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Model of the polarized foreground diffuse Galactic emissions from 33 to 353 GHz

L. Fauvet [a], J.F. Macías-Pérez [a,*], F.X. Désert [b]

[a] LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, 53 avenue des Martyrs, 38026 Grenoble cedex, France
[b] IPAG: Institut de Planétologie et d'Astrophysique de Grenoble, UJF-Grenoble 1/ CNRS-INSU, UMR 5274, F-38041 Grenoble, France

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ABSTRACT

We present 3D models of the Galactic magnetic field including regular and turbulent components, and of the distribution of matter in the Galaxy including relativistic electrons and dust grains. By integrating along the line of sight, we construct maps of the polarized Galactic synchrotron and thermal dust emissions for each of these models. We perform a likelihood analysis to compare the maps of the Ka, Q, V and W bands of the Wilkinson Microwave Anisotropy Probe (WMAP) and the 353 GHz ARCHEOPS data to the models obtained by varying the pitch angle of the regular magnetic field, the relative amplitude of the turbulent magnetic field and the extrapolation spectral indices of the synchrotron and thermal dust emissions. The best-fit parameters obtained for the different frequency bands are very similar and globally the data seem to favor a negligible isotropic turbulent magnetic field component at large angular scales (an anisotropic line-of-sight ordered component can not be studied using these data). From this study, we conclude that we are able to propose a consistent model of the polarized diffuse Galactic synchrotron and thermal dust emissions in the frequency range from 33 to 353 GHz, where most of the CMB studies are performed and where we expect a mixture of these two main foreground emissions. This model can be very helpful to estimate the contamination by foregrounds of the polarized CMB anisotropies, for experiments like the PLANCK satellite.

1. Introduction

The PLANCK[1] satellite mission [41,49], currently in flight, will provide measurements of the CMB anisotropies both in temperature and polarization over the full sky with an unprecedented accuracy [40]. In particular, it should be able to measure the tensor-to-scalar ratio, r, which sets the energy scale of inflation [34,39]. For a extended mission and in the case of no direct detection, Planck should set an upper limit of $r < 0.03$ [7,11,10], and thus provides tight constraints on inflationary models [1]. To achieve this high level of sensitivity, it is necessary to estimate accurately the temperature and polarization anisotropies from foreground diffuse Galactic emissions and from point-like and compact sources of Galactic and extraGalactic origin. A reliable estimation of the residual contamination due to the foreground emissions after application of component separation methods (see [5,31] for recent studies) is thus necessary to retrieve the cosmological information from the PLANCK data.

As summarized in [13] the main polarized foreground contributions come from the diffuse Galactic synchrotron emission [38] and from thermal dust emission [3,44]. The polarized synchrotron emission have already been modeled by [38,48,24,25,13] based on models of the Galactic magnetic field [19,20] and of the relativistic electrons in the Galaxy. Concerning the thermal dust emission, modeling based on the physical origins of this polarized emission has already been discussed in [44,38,13].

We propose here an extended analysis of the 3D joint model of the Galactic polarized diffuse emissions discussed in [13]. In the previous analysis we focused on the WMAP data at 23 GHz and ARCHEOPS at 353 GHz data where synchrotron and thermal dust emissions dominate, respectively. Here, we use complementary data: the other frequency bands of WMAP from 33 to 94 GHz, where a mixing of those emissions is expected, and the ARCHEOPS data at 353 GHz. Furthermore we apply here a pixel-to-pixel likelihood based comparison instead of a Galactic profile-based method as discussed in [13].

The paper is structured as follows: Section 2 describes the 5-year WMAP and ARCHEOPS data set used in the analysis. In Section 3 we describe in detail models for the polarized foreground emissions. Section 4 discusses the 3D model of the Galaxy using to construct the polarized Galactic emissions. The models are statistically compared to the data in Section 5 and we discuss the results in Section 6. We finally conclude in Section 7.

2. Observations

2.1. Diffuse Galactic synchrotron emission

The synchrotron emission is an important contributor to the diffuse sky emission at both radio and microwave observation frequencies.

