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Foregrounds: Models

L. C. Olivari*[1]
[1] *Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970, São Paulo, SP, Brazil*

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

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

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),

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

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

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

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:

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

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 XLVIII 2016). We note that the GNILC dust optical depth map requires the conversion from MJy/sr to μK. Again, we use the Delabrouille et al. (2013) methodology to add small-scale power to the emission template.

Table 1. The parameters of cold neutral medium (CNM) environment from Draine & Lazarian (1998b) used in the SPDUST2 code for calculating the AME emissivity as a function of frequency. $n_{\rm H}$ is the gas density, T is the gas temperature, T_d is the dust temperature, and χ is the strength of the interstellar radiation field. y, $x_{\rm H}$ and $x_{\rm M}$ are the fractions of molecular hydrogen, ions of hydrogen, and heavier ions, respectively.

Parameters	CNM value
$n_{\rm H}$ (cm^{-3})	30
T(K)	100
T_d(K)	20
χ	1
$y \equiv 2n({\rm H}_2)/n_{\rm H}$	0
$x_{\rm H} \equiv n({\rm H}^+)/n_{\rm H}$	0.0012
$x_{\rm M} \equiv n({\rm M}^+)/n_{\rm H}$	0.0003

1.3.1 *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) (Leitch et al. 1997; Draine & Lazarian 1999). It is actually one of the dominant foregrounds in the frequency range of 10−60 GHz (e.g., Davies et al. 2006; Planck Collaboration X 2016; Dickinson et al. 2018). The most accepted model for the AME mechanism is the spinning dust model, where the electric dipoles in the small dust grains spin up, producing radio emission (e.g., Draine & Lazarian 1998a,b).

In order to simulate the AME emission, we use as a template the *Planck* GNILC τ_{353} optical depth map (Planck Collaboration XLVIII 2016). We adopt the factor $8.3 \times 10^6\,\mu{\rm K}/\tau_{353}$ to convert the dust optical depth at 353 GHz to AME temperature at 22.8 GHz, in units of μK (Planck Collaboration XXV 2016).

To scale the AME emission from 22.8 GHz to the IM frequencies of ~ 1 GHz, we use the publicly available SPDUST2 code (Ali-Haïmoud et al. 2009; Silsbee et al. 2011), which calculates the spinning dust emissivity as a function of frequency for various environments of the interstellar medium. In our case, we use the cold neutral medium environment (CNM) of the interstellar medium. The parameters of the CNM environment are from Draine & Lazarian (1998b) and are listed in Table 1.

1.4 Cosmic Microwave Background

Most of the cosmic radiation that we observe today is in the form of an almost isotropic blackbody spectrum, with a mean temperature of $T_{\rm CMB} \simeq 2.726$ K, known as the cosmic microwave background (CMB) (Durrer 2008). The CMB temperature, however, is not perfectly homogeneous and has fluctuations of the order of $\pm 100\,\mu$K, making it a relevant foreground at ~ 1 GHz.

The simulated map of CMB temperature anisotropies is interpolated across COMAP frequencies through:

$$\Delta T_{\rm B}(\nu, p) = \frac{x^2 e^x}{(e^x - 1)^2} \Delta T_{\rm ther}(p), \tag{5}$$

where $x = h_{\rm P}\nu / k_{\rm B} T_{\rm CMB}$, $T_{\rm B}(\nu, p)$ is the CMB map expressed in brightness temperature, and $T_{\rm ther}(p)$ is the CMB map expressed in thermodynamic temperature. To simulate the CMB emission in thermodynamic temperature we have used the CAMB software (Lewis et al. 2000) to calculate the CMB angular power spectrum, using the standard ΛCDM concordance model parameters (Planck Collaboration XIII 2016), and the SYNFAST routine (Górski et al. 2005) to generate a Gaussian CMB map realisation for it.

1.5 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, $T_{\rm ps}$, from the differential source count, dN/dS, 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 dN/dS. This polynomial is given by

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

where $N_0 = 1\,{\rm Jy\ sr}^{-1}$ 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 $S'_{\rm max} \lesssim 0.01$ Jy), a white power spectrum given by (Battye et al. 2013; Olivari et al. 2018)

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

where ${\rm d}B/{\rm d}T = 2k_{\rm B}\nu^2/c^2$ 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

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

where $S_i(\nu)$ is the flux of the point source i at frequency ν and $\Omega_{\rm pix}$ 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

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

for each decade ΔS in flux. In this step a new maximum flux must be assumed. In this work, we consider $S_{\rm max} = 1$ 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 $C_\ell^{\rm cluster} = w_\ell \bar{T}_{\rm ps}^2$, 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, $T_{\rm B} \propto \nu^{\alpha}$. 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 $N_{\rm side}$, i.e., with a number of pixels of $N_{\rm pixel} = 12 \times N_{\rm side}^2$. This gives us a pixel size of $\approx \left(41253 \times 60^2 / N_{\rm pixel}\right)^{1/2}$ arcmin.

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