constant haze spectrum with position.

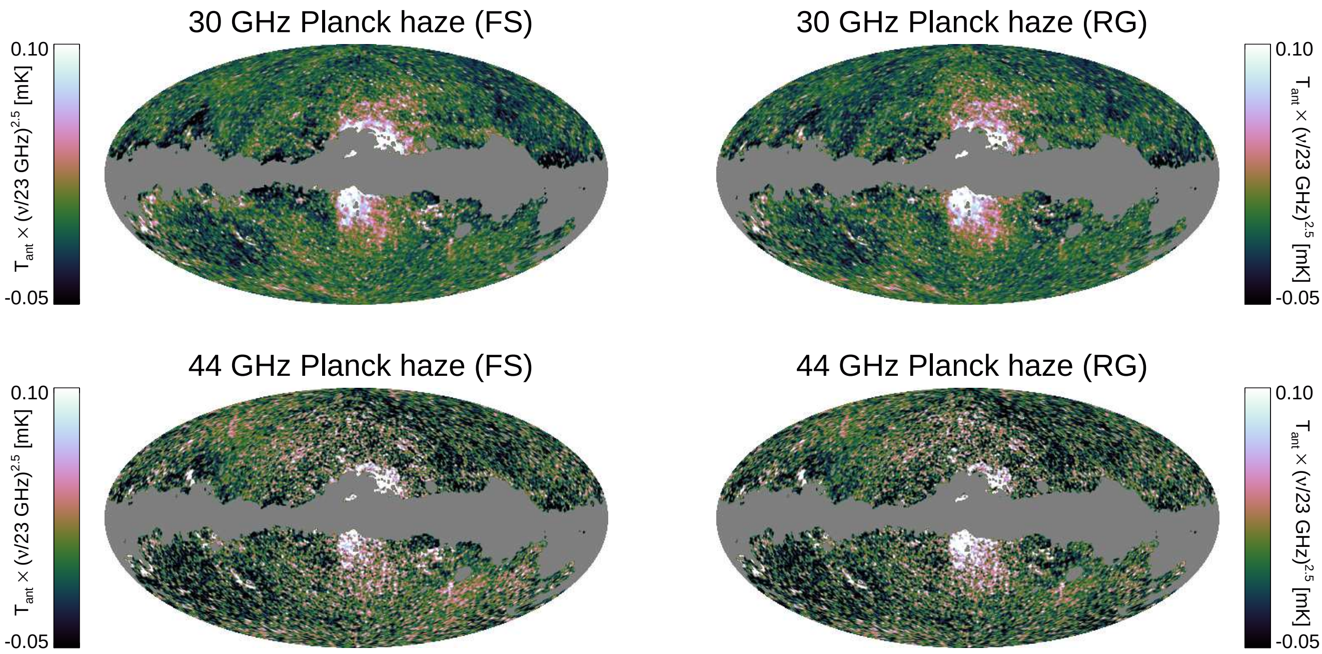

Fig. 2. *Left column*: the *Planck* haze (i.e., the same as the bottom right panel of Fig. 1), for the *Planck* 30 and 44 GHz channels using a full-sky template fit to the data. A scaling of $\nu^{2.5}$ yields roughly equal brightness residuals indicating that the haze spectrum is roughly $T_\nu \propto \nu^{-2.5}$, implying that the electron spectrum is a very hard $dN/dE_e \propto E^{-2}$. Note that the haze appears more elongated in latitude than longitude by a factor of two, which is roughly consistent with the *Fermi* gamma-ray haze/bubbles (Dobler et al. 2010). For frequencies above ~40 GHz, striping in the HFI channels (which contaminates our CMB estimate) begins to dominate over the haze emission. *Right column*: the same but for the "regional" fits described in Sect. 4.1. The overall morphology of the haze is the same, but the residuals near the mask and in the Ophiucus complex in the north GC are improved.

Table 2. Regression coefficients of the `Commander` foreground amplitude maps.

Fit type	Data sets	Fit coefficient			
		Hα [mK/R]	FDS [mK/mK]	Haslam [mK/K]	Haze [mK/arbitrary]
CMD1	*Planck* 30–353 GHz	$2.8 \times 10^{-3} \pm 2.0 \times 10^{-4}$	$1.9 \pm 4.3 \times 10^{-2}$	$1.6 \times 10^{-6} \pm 4.4 \times 10^{-8}$	$6.0 \times 10^{-2} \pm 3.4 \times 10^{-3}$
CMD2	*Planck* 30–353 GHz, *WMAP*, Haslam	$3.3 \times 10^{-3} \pm 3.9 \times 10^{-4}$	$1.0 \pm 8.4 \times 10^{-2}$	$2.4 \times 10^{-9} \pm 8.8 \times 10^{-8}$	$5.7 \times 10^{-2} \pm 6.7 \times 10^{-3}$

4.2.2. `Commander`

Comparing the low frequency, hard spectral index `Commander` solution at 23 GHz obtained with this model to our previous (less flexible) parameterisation, we find that the residuals correlated with the Haslam 408 MHz map are significantly reduced as shown in Fig. 3. Table 2 lists the fit coefficients in this case, and we now find no significant correlation with the Haslam map. As before, a template regression illustrates that the haze residual is significant and our hard spectrum power law contains both free-free and haze emission.[7] Furthermore, Fig. 6 illustrates that the fixed $\beta_S = -3.05$ power law provides a remarkably good fit to the 408 MHz data. Indeed, subtracting this soft-spectrum component from the map yields nearly zero residuals outside the mask, except for bright free-free regions which contaminate the Haslam et al. (1982) map at the ~ 10% level. It is interesting to note that this residual (as well as the negligible Haslam-correlation coefficient in Table 2) imply that fits assuming a constant spectral index across the sky for this correlated emission are reasonable. Physically, this means that electrons do diffuse to a steady-state spectrum which is very close to $dN/dE \propto E^{-3}$ (in agreement with the propagation models of Strong et al. 2011).

Taken together, Figs. 3 and 6 imply that, not only is the 408 MHz-correlated soft synchrotron emission consistent with a spectral index of −3.05 across the entire sky (outside our mask) from 408 MHz to 60 GHz, but the haze region consists of both a soft and a hard component. That is, the haze is not a simple variation of spectral index from 408 MHz to ~ 20 GHz. If it were, then our assumption of $\beta_S = -3.05$ (i.e., the wrong spectral index for the haze) would yield residuals in the difference map of Fig. 6. The map of the harder spectral index would ideally be a direct measurement of the haze spectrum. However, the signal-to-noise ratio is only sufficient to accurately measure the spectrum in the very bright free-free regions (e.g., the Gum Nebula).

[7] A close comparison between the CMD1 and CMD2 results suggests that the haze amplitude is slightly lower in the latter. However, due to the flexibility of the CMD2 model (specifically the fact that the model allows for the unphysical case of non-zero spinning dust in regions of negligible thermal dust), it is likely that some of the haze emission is being included in the spinning dust component.

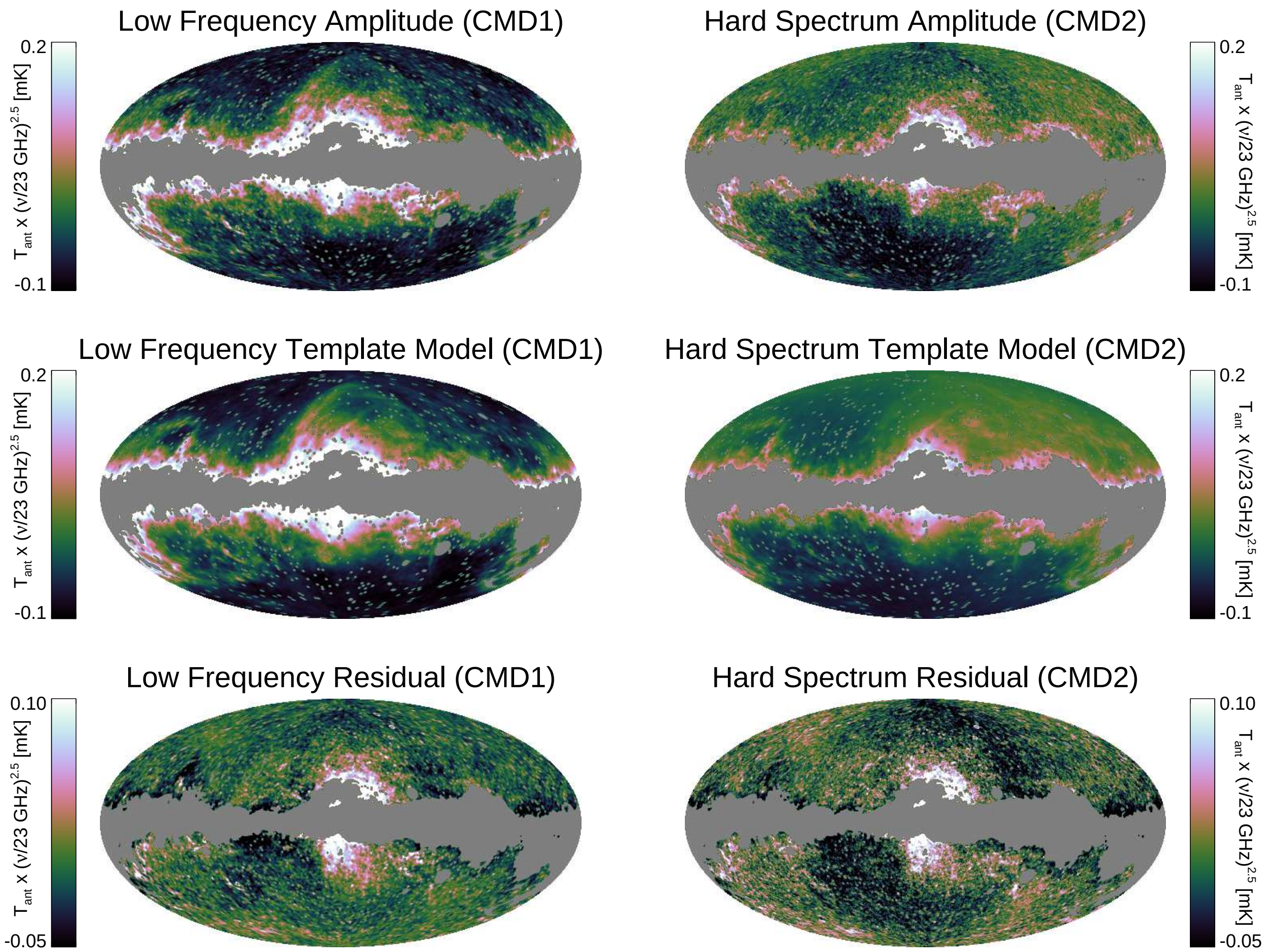

Fig. 3. *Left column, top*: The recovered amplitude of the low-frequency component at 23 GHz from our simplest `Commander` fit to the *Planck* data alone, CMD1. As shown in Pietrobon et al. (2012), while this model provides an excellent description of the data, this low-frequency component is actually a combination of free-free, spinning dust, and synchrotron emission (*top*). *Left column, middle*: a four-component template model of this component (see Table 2). *Left column, bottom*: The haze residual. The residuals are small outside the haze region indicating that the templates are a reasonable morphological representation of the different components contained in the `Commander` solution. The haze residual is strikingly similar to that found for the template-only approach in Fig. 2 (though there does seem to be a residual dipole in the `Commander` solution). *Right column*: The same, but for the CMD2 low-frequency, hard spectrum component. While there is still some leakage of dust-correlated emission in the solution, the softer synchrotron emission (mostly correlated with the 408 MHz template [see Fig. 6]) has been separated by `Commander`. The resultant map is dominated by free-free and the haze emission and the regressed haze residual (*bottom panel*) shows morphology very similar to both the template fitting and CMD1 results indicating that the haze has been effectively isolated.

In the fainter haze region, the spectral index is dominated by noise in the maps.

4.3. Spectrum and morphology

While a pixel-by-pixel determination of the haze spectrum is not possible given the relatively low signal-to-noise ratio per pixel of the haze emission, we can get a reliable estimate of its mean behaviour from the template fitting residuals in Fig. 5. The majority of previous haze studies have estimated the haze spectrum via the template coefficients $\boldsymbol{a}_\nu$ for the haze template. However, as noted in Dobler (2012), such an estimate is not only affected by the CMB bias (which we have effectively minimised by using the PILC), but may also be biased by the effect of imperfect template morphologies. The argument is as follows: consider a perfectly CMB-subtracted map which consists of the true haze $\boldsymbol{h}'$ plus another true foreground component $\boldsymbol{f}'$ which we are approximating by templates $\boldsymbol{h}$ and $\boldsymbol{f}$ respectively. Our template fit approach can be written as

$$a_{\rm H}\boldsymbol{h} + a_{\rm F}\boldsymbol{f} = b_{\rm H}\boldsymbol{h}' + b_{\rm F}\boldsymbol{f}', \tag{6}$$

where we are solving for $a_{\rm H}$ and a_F while $b_{\rm H}$ and b_F are the true amplitudes. The $a_{\rm H}$ solution to this equation is

$$a_{\rm H} = b_{\rm H} \times \frac{\Gamma_{\boldsymbol{hh}'} - \Gamma_{\boldsymbol{fh}'}\Gamma_{\boldsymbol{hf}}}{1 - \Gamma_{\boldsymbol{fh}}\Gamma_{\boldsymbol{hf}}} + b_{\rm F} \times \frac{\Gamma_{\boldsymbol{hf}'} - \Gamma_{\boldsymbol{ff}'}\Gamma_{\boldsymbol{hf}}}{1 - \Gamma_{\boldsymbol{fh}}\Gamma_{\boldsymbol{hf}}}, \tag{7}$$

where, for example, $\Gamma_{\boldsymbol{hf}'} \equiv \langle \boldsymbol{hf}' \rangle / \langle \boldsymbol{h}^2 \rangle$, and the mean is over unmasked pixels. Thus, if $h = h'$ and $f = f'$ then $a_{\rm H} = b_{\rm H}$ and we recover the correct spectrum. However, if $h \neq h'$ then the

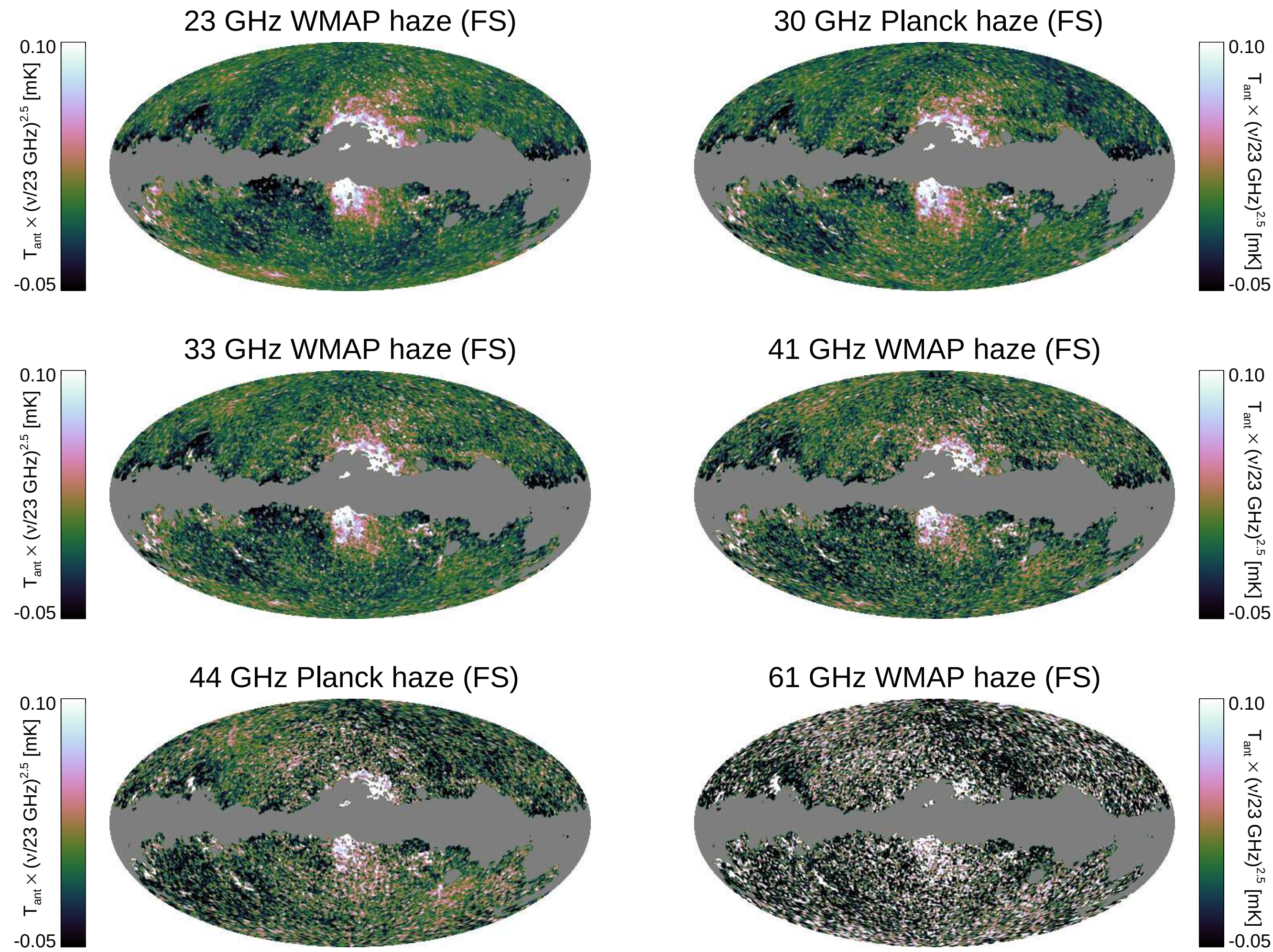

Fig. 4. The microwave haze at both *WMAP* and *Planck* wavelengths using a full-sky template fit to the data. The morphology of the haze is remarkably consistent from band to band and between data sets implying that the spectrum of the haze does not vary significantly with position. Furthermore, the $\nu^{2.5}$ scaling again yields roughly equal-brightness residuals indicating that the haze spectrum is roughly $T_\nu \propto \nu^{-2.5}$ through both the *Planck* and *WMAP* channels. In addition, while striping is minimally important at low frequencies, above ~ 40 GHz it becomes comparable to, or brighter than, the haze emission (see text).

spectrum is biased and if $f \neq f'$ it is biased and dependent upon the true spectrum of the other foreground, $b_{\rm F}$.

We emphasise that this bias is dependent on the cross-correlation of the true foregrounds with the templates (which is unknown) and that we have assumed a perfectly clean CMB estimate (which is not possible to create) and have not discussed the impact of striping or other survey artefacts (which Figs. 4 and 5 show are present). Given this, a much more straightforward estimate of the haze spectrum is to measure it directly from $\mathcal{R}_{\rm H}$ in a region that is relatively devoid of artefacts or other emission. We measure the spectrum in the GC south region $|l| < 35°$ and $-35° < b < 0°$ by performing a linear fit (slope and offset) over unmasked pixels and convert the slope measurement to a power law given the central frequencies of the *Planck* and *WMAP* data (see Fig. 7). Specifically, we fit

$$\mathcal{R}_{\rm H}^{23} = A_\nu \times \mathcal{R}_{\rm H}^{\nu} + B_\nu \tag{8}$$

over unmasked pixels in this region for A_ν and B_ν, and calculate the haze spectral index, $\beta_{\rm H} = \log(A_\nu)/\log(\nu/23\,{\rm GHz})$, for each ν. This spectrum should now be very clean and – given our use of the PILC – reasonably unbiased.

A measurement of the spectrum of the haze emission is shown in Fig. 7. It is evident that the *WMAP* and *Planck* bands are complementarily located in log-frequency space and the two experiments together provide significantly more information than either one alone.[8] In the left panel we plot $\langle \mathcal{R}_{\rm H}^{\nu} \rangle - B_\nu$ (where the mean is over the unmasked pixels in the region given above and the errors are their standard deviation). The haze spectrum is measured to be $T_\nu \propto \nu^{\beta_{\rm H}}$ with $\beta_{\rm H} = -2.55 \pm 0.05$. This spectrum is a nearly perfect power law from 23 to 41 GHz. Furthermore, if we form the total synchrotron residual,

$$\mathcal{R}_{\rm S} = \mathcal{R}_{\rm H} + a_S \cdot \boldsymbol{s}, \tag{9}$$

where s is the Haslam map, and measure its spectrum in the south GC, we again recover a nearly perfect power law with $\beta_{\rm S} = -3.1$. Our conclusion is that the haze, which is not consistent with free-free emission, arises from synchrotron emis-

[8] The close log-frequency spacing of the *WMAP* 94 GHz and *Planck* 100 GHz channels has the significant advantage that the CO (J=1→0) line falls in the *Planck* 100 GHz band while it is outside the *WMAP* 94 GHz band. This provides an excellent estimate for the CO morphology.

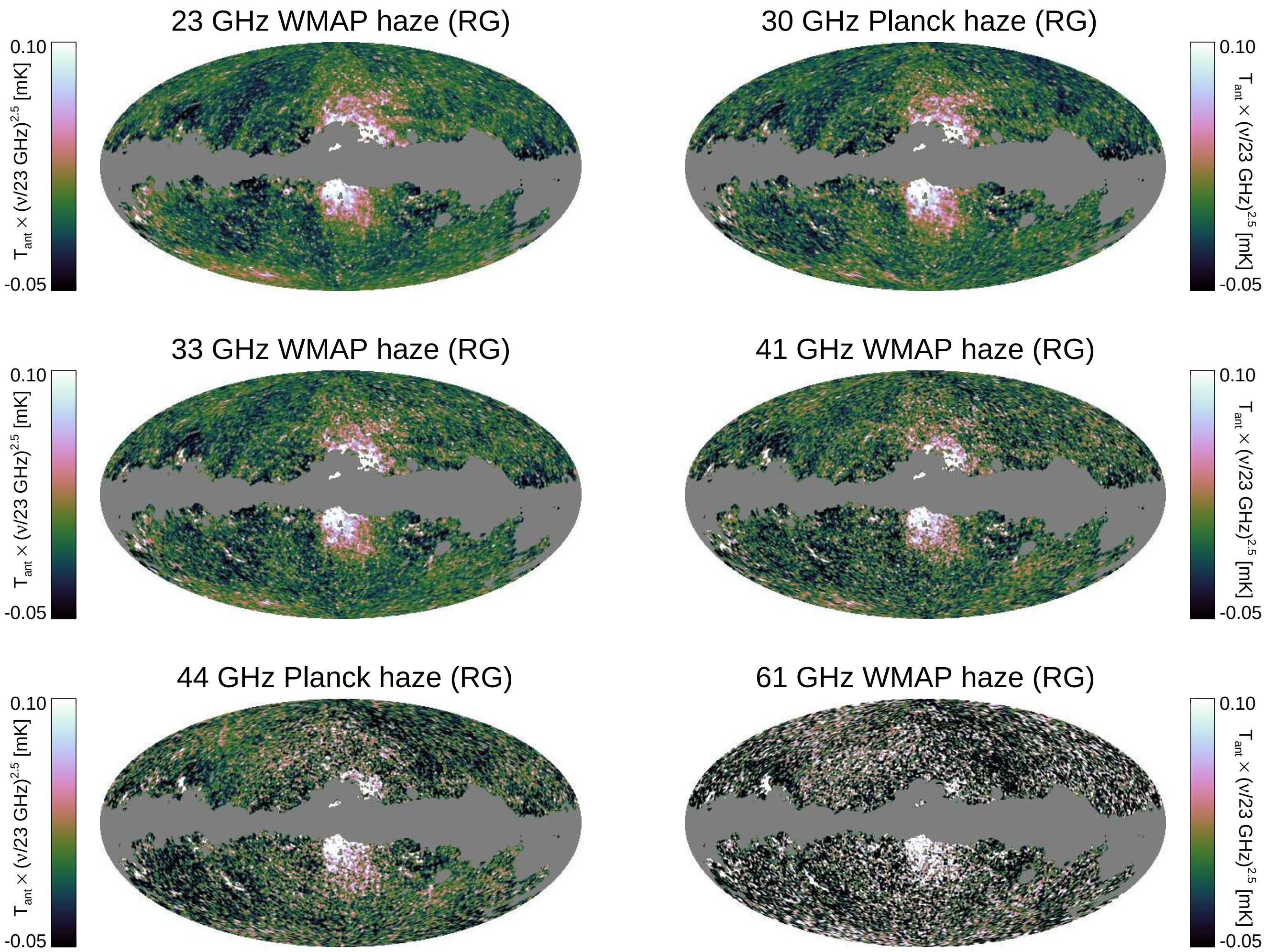

Fig. 5. The same as Fig. 4 but using the regions defined in DF08. Clearly, the residuals near the mask are significantly reduced, although, as with the full-sky fits, striping in the HFI channels (which leaks into the CMB estimate) becomes significant above ~ 40 GHz.

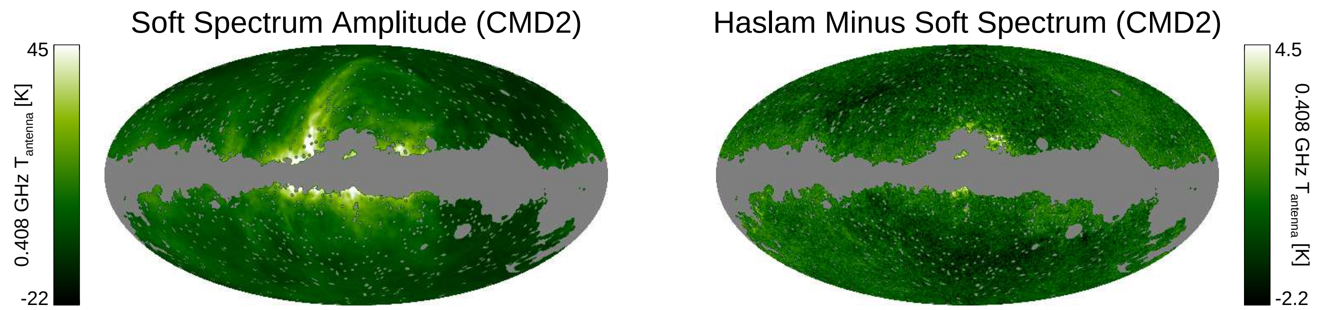

Fig. 6. *Left*: The soft synchrotron component at 408 MHz from the `Commander` CMD2 analysis. The map is strikingly similar to the Haslam map (see Fig. 1) indicating that soft synchrotron emission has a very uniform spectrum from 408 MHz to 60 GHz through all of the data sets. *Right*: The difference between the Haslam map and the `Commander` solution. This is consistent with noise across almost the entire sky with the exception of a few bright free-free clouds that are present in the Haslam data at the $\sim$ 10% level. The lack of significant haze emission in the difference map (particularly in the south) is a strong indication that the haze region consists of both a hard *and* a soft component rather than having a simple spatially variable spectral index.