* Corresponding author.
E-mail address: macias@lpsc.in2p3.fr (J.F. Macías-Pérez).
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In intensity, the 408 MHz all-sky continuum survey [21], at a resolution of 0.85 degrees, is a good tracer of the synchrotron emission and it will be used in the following as a template. In particular, we use the 408 MHz all-sky map available on the LAMBDA website in the HEALPIX pixelisation scheme [18]. We correct this map from the contribution from free-free emission which estimated to be about 30%. The corrected maps was then downgraded to the resolution of the WMAP and Archeops maps discussed below.

In polarization, Faraday rotation introduces complications into the interpretation of the radio data since strong depolarization is observed for frequencies lower than 10 GHz, particularly concerning the inner part of the Galaxy [8,48,24,25,29]. A detailed discussion on the depolarization process, based on data from the Leiden survey, can be found in [28]. For this reason the best polarized Galactic diffuse synchrotron tracers are at high frequency such as the WMAP survey [38].

We used here the 5-year WMAP Q and U low resolution maps for the frequency channels centered at 33 (Ka band), 41 (Q band), 61 (V band) and 94 GHz (W band) [37,17]. These data are available on the LAMBDA website in the HEALPIX pixelisation scheme at $N_{side} = 16$. The associated noise is estimated using the full noise correlation matrix also available on the LAMBDA website in the same resolution.

2.2. Thermal dust

The thermal dust emission is significant in the WMAP data only for frequencies above 70 GHz, then we also used here the ARCHEOPS 353 GHz Q and U maps as tracers of the polarized thermal dust emission. Those maps cover about 20% of the sky [35] and were filtered and downgraded to $N_{side} = 16$ to make them comparable to the WMAP ones.

In intensity, the most accurate measurements of the thermal dust emission are those of the IRAS satellite [36] and in particular at 100 μm. We use here predicted full-sky maps of sub millimeter and microwave emission from the diffuse interstellar dust in the Galaxy from [15] which were produced combining the IRAS data at 6.1 arcmin and the COBE DIRBE data at 40 arcmin [47]. These maps were downgraded to the resolution of the WMAP and Archeops maps presented above.

3. Emissivity model in polarization

We present in this section a realistic model of the diffuse polarized synchrotron and dust emissions using a 3D model of the Galactic magnetic field and of the matter density in the Galaxy. We will consider the distribution of relativistic cosmic-ray electrons (CREs), n_{CRE}, for the synchrotron emission and the distribution of dust grains, n_{dust}, for the thermal dust emission. Following [13] we calculate the Stokes parameters I, Q and U for the Galactic polarized emission along the line of sight as follows.

For the synchrotron emission [46] we write:

$$I_\nu^{\mathrm{sync}}(\mathbf{n}) = I^{\mathrm{Has/ff}}(\mathbf{n})\left(\frac{\nu}{0.408}\right)^{\beta_s}, \tag{1}$$

$$Q_\nu^{\mathrm{sync}}(\mathbf{n}) = I_{\mathrm{Has/ff}}(\mathbf{n})\left(\frac{\nu}{0.408}\right)^{\beta_s} \tag{2}$$

$$\frac{\int \cos(2\gamma(\mathbf{n},s))p_s\left(B_l^2(\mathbf{n},s)+B_t^2(\mathbf{n},s)\right)\mathrm{n}_{\mathrm{CRE}}(\mathbf{n},s)ds}{\int\left(B_l^2(\mathbf{n},z)+B_t^2(\mathbf{n},s)\right)\mathrm{n}_{\mathrm{CRE}}(\mathbf{n},s)ds}, \tag{3}$$

$$U_\nu^{\mathrm{sync}}(\mathbf{n}) = I_{\mathrm{Has/ff}}(\mathbf{n})\left(\frac{\nu}{0.408}\right)^{\beta_s} \tag{4}$$

$$\frac{\int \sin(2\gamma(\mathbf{n},s))p_s\left(B_l^2(\mathbf{n},s)+B_t^2(\mathbf{n},s)\right)\mathrm{n}_{\mathrm{CRE}}(\mathbf{n},s)ds}{\int\left(B_l^2(\mathbf{n},s)+B_t^2(\mathbf{n},s)\right)\mathrm{n}_{\mathrm{CRE}}(\mathbf{n},s)ds}, \tag{5}$$

