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Foregrounds: Models

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1 FOREGROUNDS

At the GHz frequencies, the foreground sky is dominated by Galactic synchrotron, Galactic free-free, Galactic thermal dust, Galactic AME, CMB, and extragalactic point sources. In what follows, we describe the models that we use to simulate each of these emissions. The values that are quoted are used as default in the software.

1.1 Galactic Synchrotron

The Galactic synchrotron emission arises from interactions between cosmic ray electrons and magnetic fields in the Galaxy. We parametrize the synchrotron brightness temperature as

$$T_{\rm syn}(\nu,p) = T_{\rm syn}(\nu_0,p)\left(\frac{\nu}{\nu_0}\right)^{\beta(p)+C\log(\nu/\nu_p)}, \qquad (1)$$

where p is the pixel (line-of-sight), $T_{\rm syn}(\nu_0,p)$ is the synchrotron template at frequency ν_0, C is the curvature amplitude, and ν_p is a pivot frequency. Positive values of C flatten and negative ones steepen the spectral law for increasing frequency. We use $C = 0.3$ and $\nu_p = 23\,$GHz (Kogut et al. 2007).

For the synchrotron radiation we use as a template the reprocessed Haslam et al. (1982) map at 408 MHz of Remazeilles et al. (2015). This map includes small-scale fluctuations (i.e., it has 'infinite resolution'). The approach used for artificially adding these fluctuations is described in Delabrouille et al. (2013). We consider that the synchrotron spectral index is spatially variable. We use two models for this: the Miville-Deschênes et al. (2008) model, which used WMAP intensity and polarization data to do a separation of the Galactic components, and the Giardino et al. (2002) model, which was derived using the full-sky map of synchrotron emission at 408 MHz from Haslam et al. (1982), the northern-hemisphere map at 1420 MHz from Reich & Reich (1986) and the southern-hemisphere map at 2326 MHz from Jonas et al. (1998). In the Miville-Deschênes et al. (2008) model the synchrotron spectral index has a mean value of -3.00 and a standard deviation of 0.06, while these values are -2.9 and 0.1 for the Giardino et al. (2002) model. The Miville-Deschênes et al. (2008) model is good for frequencies $\gtrsim 10\,$GHz, while the Giardino et al. (2002) model is good for frequencies $\lesssim 2.3\,$GHz.

1.2 Galactic Free-Free

The Galactic free-free emission (also known as bremsstrahlung) arises from electron-ion scattering in interstellar plasma and is called 'free-free' because of the unbound state of the incoming and outgoing electron. It is known that this emission can be traced with Hα line emission. This justify our use of the Hα map of Dickinson et al. (2003) as a template for it. This map includes small-scale fluctuations (i.e., it has 'infinite resolution'). The approach used for artificially adding these fluctuations is described in Delabrouille et al. (2013). The following relationship between radio emission (given in K) and Hα emission (given in R) can be used to produce free-free maps at the appropriate frequency (Dickinson et al. 2003),

$$T_{\rm ff} = 8.396\times10^3 a(\nu,T_e)\times\nu_{\rm GHz}^{-2.1}T_4^{0.667}10^{0.029/T_4}\times(1.08)\times I_{\rm H\alpha}, \qquad (2)$$

where $I_{\rm H\alpha}$ is the Hα template, T_4 is the electron temperature in units of $10^4\,$K, and the factor $a(\nu,T_e)$ is given by

$$a(\nu,T_e) = 0.366\,\nu_{\rm GHz}^{0.1}\,T_e^{-0.15}\times\left\{\ln[4.995\times10^{-2}\nu_{\rm GHz}^{-1}] + 1.5\ln(T_e)\right\}, \qquad (3)$$

with T_e the electron temperature in K. We assume an electron temperature of $T_e = 7000\,$K.

1.3 Galactic Thermal Dust

The Galactic thermal dust radiation is the product of the re-emission of ultraviolet light absorbed by the various populations of dust grains that are present in the Galaxy. The primordial origin of the radiation is the ultraviolet emission from stars. The model of dust emission that we use is a modified blackbody spectrum with three parameters:

$$T_{\rm B,d}(\nu,p) = T_{\rm B,d}(\nu_0,p)\left(\frac{e^{\gamma(p)\nu_0}-1}{e^{\gamma(p)\nu}-1}\right)\left(\frac{\nu}{\nu_0}\right)^{\beta(p)+1}, \qquad (4)$$

where $T_{\rm B,d}(\nu_0,p)$ is a thermal dust brightness temperature template at frequency ν_0, $\beta(p)$ is a thermal dust spectral index template, and $\gamma(p) = h/k_{\rm B}T_{\rm d}(p)$, where $k_{\rm B}$ is the Boltzmann constant, h is the Planck constant and $T_{\rm d}(p)$ is a thermal dust (thermodynamic) temperature template. The templates that are used are the GNILC *Planck* templates for dust at 353 GHz (Planck Collaboration et al. 2016c). We note that the GNILC dust optical depth map requires the conversion from MJy/sr to μK.

1.4 Galactic Anomalous Microwave Emission

There is strong evidence for a fourth Galactic foreground component in the microwave range: the so-called anomalous microwave emission (AME). This emission is spatially correlated with the 100 μm dust map and the currently most plausible candidate is tiny Polycyclic Aromatic Hydrocarbons (PAH) particles spinning with dipole moments, i.e., 'spinning dust'. To simulate the Galactic AME emission we use as a template the *Planck* τ_{353} optical depth map. This quantity is known to be a good tracer of the Galactic AME emission. This template has to be re-scaled to the appropriated unity (μK) and frequency (~ 30 GHz). For the first, we use the ratio $8.3 \times 10^6\,\mathrm{K}/\tau_{353}$ (Planck Collaboration et al. 2016a) and for the second, we use the emission law of a population of spinning dust grains implemented in the SPDUST software (Ali-Haïmoud et al. 2009; Silsbee et al. 2011).

1.5 Cosmic Microwave Background

Most of the cosmic radiation that we observe today is in the form of an almost isotropic blackbody spectrum, with a temperature of order of 2.7 K, known as the cosmic microwave background (CMB). When expressed in thermodynamic temperature, this component is the same for all frequency channels and has fluctuation of the order of 500 μK. As the maps of the other emissions are given in brightness temperature, we need to have CMB maps expressed in this quantity as well, i.e., we need to go from $\mu\mathrm{K}_{\mathrm{CMB}}$ to $\mu\mathrm{K}_{\mathrm{RJ}}$. This can be done with the following formula:

$$T_{\mathrm{B}}(\nu, p) = \frac{\gamma(p)\nu}{e^{\gamma(p)\nu} - 1} T_{\mathrm{ther}}(p), \tag{5}$$

where $\gamma(p) = h/k_{\mathrm{B}} T_{\mathrm{ther}}(p)$, $T_{\mathrm{B}}(\nu, p)$ is the CMB map expressed in brightness temperature, and $T_{\mathrm{ther}}(p)$ is the CMB map expressed in thermodynamic temperature. This makes the CMB to evolve with frequency. To simulate the CMB emission in thermodynamic temperature we use the CAMB software (Lewis et al. 2000) to calculate its angular power spectrum and the SYNFAST routine (Górski et al. 2005) to generate its template map. As for the cosmological parameters, we assume a ΛCDM cosmology with the parameters being given by the Planck Collaboration et al. (2016b) best-fit results.

1.6 Extragalactic Point Sources

Extragalactic radio sources are an inhomogeneous mix of radio galaxies, quasars, star-forming galaxies, and other objects. In this work, we follow Olivari et al. (2018) and calculate the contribution of point sources, T_{ps}, from the differential source count, $\mathrm{d}N/\mathrm{d}S$, representing the number of sources per steradian, N, per unit flux, S. At 1.4 GHz, we have access to a number of compilations of source counts. We choose to use data collected by Battye et al. (2013) from continuum surveys at 1.4 GHz between 1985 and 2009. We also use the fifth order polynomial that was fitted by Battye et al. (2013) to these data as our source count $\mathrm{d}N/\mathrm{d}S$. This polynomial is given by

$$\ln\left(\frac{S^{2.5}\mathrm{d}N/\mathrm{d}S}{N_0}\right) = \sum_{i=0}^{5} a_i \left[\ln\left(\frac{S_i}{S_0}\right)\right]^i, \tag{6}$$

where $N_0 = 1\,\mathrm{Jy\ sr}^{-1}$ and $S_0 = 1$ Jy are normalizing constants. A least-squares fit gives the best-fitting coefficients: $a_0 = 2.593$, $a_1 = 0.093$, $a_2 = -0.0004$, $a_3 = 0.249$, $a_4 = 0.090$ and $a_5 = 0.009$.

The Poisson distributed sources have, in the limit of a large number of sources (i.e., for $S'_{\mathrm{max}} \lesssim 0.01$ Jy), a white power spectrum given by (Battye et al. 2013; Olivari et al. 2018)

$$C_\ell^{\mathrm{Poisson}} = \left(\frac{\mathrm{d}B}{\mathrm{d}T}\right)^{-2} \int_0^{S'_{\mathrm{max}}} S^2 \frac{\mathrm{d}N}{\mathrm{d}S} \mathrm{d}S, \tag{7}$$

where $\mathrm{d}B/\mathrm{d}T = 2k_{\mathrm{B}}\nu^2/c^2$ and ν is the observed frequency. However, for $S > 0.01$ Jy, the source density on the sky becomes too low and these bright sources must be injected directly into the map. To do this, we first estimate the mean brightness temperature by

$$T_{\mathrm{ps}}(\nu, \hat{n}) = \left(\frac{\mathrm{d}B}{\mathrm{d}T}\right)^{-1} \Omega_{\mathrm{pix}}^{-1} \sum_{i=1}^{N} S_i(\nu), \tag{8}$$

where $S_i(\nu)$ is the flux of the point source i at frequency ν and Ω_{pix} is the pixel size. We then randomly distribute in the sky N of sources with flux $S(\nu)$ such that these sources respect the underlying source count, i.e., we calculate

$$\int_{\Delta S} \frac{\mathrm{d}N}{\mathrm{d}S} \mathrm{d}S, \tag{9}$$

for each decade ΔS in flux. In this step a new maximum flux must be assumed. In this work, we consider $S_{\mathrm{max}} = 1$ Jy. Sources with larger fluxes are assumed to have been removed (masked) from the data before component separation.

The power spectrum due to the clustered sources can be simply estimated as $C_\ell^{\mathrm{cluster}} = w_\ell \bar{T}_{\mathrm{ps}}^2$, where w_ℓ is the Legendre transform of the angular correlation function, $w(\theta)$. At the 1 GHz regime, the clustering of radio sources at low flux densities (<10 mJy) is not well known. To make an estimate, we use $w(\theta)$ measured from NVSS, which can be approximated as $w(\theta) \approx (1.0 \pm 0.2) \times 10^{-3}\theta^{-0.8}$ (Overzier et al. 2003), where θ is in degrees. Legendre transforming this expression, Battye et al. (2013) find $w_\ell \approx 1.8 \times 10^{-4}\ell^{-1.2}$.

A power-law frequency scaling is assumed for the point source brightness temperature, $T_{\mathrm{B}} \propto \nu^\alpha$. The value of α is randomly chosen for each pixel of the simulated map from a Gaussian distribution with mean $\alpha_0 = -2.7$ and standard deviation $\sigma_\alpha = 0.2$ (Bigot-Sazy et al. 2015; Olivari et al. 2018).

2 PIXELIZATION

To produce maps for the foregrounds, we use the HEALPIX package (Górski et al. 2005) with a resolution of N_{side}, i.e., with a number of pixels of $N_{\mathrm{pixel}} = 12 \times N_{\mathrm{side}}^2$. This gives us a pixel size of $\approx \left(41253 \times 60^2/N_{\mathrm{pixel}}\right)^{1/2}$ arcmin.

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