sion with a spectral index that is harder than elsewhere in the Galaxy by $\beta_{\rm H} - \beta_{\rm S} = 0.5$. Within the haze region, this component represents $\sim$ 33% of the total synchrotron and 23% of the total Galactic emission at 23 GHz (*WMAP* K-band) while emissions correlated with Haslam, Hα, and FDS contribute 43%, 4%, and 30% respectively.

The $\beta_{\rm H} = -2.55$ spectral index of the haze is strongly indicative of synchrotron emission from a population of electrons with

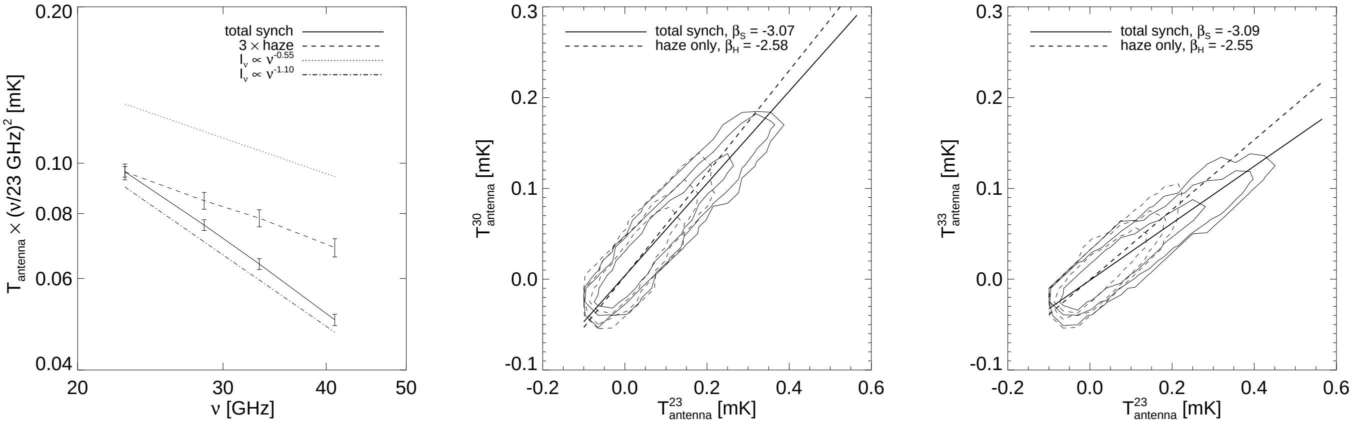

Fig. 7. *Left*: The spectrum measured from the residual in Fig. 5 in the region $|l| < 25°$, $-35° < b < -10°$. The haze spectrum is very nearly a power law with spectral index $\beta_H = -2.55$, while the total synchrotron emission in the region has a spectral index of $\beta_S = -3.1$ (see Sect. 4.3), significantly *softer* than the haze emission. This spectrum should be free from biases due to template uncertainties. *Middle* and *right*: Scatter plots (shown in contours) for both the haze (dotted) and total synchrotron (solid) emission using *WMAP* 23–33 GHz and *Planck* 30 GHz.

a spectrum that is harder than elsewhere in the Galaxy. The other possible origins of the emission in this frequency range (namely, free-free and spinning dust) are strongly disfavored for several reasons. First, the spinning dust mechanism is very unlikely since there is no corresponding feature in thermal dust emission at HFI frequencies. While it is true that environment can have an impact on both the grain size distribution and relative ratio of spinning to thermal dust emission (thus making the FDS models an imperfect tracer of spinning dust, e.g., Ysard et al. 2011), to generate a strong spinning dust signal at LFI frequencies while not simultaneously producing a thermal signal a highly contrived grain population would be required, in which small grains survive but large grains are completely destroyed. Furthermore, the FDS thermal predictions yield very low dust-correlated residuals (see Fig. 5) indicating a close correspondence between thermal and spinning-dust morphology. Finally, this spectrum is significantly softer than free-free emission, which has a characteristic spectral index ≈ -2.15. Since the Hα to free-free ratio is temperature-dependent, the possibility exists that the haze emission represents some mixture of synchrotron and free-free without yielding a detectable Hα signal. However, in order to have a measured spectral index of $\beta_H \approx -2.5$ from 23 to 41 GHz, free-free could only represent 50% of the emission if the synchrotron component had a spectral index ≈ -3. Since such a steep spectral index is ruled out by the lack of a strong haze signal at 408 MHz, the synchrotron emission must have a harder spectrum and the free-free component (if it exists) must be subdominant.[9] These considerations, coupled with the likely inverse-Compton signal with *Fermi* (see Dobler et al. 2010; Su et al. 2010), strongly indicate a separate component of synchrotron emission.

4.4. Spatial correspondence with the Fermi haze/bubbles

The gamma-ray emission from the *Fermi* haze/bubbles (Dobler et al. 2010; Su et al. 2010) is consistent with the inverse-Compton emission from a population of electrons with the energy spectrum required to reproduce the $\beta_H = 2.55$ haze emission measured in this paper. Furthermore, the *Fermi* “haze” has a very strong spatial coincidence with the *Planck* microwaves at low latitude (below $|b| \sim 35°$) as we show in Fig. 8. This suggests a common physical origin for these two measurements with the gamma-ray contribution extending down to $b \approx -50°$, while the microwaves fall off quickly below $b \approx -35°$. As in Dobler (2012), the interpretation is that the magnetic field within the haze/bubbles sharply decreases above ~ 5 kpc from the Galactic plane while the cosmic-ray distribution extends to $\sim$ 10 kpc and continues to generate gamma-ray emission (e.g., by inverse Compton scattering CMB photons). In Fig. 9 we show a full-sky representation of the *Planck* haze emission overlaid with the *Fermi* gamma-ray haze/bubbles from Dobler et al. (2010).

5. Summary

We have identified the presence of a microwave haze in the *Planck* LFI data and performed a joint analysis with 7-year *WMAP* data. Our findings verify not only that the haze is real, but also that it is consistent in amplitude and spectrum in these two different experiments. Furthermore, we have used *Planck* HFI maps to generate a CMB estimate that is nearly completely clean of haze emission, implying that we have reduced systematic biases in the inferred spectrum to a negligible level. We find that the unbiased haze spectrum is consistent with a power law of spectral index $\beta_H = -2.55 \pm 0.05$, ruling out free-free emission as a possible explanation, and strengthening the possibility of a hard synchrotron component origin. The spectrum of softer synchrotron emission found elsewhere in the Galaxy is $\beta_S = -3.1$, consistent with a cosmic-ray electron population that has been accelerated in supernova shocks and diffused throughout the Galaxy. This spectrum is significantly softer than the haze emission, which is not consistent with supernova shock acceleration after taking into account energy losses from diffusion effects.

The microwave haze is detected in the *Planck* maps with both simple template regression against the data and a more sophisticated Gibbs sampling analysis. The former provides an excellent visualisation of the haze at each wavelength on large scales while the latter allows a pixel-by-pixel analysis of the

[9] In addition, the lack of a bremsstrahlung signal in X-rays requires a fine tuning of the gas temperature to be $\sim 10^6$ K, a temperature at which the gas has a very short cooling time. This also argues against a free-free explanation as described in McQuinn & Zaldarriaga (2011).

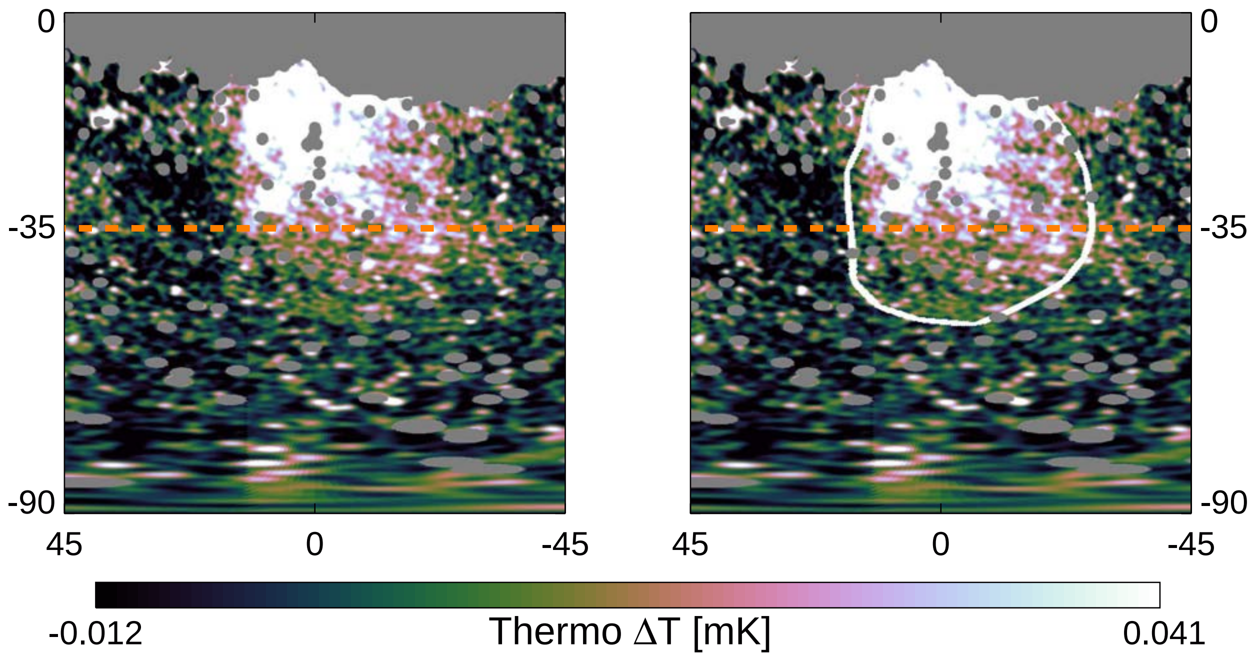

Fig. 8. *Left*: The southern *Planck* 30 GHz haze from Fig. 5. *Right*: The same but with contours of the *Fermi* gamma-ray haze/bubbles (Su et al. 2010) overlaid in white. Above $b = -35°$ (orange dashed line), the morphological correspondence is very strong suggesting that the two signals are generated by the same underlying phenomenon.

complete data set. While the template analysis allows us to derive the $\beta_{\rm H} = -2.55$ spectrum with high confidence, spectral determination with the Gibbs approach is more difficult given that noise must be added to the analysis to ensure convergence in the sampling method, and that a significantly more flexible model (in particular, one in which the spectrum of synchrotron is allowed to vary with each pixel) is used. However, not only is the spatial correspondence of the haze derived with the two methods excellent, but the Gibbs method allows us to show conclusively that the microwave haze is a separate component and not merely a variation in the spectral index of the synchrotron emission.

The morphology of the microwave haze is nearly identical from 23 to 44 GHz, implying that the spectrum does not vary significantly with position. Although detection of the haze in polarisation with *WMAP* remains unlikely given the noise level of the data (Dobler 2012), future work with *Planck* will concentrate on using its enhanced sensitivity to search for this component.

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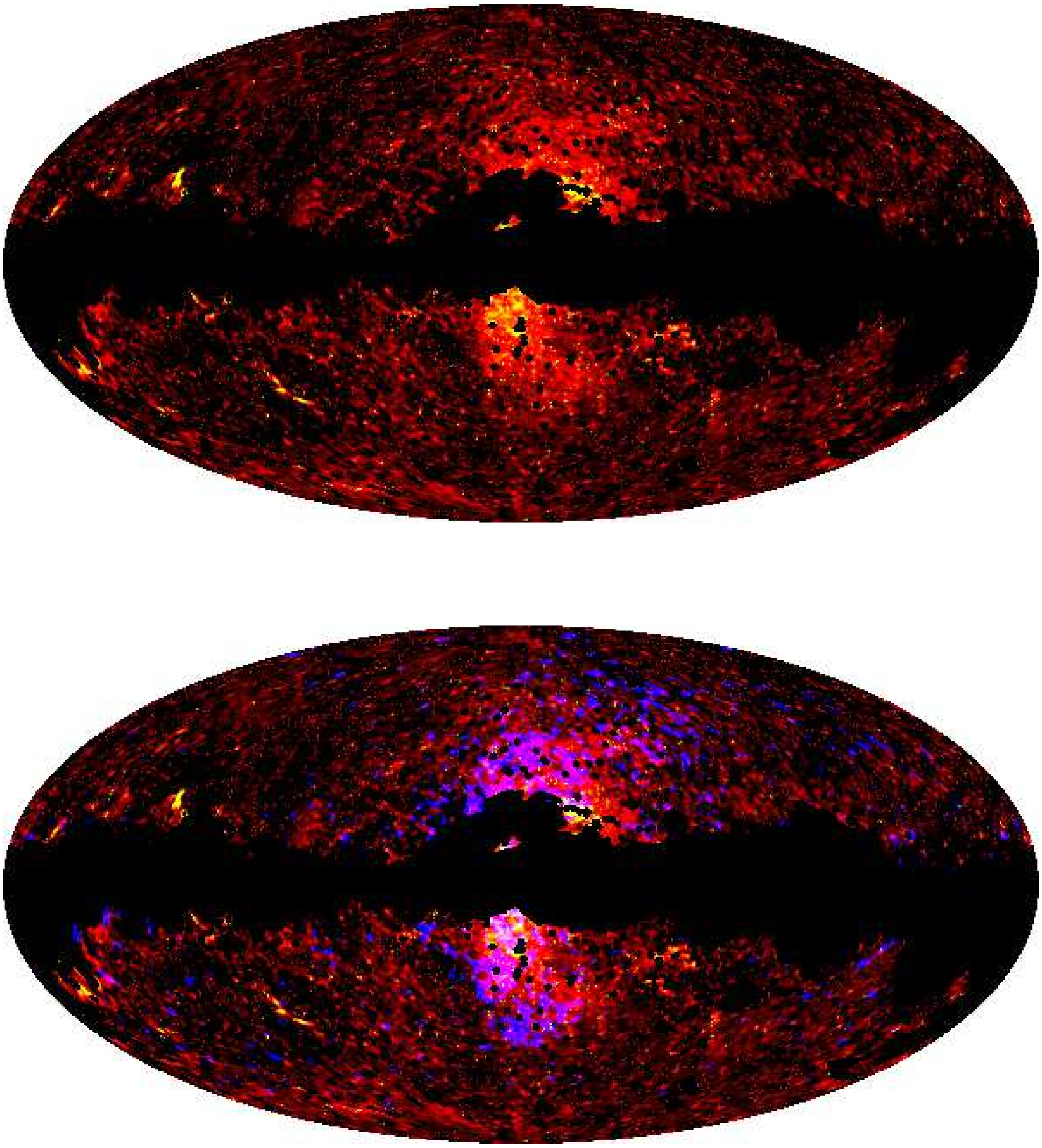

Fig. 9. *Top*: The microwave haze at *Planck* 30 GHz (red, $-12\ \mu$K < $\Delta T_{\rm CMB}$ < 30 μK) and 44 GHz (yellow, 12 μK < $\Delta T_{\rm CMB}$ < 40 μK). *Bottom*: The same but including the *Fermi* 2-5 GeV haze/bubbles of Dobler et al. (2010) (blue, 1.05 < intensity [keV cm^{-2} s^{-1} sr^{-1}] < 1.25; see their Fig. 11). The spatial correspondence between the two is excellent, particularly at low southern Galactic latitude, suggesting that this is a multi-wavelength view of the same underlying physical mechanism.

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