where $B_n(\mathbf{n},s)$ is the magnetic component along the line-of-sight $\mathbf{n}$, and $B_l(\mathbf{n},s)$ and $B_t(\mathbf{n},s)$ the magnetic field components on a plane perpendicular to the line-of-sight. Notice that the 3 vectors n, l, t form an orthonormal basis being l and t oriented to the north and to the east respectively in a plane perpendicular to n. The polarization fraction p_s is set to 75% [46]. The polarization angle $\gamma(\mathbf{n},s)$ is given by:

$$\gamma(\mathbf{n},s) = \frac{1}{2}\arctan\left(\frac{2B_l(\mathbf{n},s)\cdot B_t(\mathbf{n},s)}{B_l^2(\mathbf{n},s)-B_t^2(\mathbf{n},s)}\right). \tag{6}$$

The distribution of relativistic electrons, $\mathrm{n}_{\mathrm{CRE}}$, is described in detail in Section 4. $I_{\mathrm{Has/ff}}$ is the reference map in intensity constructed from the *408 MHz all sky continuum survey* [21] after subtraction of the bremsstrahlung (*free–free*) emission and ν is the frequency of observation. To subtract the free–free contribution we used the WMAP K-band free–free foreground map generated from the maximum entropy method (MEM) [22,2]. Notice that we do not use the synchrotron MEM intensity map at 23 GHz [22] as a synchrotron template to avoid any possible Anomalous Microwave Emission (AME) contamination (the WMAP team made no attempt to fit for the latter). The spectral index β_s used to extrapolate maps at various frequencies is a free parameter of the model. The SED of the synchrotron emission in the radio and microwave domain, and in particular in the 33 to 353 GHz range, can be well approximated by a power law in antenna temperature units [46]. This is due to the fact that the energy spectrum of the Galactic relativistic electrons producing the radio and microwave synchrotron emission is also well approximated by a power law [26].

For the thermal dust emission we write

$$I_\nu^{\mathrm{dust}}(\mathbf{n}) = \mathrm{I}_{\mathrm{fds}}(\mathbf{n})\left(\frac{\nu}{353}\right)^{\beta_d}, \tag{7}$$

$$Q_\nu^{\mathrm{dust}}(\mathbf{n}) = \mathrm{I}_{\mathrm{fds}}(\mathbf{n})\left(\frac{\nu}{353}\right)^{\beta_d}, \tag{8}$$

$$\frac{\int\cos(2\gamma(\mathbf{n},s))\sin^2(\alpha)f_{\mathrm{norm}}p_d\mathrm{n}_{\mathrm{dust}}(\mathbf{n},s)ds}{\int\mathrm{n}_{\mathrm{dust}}(\mathbf{n},s)ds}, \tag{9}$$

$$U_\nu^{\mathrm{dust}}(\mathbf{n}) = \mathrm{I}_{\mathrm{fds}}(\mathbf{n})\left(\frac{\nu}{353}\right)^{\beta_d}, \tag{10}$$

$$\frac{\int\sin(2\gamma(\mathbf{n},s))\sin^2(\alpha)f_{\mathrm{norm}}p_d\mathrm{n}_{\mathrm{dust}}(\mathbf{n},s)ds}{\int\mathrm{n}_{\mathrm{dust}}(\mathbf{n},s)ds}, \tag{11}$$

where the dust polarization fraction p_d is set to 10% [44] based on the ARCHEOPS data, and $\mathrm{n}_{\mathrm{dust}}(r,z)$ is the dust grain distribution discussed in Section 4. The $sin2(\alpha)$ term accounts for the geometrical suppression and f_{norm} is an empirical factor which accounts for the misalignment between dust grains and the magnetic field lines (see [13] for details). The reference map, $\mathrm{I}_{\mathrm{fds}}$ was taken to be model 8 in [15] at 545 GHz. The spectral index β_d used to extrapolate maps at various frequencies is a free parameter of the model. In the following we work on antenna temperature, Rayleigh–Jeans units. Assuming nearly constant dust temperature across the sky then a power-law approximation for the thermal dust emission in antenna temperature units can be used [43].

4. A 3D modeling of the Galaxy

We describe here the 3D model of the Galaxy as used in the previous Stokes parameter definitions both for synchrotron and dust.

4.1. Matter density model

In galactocentric cylindrical coordinates (r,z,ϕ) we consider an exponential distribution of relativistic electrons n_{CRE} on the Galactic disk motivated by [9]: